EXPERIMENTAL STUDY OF THE EFFECT OF A CONTACT CONDITIONER ON SLIDING ELECTRIC CONTACT

A Thesis by

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I have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science with a major in Industrial Engineering.

Vis Madhavan, Committee Chair

We have read this thesis and recommend its acceptance

Lawrence Whitman, Committee Member

T. S. Ravigururajan, Committee Member
DEDICATION

To my beloved parents and my sister
ACKNOWLEDGEMENTS

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A final acknowledgement is due to the Naval Research Lab for providing the financial support for this work and my graduate education.
This thesis is aimed at studying the tribology of sliding contacts subject to high current densities. A flat-ended Copper tip sliding on a flat Copper plate was the test configuration and current densities of the order of 10, 500 and 1000 A/mm$^2$ were used. The friction coefficient, contact resistance and material transfer were studied for clean metal-to-metal contacts and compared with those for the case where a solid lubricant interface conditioner (SLIC) was used.

Three types of tests were carried out. Static tests were done with and without pre-application of conditioner to evaluate the repeatability of contact resistance measurement and to study the effect of applied load and conditioner on the conductivity of the interface. It was found that pre-application of a thick layer of SLIC increases the contact resistance by 20 %. Circular tests, with the pin repeatedly traversing a circle, were done to evaluate the effect of sliding distance on the frictional coefficient and contact resistance with and without pre-application of solid conditioner. It was found that the conditioner reduces the friction coefficient in half and increases the time to failure many-fold. However, there was a small increase in contact resistance with conditioner.

The wear rate of the tip increased with increase in contact pressure and current density. Spiral tests, where the tip was moved outward from the center of the plate, were done to study the transfer of material between the pin and the plate and the effect of change in surface velocity.
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1.1 Introduction

The electromagnetic rail gun is a cost-effective and powerful gun under development by all the branches of the military. The gun is expected to be capable of accelerating projectiles to speeds of the order of a few km/s, capable of reaching targets 500 km away in less than 10 minutes. It operates by delivering a pulse of high current to an armature sliding on two rails. The current interacts with its self generated electro-magnetic field and results in a high force that accelerates the armature out of the gun. Extensive research in the field of hypervelocity weapons has resulted in the development of prototype guns that can launch a projectile with a kinetic energy of 10MJ at a speed of 2.5 km/s. Failure of the sliding contact interface, by way of wear of the armature and rail and arcing along the contact, increases the contact impedance, reduces the current and reduces the energy of launch. It has been observed from experiments that the sliding interface suddenly becomes resistive at high velocity and at high current level. Because of this most launchers have failed to achieve constant acceleration during launch. Several attempts have been made to overcome the instability, including hardening of the rails, controlling the interface contact pressure, reducing the area current density and modifying the current wave form, but the problem of transition to arcing is still unresolved.

It has been proposed [Singer et al., 1995] that a solid lubricant conditioner could potentially reduce the metal transfer, wear along the rails and inhibit the transition to arcing. Initial tests with a SLIC conditioner lead to significant improvement in rail life and shot-to-shot repeatability. This thesis addresses the develop application of three types of tests to study the
effect of contact conditioner on the contact resistance, coefficient of friction and transfer of armature material to the rails.

1.2 Thesis Organization

In Chapter two, a survey of the previous literature on sliding contacts in general, and sliding electric contacts in particulars, is given. Chapter three discusses in detail the experimental setup for low and high current tests for the measurement of coefficient of friction and contact resistance. Results are presented and discussed in Chapter four and conclusions and suggestions for future work are given in chapter five.
CHAPTER 2: LITERATURE REVIEW

This chapter begins with a review of the terminology used in the literature and provides a brief discussion of the relevant research work done earlier on the tribology of sliding electrical contacts.

A] Terminology used in the literature on electrical contacts

Electrical contacts are those through which electric current is expected to be conducted. The mechanical and molecular interactions across the interface determine the coefficient of friction and the contact resistance between two surfaces in contact, which are of prime interest in this study.

Electrical contacts are broadly classified into static contacts, in which the contacting bodies are not subjected to relative movement, sliding contacts, which are expected to perform their electrical function while their relative sliding of the two bodies in contact and a third category called wiping contacts. During opening and closing of switches and relays, contacts are often referred to as “wiping” rather than sliding contacts because electrical contacts are not usually expected to conduct efficiently during wiping motion. Some tangential motion will exist between the surfaces in any static mechanical contact. The members could be subjected to small relative motion because of the thermal expansion resulting from temperature variation and/or mechanical vibration. This is often referred to as “fretting“.

Real surfaces are not exactly flat and have many asperities. When a contact is made between two conducting bodies, the asperities of the surfaces, will typically penetrate the natural oxide and other contaminant surface layers and establish conductive contact spots. As the normal force across the contact increases, the number and area of these conductive contact spots
increases, resulting in decreasing contact resistance. For two bodies in contact to move relative to one another, the bonds across the contact spots need to be sheared. This gives rise to the adhesion component of friction. In a case where the asperities of one of the contact bodies are much harder than the other, the hard asperities would plow through the softer body, giving rise to the abrasion or plowing component of friction force.

Wear is defined as a removal of material from surfaces as a result of one contacting surface moving over the other. The two main mechanisms of wear under most sliding contact conditions are adhesion and abrasion. Adhesive wear occurs if the bond at the contact spots of the touching asperities is stronger than the cohesive strength of the bulk material in one of the bodies, and a portion of the asperity of the softer body is sheared off and transferred to the harder body.

Two-body abrasive wear is caused by plowing of the surface of the softer body by the opposing member that is rough and substantially hard. When hard wear particles get embedded into one or both of the counterfaces and come further wear, the wear made is termed as three-body abrasion. The rate of abrasion and adhesion wear are proportional to the load and sliding distance and inversely proportional to the hardness of the softer material.

The Zone of Closest Approach (ZCA) is the macroscopic area between the two bodies in sliding contact, which at any instant of time contains all the interacting asperities (A-spots), [Slade 1999]. The ZCA is a subset of the “Apparent Area” of static contact and changes over time. The apparent area is the sum of all ZCA’s on the interacting surfaces. Figure 2.1 shows the apparent area, an instantaneous Zone of Closest Approach and the A-spots within the ZCA.
In sliding experiments with current, conduction between two bodies occurs through the A-spots as shown in Figure 2.2. When the current is constricted to pass through the A-spot, it leads to the contact or constriction resistance. The constriction resistance ‘R’ is given by
\[ R = \frac{\rho}{2a} \]
where ‘\( \rho \)’ is the resistivity of contact and ‘a’ is the radius of constriction.

When the contact load increases the total area of the contact spot increases, causing ‘a’ to increase, thereby decrease to resistance.

Softening and melting voltages are 120 and 430 mV respectively.
**B] Lubrication**

Lubrication is broadly defined as a practice of coating contact surfaces to reduce the mechanical wear and friction and degradation due to fretting. The objective of lubrication is to preserve the physical integrity of the contact surface. The lubricant is squeezed away from the point of highest pressure and hence the metallic conduction through the contact is not disturbed. Because of lubrication, the oxidation of clean metal surfaces is virtually prevented and a high area of metallic contact is maintained resulting in low contact resistance. Lubricants can be mainly classified into fluids (including thin metallic film of low melting point metals) greases and solid lubricants.

**2.1 Liquid and Solid lubrication and sliding contact in electromagnetic rail gun:**

[Drobyshevski et al., 1999] have carried out theoretical studies on the effect of liquid film lubrication in rail guns launching. Indium as a liquid lubricant has been used. They noticed that the achievement of high velocities is limited by (a) Velocity Skin Effect (VSE) (b) wearing of contact surface due to in-homogeneities of the electric current (c) friction and heating. Introduction of Indium into the contact between rail and armature reduced the friction between these surfaces and improved the electrical contact and reduced the armature overheating in the zone of electrical contact.

They conclude that the electrically conductive liquid Indium removes the negative consequences of dry friction between the interfaces, replacing it with relatively low hydrodynamic friction.

[Slade 1999], noted that fluid lubricants in sliding contact are studied by many researchers, especially on ferrous metals and other compounds, which contain chlorine, sulfur or phosphate that reduces the friction.
Various authors have studied the effect of solid lubricants on the friction coefficient, but only a few studies have been carried upon the electrical contact resistance in the presence of solid lubricants. A few researchers have used the electrical contact resistance as a measure of the wear of solid lubricant films. In reciprocating pin and flat experiments, Singer et al. [1995] found that thin film MoS\(_2\) coatings were worn out during the first 5-10% of sliding life. Nonetheless, MoS\(_2\) persisted for the remaining 90% of sliding life by pickup from the periphery of wear track. Chao et al. [1993] investigated the relative trends for contact resistance and coefficient of friction as a function of humidity. Tests were done on burnished MoS\(_2\) films applied to a gold plated track in a copper hoop, with a gold plated copper slider, in a humidified nitrogen atmosphere. Gold plating of the copper surface was done to help eliminate the problem of chemical attack. From the test results, it was concluded that the coefficient of friction is equal to 0.14 for 20 to 50% relative humidity. Above the relative humidity of 90%, coefficient of friction is 0.22. By contrast contact resistance dropped very slowly from its level for less than 20% of humidity and dropped faster for above 50% of humidity.

Studies were done by [Jisheng et al., 1996], to investigate the ability of triboscopy to monitor the sliding wear behavior of MoS\(_2\) coatings and to find the relation between wear and electrical contact resistance. Local fluctuations of Rc (electrical contact resistance) were observed long before any rise or fluctuation in coefficient of friction. The friction coefficient was found to be insensitive to changes in MoS\(_2\) coating thickness until significant areas of underlying material were exposed.

[Antler et al., 1963], noted that the use of conditioner is associated with noise in the contact resistance value and attributed it to hydrodynamic lift during the rubbing action of the lubricant.
In sliding without any conditioner, the contact resistance can fluctuate and under conditions such as stick-slip, which can give rise to electrical opening due to mechanical separation: roller debris formation, which doubles constriction resistance and surface hardening which decreases the area of metallic contact.

[Slade, 1999] found that graphite is well burnished on contact lubricants, but it is not sufficiently conductive to assure a low contact resistance. A plastic solid microcrystalline wax can be used on wiping contacts if they are rough.

**2.2 High current sliding contact:**

A homopolar generator is a DC electrical generator in which the magnetic field has the same polarity at every point, so that the armature passes through the magnetic field lines of force continually in the same direction. It is characterized by low voltage and high current and requires a large magnetic field for useful operation. As an example, for one such device, the output current is 4776 A for the speed of 6500 rpm and a voltage of 1.07 volts and the internal resistance of the generator is 62.5 micro-Ohms.

Carbon fiber brushes transfer 12.4 MA/m² (8000 A/in²) with contact drop less than 50 mV. In short term test current densities are of the order of 23.2 MA/m².

In experiments of sliding contact with current pulses, if the voltage across the contact reaches a threshold value, which is 0.12 Volts for Cu to Cu contact, the contact gets softened, [Slade, 1999]. According to studies done by [Slade 1999], arcing entirely depends on contact materials, the arc always initiates when metal vapors are formed at the interface. Typically, metal vapors in Cu will be formed at an ionization potential of 7.7 Volts. The author calculated the melting and softening voltage for different pairs of contacts.
Figure 2.3 shows a typical arc formation mechanism as a contact junction assuming a typical inductance of the circuit the voltage keeps increasing as the current falls. As a function of time. As the asperities move apart there is softening and melting of the asperities, causing the asperities to be linked by a molten strand. When the strand eventually breaks the voltage is high enough to cause an arc.

Figure 2.3: Typical arc formation mechanism as voltage increases as a function of time from Slade [1999] Initial contact (initial contact due to normal force applied), stable area of contact due to melting of the interface, point contact and arcing (typically arises due to opening of the contact), development of arc.
2.2.1 Arc Volt-Ampere characteristics:

<table>
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<th>V melt</th>
<th>I min</th>
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<tr>
<td>In case of Cu</td>
<td>0.43V</td>
</tr>
<tr>
<td>Probability of glow as V increases</td>
<td>Arc always formed</td>
</tr>
<tr>
<td>Probability arc decreases as I decrease</td>
<td>Arc formation depends upon current inductance</td>
</tr>
<tr>
<td>V soft</td>
<td>(0.12V)</td>
</tr>
<tr>
<td>No arc formed</td>
<td></td>
</tr>
<tr>
<td>V min</td>
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![Diagram](image)

Figure 2.4: Voltage and current range required to sustain an arc and actual region of interest which minimizes arcing effect from [Slade 1999]

2.2.2 Blow-off effect:

When the current is cut off at the end of a pulse, the interaction of current and magnetic field around the contact produces a force which tends to separate the contact. This phenomena is called blow-off force. When the circuit is pulsed, current is passed through a pair of contacts. Figure 2.5 shows a schematic of the blow-off force acting in the reverse direction of the spring force or force required to make a contact.
Previous studies have shown that, as the blow-off force, $F_b$, on the contact increases, the resultant normal contact force, $F_n$, decreases, sometimes creating a small air gap between the anode and cathode. The spark jumps the gap and arcing is produced. The arc melts the contact surface. When the air comes in contact with molten metal, it forms oxides, nitrides and carbonates which is often visible as discoloration. The surface film formed on the contact will increase the contact resistance, which in turn would result in increased temperature at the contact spot for subsequent pulses.

2.3 Types of brushes

Solid, metal wire brushes

In our experiments the tip sliding over the plate can be considered similar to a brush sliding over a commutator as slip rings. There is a large body of literature from electrical contact research community on brushes.

The following are the common types of brush material
Electrographite: It is a form of carbon approaching a diamond in purity. It has the best commutating characteristic and the lowest friction coefficient. However, where high current densities are required and where a high mechanical strength is a factor, it is better to use another type of material.

Carbon-graphite: Carbon grades are stronger than the electrographite material and have definite polishing action. There is a limit to speeds at which they can operate due to their higher coefficient of friction. Their current carrying capacity is also not as high as electrographite due to their higher specific electrical resistivity.

Graphite: Graphite brushes are characterized by low coefficient of friction and cleaning action due to ash contained.

Resin-Bonded: This type of brush is used on machines with high commutating voltage. The current carrying capacity of this brush is limited because of their high electrical resistivity.

Metal graphite: Metal graphite brushes are subjected to rapid wear when they operate at absolute humidity level below 1 grain per cubic foot or at dewpoint of -10 degree Celsius. Metal graphite brushes are used for applications where exceptionally high current capacity is required and where the contact voltage drop is low. Silver with graphite brushes provide unusually low electrical noise, low and stable contact resistance, low friction and high conductivity. For these reasons, silver-graphite brushes are used for slip ring commutators of low voltage high current generator and motor.

Solid lubricated composite material for brushes: Composites of carbon, graphite and metals are used for high-current long-life application. They have graphite for lubrication and better conductivity and carbon forms resin binder which provides strength and bulk resistance. Graphite under high relative humidity is susceptible to a high wear rate which is called dusting.
wear. As an alternative to graphite, molybdenum disulfide (MoS$_2$), Niobium diselenide etc. have been used to replace graphite.

However, performance of metallic brushes proves to be unsatisfactory due to high friction and wear associated with electrical erosion, oxide formation and contact welding. Studies done by Reochner [] on high current electrical machinery demonstrated the feasibility of efficient conduction of very high current densities through sliding metallic contacts. When the interface conditions are well controlled, current densities as high as 23.2 A/mm$^2$ were shown to be feasible. Friction and wear with metallic brushes is also found to be acceptable. Even at high current densities, Ohmic heat generation is small due to low contact resistance and heat removal from the interface is effective because of the excellent thermal conductivity of metals such as copper. Exclusion of air prevents gross oxidation associated with high rate of abrasive wear or high contact film resistivity.
CHAPTER 3: METHODOLOGY

This study is aimed at developing techniques to study the effect of solid lubricant conditioners on sliding electrical contacts. The key quantities of interest are the (a) Friction coefficient, (b) Contact resistance (c) Amount of material transfer, and (d) Wear rate.

The tests were carried out using a copper tip in contact with a copper plate that could be rotated. The tip was mounted on a two axis force transducer and was loaded on to the plate using low stiffness springs. The tip was cylindrical, with a flat face, resulting in a flat-on-flat contact configuration. The face of the tip was finished so that it was parallel to the plate with the load applied, as described in detail later. This configuration helped keep the nominal contact area independent of wear of the tip.

Three types of tests, static, circular and spiral, were carried out at three current levels, namely, 10A, 500 A and 1000 A. It was expected that 500 A would result in softening of the Cu-Cu interface and 1100 A would result in melting of the interface. While the low current of 10 A was applied continuously, the higher currents were applied as 4 ms long pulse.

Static tests with and without solid lubricant, were carried out to evaluate the effect of conditioner on the contact resistance with respect to load. In static tests, the contact pressure was varied to study its effect on the contact resistance. In static tests, the contact pressure was varied to study the effect on contact resistance. In first type of static test, a cyclic load of 4-8-12-16-12-8-4-lbs. corresponding to contact pressures of approximately 10, 20, 30, 40, 30, 20, 10 MPa was applied. The contact was taken through four load cycles without breaking the contact (i.e. without unloading fully) and the trend in the contact resistance was noted. The second type of
testing involves a single load unload cycle, but was repeated at 10 different spot with tip prepared afresh for each contact.

Circular tests, similar to the pin-on-disc tests where the tip remains fixed at a constant radius while the plate is rotated, thereby forming a ring of constant radius, were carried out to determine the effect of sliding distance on the contact resistance and coefficient of friction (with and without application of solid lubricant). The tests were carried out at two different contact pressures and at three different radial locations, to get three sliding velocities. The forces, current through the tip and the voltage across the contact resulted to obtain the coefficient of friction, contact resistance and time to failure of the contact.

Spiral tests, where the tip is moved radially outward while the plate is rotated, were carried out to achieve one pass sliding contact so that a transfer of the material across the contacts could be studied. These tests can also be used to evaluate the effect of increasing sliding velocity on the contact resistance and coefficient of friction.

**Description of static test**

Static tests of Cu tip-Cu Plate contact with and without conditioner (SLIC), at 10 A and 500 A, were conducted to evaluate the effect of conditioner on the contact resistance. In a static test the tip is loaded against the plate through a cycle of predetermined loads (4-8-12-16-12-8-4 lbs). The contact is not made or broken while current is supplied in order to prevent arcing. At each load, the contact resistance is measured. For 500 A, 10 pulses of current are applied at each load and the contact resistance during each pulse is measured and averaged. The amount of tip material transferred to the plate is also studied. The variability in contact resistance measured was studied by repeating the test at different spots, with tip and contact spot on the plate being finished with
600 grit sand paper prior to testing at each repetition. Shake-down behavior of the contact is also studied by cyclic loading unloading test at same spot, without complete unloading.

**Description of spiral tests**

For each plate, circular tests were carried out at diameters of 14, 40 and 60 mm, (Sliding speeds of 0.4, 1.15 and 1.72 m/s). The tip is loaded on the plate to a load of 2.53 lb (Contact pressure of 10 MPa), for low current test, a contact current of 10 A is passed through contact, while in high current tests, current pulses of 500 A and 1100 A are passed once per each revolution of plate, at the same spot on the plate The test is continued until the frictional force increases and becomes close to the normal force, and a squealing sound is heard. The tests with and without conditioning are compared to study sliding distance before the tip fails, and change in contact resistance and the coefficient of friction with sliding distance and speed.

**Description of spiral**

For the spiral tests, the Cu tip is loaded at the centre of plate, the lathe is turned on and the carriage is moved radially outward carrying the tip to have a spiral on a plate. For the test low current test, a contact current of 10 A is passed, while for test at high current, the current of 500 and 1100 A is pulsed at a frequency of 12 Hz. These tests are carried out at a pressure of 10 and 30 MPa and this test is instrumental in evaluating the effect of varying surface velocities on the coefficient of friction, contact resistance and material transfer.
3.1 Experimental setup

A schematic of the experimental setup is illustrated in Figure 3.1.

![Experimental setup schematic](image)

Figure 3.1: Experimental setup on lathe.

The experimental setup consists of a lathe with a face plate to hold the copper plates, a tip holder mounted on the carriage that can be used to hold the tip against the plate at different loads, equipment and circuitry to apply different levels of current, and instrumentation to measure force, contact resistance and transfer of material from the tip to the plate.

![Experimental setup components](image)

Figure 3.2: Plate and tip holding arrangement.
3.1.1 Plate holder

Figure 3.2 shows the copper plate held on work holding arrangement. The work holder comprises of a nonconductive base made up of Delrin, which is held in an expanding mandrel. A circular aluminum disc is mounted on Delrin base so that the contact current can be passed through sliding brushes held against the periphery of the aluminum disc.

3.1.2 Tip holder

[Diagram]

Figure 3.3: Schematic of tip holding arrangement.

Figure 3.3 shows a schematic of the tip holding arrangement. The tip is a piece of copper wire held in a clamp. The clamp is partially made up of insulating material so that there is no electric conductivity between the tip and the load cell. The clamp is fixed to a load cell that measures the frictional force, which in turn is mounted on a load cell that measures the normal force. The load cells used are Kistler model 9212 with high sensitivity and natural frequency of 70 KHz. The load cells are mounted on a rigid shaft held in a linear bearing. The tip is loaded by means of a highly compressed weak spring, that helps keep the normal load constant even when tip wear is significant.
The individual load cells used for measuring $F_F$ and $F_N$, are aligned such that their measuring axes are along $F_F$ and $F_N$, respectively. However, their output voltages are slightly sensitive to off axis forces. This leads to cross talk, i.e., the piezo reading $F_F$ is also affected by $F_N$, and vice versa. To account for this the force measuring system is calibrated as described in Appendix B.

### 3.1.3 Circuit to supply high current pulses

The 10A contact current for low current tests is given by a power source (BK PRECISION, Model: 1745 DC power supply)

The following (Figure 3.4) is a schematic of the circuit developed by us for providing pulses of high current.

![Circuit Diagram](image)

**Figure: 3.4 Solid-state triggering circuit.**

The power source is an automotive battery (12 Volt DC). The typical internal resistance of these batteries is 10 to 50 micro-Ohm. The switching is done by BTS555 high current power switches in parallel, which are triggered by pulses generated by a LM555 timer in astable multi-
vibrator mode as shown. The switching On and Off times rise and fall time of the BTS555 are about 400 micro-seconds and 125 micro-seconds respectively. The Onstate resistance of BTS555 is about 2.5 mΩ, that of several in parallel is expected to be smaller than 1 mΩ.

A high precision resistance is mounted in series which is used for current sensing and current regulation. The resistance value is adjusted so as to get the required current magnitude. This is done by calculating the resistance of the entire circuit and then calculating the resistance required to be added to the circuit to get the desired current pulse.

An astable multi-vibrator built of a LM555 was used to generate triggering pulses at 11 Hertz frequency. For the astable mode, the frequency and the duty cycle can be set using two external resistances and one capacitor. The BTS555 are triggered and reset by the falling and rising edges of the trigger pulse, respectively. For the spiral test, a pulse frequency 1.33 times the spindle frequency was chosen so that pulses would be spread out over a different angle, thereby minimizing chances of overlap of the pulses. For the circular tests, a LED-PDD combination was used to trigger the circuit at the same angular position of the plate, so that pulses would overlap over one another.

A reverse surge protection circuit is employed to prevent the reverse surge of current caused by the inductance of the circuit when the BTS555’s are switched off. The entire circuit is constructed using heavy gauge cable (10AWG X 3C) of 15mm diameter to minimize the resistance of the cables and connections.

3.1.4 Data acquisition system for forces and contact resistance

The piezo electric load cells develop charge proportional to the load applied. This charge is amplified and converted into a voltage by Kistler 5210 charge amplifiers. These voltages, as well as the voltage across the sense resistance and the contact junction, are read by a NI DAC.
A data logger is used. The copper plates used are made of C1110, commercially pure copper. The copper tip is 99.99% pure copper wire. The Cu plate and tip are cleaned and finished to a reproducible finish, 120, 240, 400 and 600 grit in sequence, using a multi-directional sander sand paper. The typical roughness is \( Ra=0.085 \) and \( Rq=0.12 \) microns. This procedure ensures that oxide layers and contaminants (if any) are removed and the overall plate waviness is reduced. Sand paper of 600 grit size is pasted on the face plate using a double stick tape. The tip is then loaded on the faceplate of the lathe to the same load required for the test and the carriage is moved in and out radially, while simultaneously rotating the spindle so that the tip conforms to the plate at the working pressure. The sand paper is removed and the finished Cu plate is loaded on the faceplate of the lathe. The Cu tip and Cu plate are both cleaned with acetone to remove any contaminants. If a conditioner is used, a stick of conditioner is held by

3.2 Experimental procedure for a typical test

The copper plates used are made of C1110, commercially pure copper. The copper tip is 99.99% pure copper wire. The Cu plate and tip are cleaned and finished to a reproducible finish. The plate is abraded by sand papers of 120, 240, 400 and 600 grit in sequence, using a multi-directional sander sand paper. The typical roughness is \( Ra=0.085 \) and \( Rq=0.12 \) microns. This procedure ensures that oxide layers and contaminants (if any) are removed and the overall plate waviness is reduced. Sand paper of 600 grit size is pasted on the face plate using a double stick tape. The tip is then loaded on the faceplate of the lathe to the same load required for the test and the carriage is moved in and out radially, while simultaneously rotating the spindle so that the tip conforms to the plate at the working pressure. The sand paper is removed and the finished Cu plate is loaded on the faceplate of the lathe. The Cu tip and Cu plate are both cleaned with acetone to remove any contaminants. If a conditioner is used, a stick of conditioner is held by...
hand and pressed against the plate while the plate is rotated. The SLIC stick is moved radially in and out several times until the color of the plate is noticed to get dark (black), which is an indication that a thin layer of SLIC has adhered to the plate.

The tip is then loaded to the test load and then checked for conformity by using a magnifying glass. Static tests are carried out without any motion of the tip on the plate. For the ring test, only the spindle carrying the plate rotate while the tip remains stationary. For the spiral test the rpm of the lathe is set to the specified value of 550rpm, and the carriage on which the tip holding set-up is mounted is moved away from the spindle axis. The tip slides on the plate and simultaneously the current pulses are applied by triggering the high current supply power through a triggering circuit. After the test is conducted, the spindle and current are stopped, and the Cu tip is unloaded, and the Labview data acquisition system is stopped. The obtained voltage is converted into load (lb) after averaging in the region where the tip was in contact with the plate. The frictional and normal forces from the voltage readings are calculated and the coefficient of friction is obtained. For evaluating the volumetric transfer of the tip material on the plate, profilometry is carried out on the area of interest using a 3D Optical Profilometer.
CHAPTER 4: RESULTS AND DISCUSSION

As discussed in Chapter 3, three types of tests were carried out to study the effect of a solid lubricant interface conditioner (SLIC) on Cu-Cu sliding electrical contacts. Static tests, with and without application of SLIC were carried out to evaluate the effect of the conditioner on the contact resistance. Circular tests, with the tip repeatedly traversing a circle (similar to a pin-on-disc test), were carried out with and without SLIC to study the effect of the conditioner on the friction coefficient and sliding distance before contact breakdown occurs. Spiral tests, with the tip moved radially outward from the centre of the disc, resulting in a single pass sliding contact, were carried out to evaluate the effect of the conditioner on the material transfer from the tip to the disc. These tests were done at low, softening and melting currents of 10, 500 and 1100 A under two normal pressures of 10 and 30 MPa.

4.1.1 Static tests at low current of 10 A:

In static tests, the contact pressure was varied to study its effect on the contact resistance. In the first type of static test, a cyclic load of 4-8-12-16-12-8-4 lbs corresponding to contact pressures of approximately 10, 20, 30, 40, 30, 20 and 10 MPa was applied. The contact was taken through four load cycles without breaking the contact (i.e. without unloading fully) and the trend in contact resistance was noted. Figure 1 and 2 show the trend with and without SLIC. It can be seen that the contact resistance decrease with pressure and with increase in number of load cycles.

The second type of testing involves a single load-unload cycle, but was repeated at 10 different spots with the tip prepared afresh for each contact. This was done to evaluate the
repeatability of the values obtained. Figure 3 and 4 show the results obtain with and without SLIC. It can be seen that the range of the measurement at each load is within +/- 20 micro-Ohm.

Figure 4.1: Typical results of variation of contact resistance for four cycles of loading and unloading without conditioner.

Figure 4.2: Typical results of variation of contact resistance for four cycles of loading and unloading with conditioner.
Figure 4.3: Repeatability of contact resistance measurements for 10 load-unload cycles at 10 point on an unconditioned plate.

Figure 4.4: Repeatability of contact resistance measurements for 10 load-unload cycles at 10 point on a conditioned plate.

**Observations from static tests at 10 A:**

1. For cyclic loading tests without SLIC, the contact resistance was found to vary between 408 and 452 micro-Ohms (as shown in Figure 4.1). The contact resistance decreases by 10% when the contact pressure is increased from 10MPa to 40MPa.
2. For cyclic tests with SLIC, the contact resistance varied between 630 and 680 micro-Ohms (as shown in Figure 4.2). A similar pattern of decrease in contact resistance with increase in pressure is noted.

3. From the repeatability tests with and without SLIC (results of which are shown in Figure 4.3 and 4.4) it can be concluded that the contact resistance measurement lie in a band 40 micro-Ohms wide. Assuming a normal distribution, this corresponds to a standard deviation of approximately 10 micro-Ohms.

4. From the result shown in Figure 4.1 through 4.4, we can conclude that per-conditioning with SLIC till there is a slight change in color of the light reflected increases the contact resistance by 220 micro-Ohm (~ 50% increase).

5. The increase in contact resistance with SLIC is also reflected in the value at which the contact resistance stabilizes in the cyclic tests, at 630 and 402 micro-Ohms for the tests with and without SLIC, respectively.

6. It was also observed that if a thinner layer of SLIC were applied by rubbing the SLIC on the plate by hand, there was no appreciable increase in contact resistance (as shown in Figure 4.5).
4.1.2 Static tests at 500 A

Static tests at 500 A were done in a similar way as at 10 A. 4 ms long 500 A current pulses were applied and the contact resistance during the pulses was measured. Figure 6 and 7 shows the results with and without SLIC.

Figure 4.5: Variation in contact resistance with load cycle for a thinner layer of SLIC applied by rubbing the SLIC on the plate by hand.

Figure 4.6: Results for the contact resistance for 500 A pulse current, over four cycle of loading and unloading without SLIC.
Summary of observations of static tests at 500 A:

1. For cyclic loading test without SLIC contact resistance was found to vary from 550-580 micro-Ohms (as shown in Figure 4.6). The contact resistance is found to be greater than that for the low current tests, by 100 micro-Ohms. This may be due to the heating up of the contact junctions, the typical time constant for which is less than are microsecond. The contact resistance decreases by 5% when the contact pressure is increased from 10MPa to 40MPa.

2. For the cyclic load with SLIC the contact resistance varied between 610-660 micro-Ohms (as shown in Figure 4.7), A similar pattern of decrease in contact resistance with increase in pressure is noted.

3. Per-conditioning with SLIC increases the contact resistance by 100 micro-Ohms (a 20% increase).

4.2.1 Circular tests at low current of 10 A:

Circular tests were carried out at 10 A current with and without pre-application of SLIC. In these tests the tip was loaded to a nominal contact pressure of 10 MPa at predetermined radii.
of 14, 40 and 60 mm from the center of the plate, the current was turned on, and the plate was rotated at 550 rpm to form a circular wear track of constant diameter. The sliding velocities at ring 1, ring 2 and ring 3 are 0.4, 1.15 and 1.72 m/s, respectively. The contact resistance and coefficient of friction were tracked and the test stopped when audible squealing was heard, which corresponded to a sudden increase in friction coefficient. Figure 4.8 through 4.11 shows typical variation in contact resistance and coefficient of friction, on a function of time. It can be seen that there is an abrupt increase in coefficient of friction at failure. The number of passes and sliding distance to failure are also noted, as shown in Table 4.1

**TABLE 4.1**

**COMPARISON OF COEFFICIENT OF FRICTION, CONTACT RESISTANCE, SLIDING DISTANCE AND NUMBER OF PASSES TO FAILURE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT.**

<table>
<thead>
<tr>
<th>Circular, 10 A</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.65</td>
<td>0.68</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>550</td>
<td>400</td>
</tr>
<tr>
<td>Sliding distance to failure (meter)</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>Number of passes to failure</td>
<td>568</td>
<td>278</td>
</tr>
</tbody>
</table>
Figure 4.8: Typical plot showing noise in contact resistance, test without SLIC.

Figure 4.9: Typical plot showing noise in Coefficient of friction, test without SLIC.

Figure 4.10: Typical plot showing noise in Coefficient of friction, test with SLIC.
Summary of observations of circular test at 10 A:

1. The circular tests at 10 A are stopped when a squealing noise is heard. This is accompanied by a sharp increase in coefficient of friction.

2. The coefficient of friction is reduced to half with SLIC as compared to that without SLIC and the number of passes to failure is an order of magnitude higher.

3. The average contact resistance with SLIC is found to be larger by 160 micro-Ohms. This is comparable to the increase in load in a static test of 10 MPa.

4. Though the noise in contact resistance is small in tests without conditioner (of the order of 20 micro-Ohms, see Figure 4.8) it can be observed that there are variations in contact resistance from test to test.

5. The rings observed at the end of the tests are about 3 mm wide, whereas the tip is only about 1.2 mm wide. This implies that, due to the play in the linear bearing in the setup, the tip moves to different radii as and when the friction at a radius increases. It is only when all the play in the mechanism is used up that failure sets in.

6. We observed less noise in the force data (as shown in Figure 4.10) in the test done on the plate pre-conditioned with SLIC, which indicates that SLIC acts as good lubricant and
promotes smooth sliding. Conversely, there is more noise in the contact resistance with SLIC than without SLIC (as shown in Figure 4.11).

7. Macro scale and micro scale variations in the tip plate contact geometry are not likely to be a factor, since during each test wear is high enough to reduce the length of the tip by 0.5 mm.

### 4.2.2 Circular tests under intermediate current pulses of 500 A at 10 MPa

The results of circular tests at the intermediate current of 500 A and contact pressure of 10 MPa are given in tables below.

#### TABLE 4.2

**COMPARISON OF COEFFICIENT OF FRICTION, CONTACT RESISTANCE, SLIDING DISTANCE AND NUMBER OF PASSES TO FAILURE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT**

<table>
<thead>
<tr>
<th>Circular, 500 A, 10 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.61</td>
<td>0.65</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>490</td>
<td>551</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>42</td>
<td>68</td>
</tr>
<tr>
<td>No of passes</td>
<td>954</td>
<td>541</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circular, 500 A, 10 MPa Repetition 1</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.67</td>
<td>0.8</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>482</td>
<td>406</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>97</td>
<td>115</td>
</tr>
<tr>
<td>Number of passes</td>
<td>2205</td>
<td>915</td>
</tr>
</tbody>
</table>
Observations of circular test at 500 A at 10 MPa:

1. The tests are stopped when the normal force is found to decrease suddenly. This occurs when the wear of the tip makes the spring-based mechanism feeding the tip “bottom out”. This corresponds to close to 2mm of wear of the tip.

2. The coefficient of friction is reduced to half with SLIC and the number of passes to failure is larger by a factor of about 5.

3. The average contact resistance with SLIC is higher by 180 micro-Ohms in the first set of tests and by 80 micro-Ohms in the second repetition.

4. Features such as the noise and the variability in the contact resistance data, the width of the rings, etc., are all the similar to that in the 10 A test.

4.2.3 Circular tests under intermediate current pulses of 500 A at 30 MPa

Table 4.3 gives the result of the tests carried at higher contact pressure of 30 MPa keeping the current at 500 A.
Table 4.3

Comparison of Coefficient of Friction, Contact Resistance, Sliding Distance and Number of Passes to Failures with and Without Pre-application of Solid Lubricant.

<table>
<thead>
<tr>
<th>Conditioned with SLIC</th>
<th>Unconditioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction (Uncond.)</td>
<td>0.8</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>529</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>15</td>
</tr>
<tr>
<td>Number of passes</td>
<td>341</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conditioned with SLIC</th>
<th>Unconditioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction (Atl.)</td>
<td>0.8</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>465</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>9</td>
</tr>
<tr>
<td>Number of passes</td>
<td>204</td>
</tr>
</tbody>
</table>

Observations of circular test of 500 A, 30 MPa contact pressure

1. Again, the tests are stopped when the normal force dropped suddenly, due to tip wear.

The tip wear is found to be several times (about 4 ×) faster at higher contact pressure.

2. The tip wear without SLIC is 5.5 × faster while that with SLIC is 3× faster.(Figure in appendix H)

   a. Expressed another way, SLIC decreases the wear rate by a factor of 5 at 10 MPa, but by a factor of 10 at 30 MPa. i.e., SLIC also decreases the effect of contact pressure on wear rate.
3. Another significant difference compared to the tests at 10 MPa is that the average contact resistance with SLIC is slightly smaller than that with SLIC.

4.2.4 Circular tests at high current of 1100 A

Table 4.4 gives the results of the tests at 1100 A, with a contact pressures of 10 and 30 MPa.

<table>
<thead>
<tr>
<th>TABLE 4.4</th>
<th>COMPARISON OF COEFFICIENT OF FRICTION, CONTACT RESISTANCE, SLIDING DISTANCE AND NUMBER OF PASSES TO FAILURE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Circular, 1100 A, 10 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.2</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>Test 1</td>
<td>584</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>508</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>Test 1</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>28</td>
</tr>
<tr>
<td>Number of passes</td>
<td>Test 1</td>
<td>682</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>636</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Circular, 1100 A, 30 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.25</td>
</tr>
<tr>
<td>Contact resistance (µ Ohms)</td>
<td>Test 1</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>467</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>Test 1</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>12</td>
</tr>
<tr>
<td>Number of passes</td>
<td>Test 1</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>2319</td>
</tr>
</tbody>
</table>
Observations of circular test of 1100 A, 10 and 30 MPa contact pressure:

1. At the high current of 1100 A, it is found that the wear of the tip is faster, when compared to the wear rate of 500 A, by a factor of about 1.8 (on the average) for 10 MPa and 1.4 for 30 MPa.
   
   a. The effect of current is independent of whether SLIC is applied.

2. SLIC is still effective in decreasing the wear rate of the tip and reduces the wear rate by a factor of 4.5 at 10 MPa and 8.5 at 30 MPa

3. For contact without SLIC, the wear rate is higher by $4.3 \times$ when the pressure is increased from 10 MPa to 30 MPa, while with SLIC the wear rate increases only by $2.3 \times$

4. No consistent trend is observed when ring 1, ring 2 and ring 3 are compared

5. Surprisingly, it is noted that at 10 MPa the coefficient of friction with SLIC is much lower at 1100 A as compared to 500 A, and is nearly the same as that of with SLIC.

Tables 4.5, 4.6 and 4.7 compare the effects of SLIC, contact pressure and current on the number of passes to failure.

TABLE 4.5

RATIO OF THE AVERAGE NUMBER OF PASSES TO FAILURE WITH AND WITHOUT SLIC FOR THE VARIOUS TESTING CONDITIONS

<table>
<thead>
<tr>
<th>Ratio of # of pass to failure Average (Ring1, 2, 3)</th>
<th>500 A 10 MPa</th>
<th>500 A 10 MPa</th>
<th>1100 A 10 MPa</th>
<th>1100 A 10 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>with and without SLIC</td>
<td>4.91</td>
<td>9.57</td>
<td>4.50</td>
<td>8.47</td>
</tr>
</tbody>
</table>
Summary of observations from circular tests.

From the above tables summarizing the ratio of contact resistance with and without SLIC, we can see that there is only a slight increase in contact resistance with SLIC of about 10% (on the average). There is a more significant increase in contact resistant when the contact pressure is lowered from 30 MPa to 10 MPa, of about 25%. There is no discernible difference between the contact resistance in the softening and melting region.

This is surprising, considering that one would expect the contact resistance under the melting region to be the smaller than that of the softening region. However between 10 A continuous current testing and pulsed high current testing, the contact resistance is lower by 170 micro-Ohms with SLIC, and is lower by 60 micro-Ohms without SLIC.
4.3 1 Spiral test at 10, 500 and 1100 A at 10 and 30 MPa.

Spiral tests were carried out with 10, 500 and 1100 A current with and without pre-application of conditioner at both 10 and 30 MPa. In these tests the tip was loaded to a nominal contact pressure given above, the current was turned on, the plate was rotated at 550 rpm and at the same time the tip was moved outwards to produce a spiral. For the 10 A tests, there was no deposition of tip material on the plate with and without pre-application of SLIC. For 500 and 1100 A, the current was pulsed for 4 ms at the frequency of 11 Hz, resulting in a typical total of 40 pulses per test. Not all of the current pulses lead to detectable spots. The number of spots produced on these plates and the average size of the spots are compared for the tests with and without SLIC. The coefficient of friction and contact resistance during the current pulses were also compared. Figure 11 and 12 show graphs of the electrical and force measurement during typical tests with and without SLIC. Note that the data shown in the figures as well as in all the subsequent tables is data that was obtained during the time when the current pulses were applied and the data between the pulses has been discarded. It was noticed that there was a lot of drift in the forces in some of the tests, especially those at 1100 A. Table 4.8 and 4.9 below shows the actual average nominal pressure during the tests.

TABLE 4.8

<table>
<thead>
<tr>
<th>Actual normal pressure (MPa)</th>
<th>10 MPa, 500 A</th>
<th>10 MPa, 500 A Repetition 1</th>
<th>30 MPa, 500 A, Repetition 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of tests</td>
<td>With SLIC</td>
<td>without SLIC</td>
<td>With SLIC</td>
</tr>
<tr>
<td>10 MPa, 500 A</td>
<td>23.4</td>
<td>15.3</td>
<td>23.4</td>
</tr>
</tbody>
</table>
TABLE 4.9
ACTUAL NORMAL PRESSURE APPLIED AT THE TIME OF TEST AT 1100 A

<table>
<thead>
<tr>
<th>Type of test</th>
<th>10 MPa, 1100 A</th>
<th>30 MPa, 1100A, Repetition1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With SLIC</td>
<td>Without SLIC</td>
</tr>
<tr>
<td>Actual normal pressure (MPa)</td>
<td>8.54</td>
<td>10.6</td>
</tr>
</tbody>
</table>

It can be seen that it is better to consider the first test at 30 MPa of 1100 A and the third test at 10 MPa of 1100 A. Tables 4.13 through 4.14 summarize the results obtained from the above mentioned tests. Tables 4.15 and 4.16 summarize the average contact resistance and coefficient of friction across repetitions.

TABLE 4.10
COMPARISON OF COEFFICIENT OF FRICTION AND CONTACT RESISTANCE FOR THE SPIRAL TESTS ON THE PLATE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT ON THE INTERFACE.

<table>
<thead>
<tr>
<th>Spiral, 10 A, 30 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.3</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 1</td>
<td>600</td>
</tr>
</tbody>
</table>
### TABLE 4.11

**COMPARISON OF COEFFICIENT OF FRICTION AND CONTACT RESISTANCE FOR THE SPIRAL TESTS ON THE PLATE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT ON THE INTERFACE.**

<table>
<thead>
<tr>
<th>Spiral, 500 A, 10 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.54</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 1</td>
<td>486</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>467</td>
</tr>
</tbody>
</table>

### TABLE 4.12

**COMPARISON OF COEFFICIENT OF FRICTION AND CONTACT RESISTANCE FOR THE SPIRAL TESTS ON THE PLATE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT ON THE INTERFACE.**

<table>
<thead>
<tr>
<th>Spiral, 500 A, 30 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.29</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 1</td>
<td>354</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>350</td>
</tr>
</tbody>
</table>

### TABLE 4.13

**COMPARISON OF COEFFICIENT OF FRICTION AND CONTACT RESISTANCE FOR THE SPIRAL TESTS ON THE PLATE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT ON THE INTERFACE.**

<table>
<thead>
<tr>
<th>Spiral, 1100 A, 10 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Test 3</td>
<td>0.50</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 1</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>485</td>
</tr>
<tr>
<td></td>
<td>Test 3</td>
<td>591</td>
</tr>
</tbody>
</table>
TABLE 4.14

COMPARISON OF COEFFICIENT OF FRICTION AND CONTACT RESISTANCE FOR THE SPIRAL TESTS ON THE PLATE WITH AND WITHOUT PRE-APPLICATION OF SOLID LUBRICANT ON THE INTERFACE

<table>
<thead>
<tr>
<th>Spiral, 1100 A, 30 MPa</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 2</td>
<td>0.45</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 2</td>
<td>637</td>
</tr>
</tbody>
</table>

Figure 4.12: Typical graph of the contact resistance and power dissipated through the interface for the spiral test on the plate without SLIC.

Figure 4.13: Typical graph of coefficient of friction for the spiral test on the plate without SLIC.
### TABLE 4.15

**COMPARISON OF CONTACT RESISTANCE ACROSS THE CURRENT DENSITIES AND NORMAL PRESSURES; WITH AND WITHOUT SLIC**

<table>
<thead>
<tr>
<th>Contact resistance in spiral test</th>
<th>10 MPa Nominal (Actual pressure in brackets)</th>
<th>30 MPa Nominal (Actual pressure in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without SLIC</td>
<td>With SLIC</td>
</tr>
<tr>
<td>500 A</td>
<td>476 (23.4)</td>
<td>554 (18.7)</td>
</tr>
<tr>
<td>1100 A</td>
<td>500 (10.6)</td>
<td>503 (8.5)</td>
</tr>
</tbody>
</table>

### TABLE 4.16

**COMPARISON OF COEFFICIENT OF FRICTION ACROSS THE CURRENT DENSITIES AND NORMAL PRESSURE WITH AND WITHOUT SLIC**

<table>
<thead>
<tr>
<th>Evaluation of coefficient of friction in spiral test</th>
<th>10 MPa Nominal (Actual pressure in brackets)</th>
<th>30 MPa Nominal (Actual pressure in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>without SLIC</td>
<td>With SLIC</td>
</tr>
<tr>
<td>500 A</td>
<td>0.60 (23.4)</td>
<td>0.40 (18.7)</td>
</tr>
<tr>
<td>1100 A</td>
<td>0.51 (10.6)</td>
<td>0.32 (8.5)</td>
</tr>
</tbody>
</table>
Figure 4.14: Pictures showing the number of spots produced during typical spiral tests. Note that the black spots are made with a permanent marker to identify the spot for subsequent analysis.
Figure 4.15: Typical profiles of the spots observed at 500 A with and without SLIC at 10 MPa normal pressure.

Figure 4.16: Typical profiles of the spots observed at 500 A with and without SLIC at 30 MPa normal pressure. The same X, Y and Z scales are used for all the images.
Observations from spiral tests at 10, 500 and 1100 A, at 10 and 30 MPa contact pressure.

1. Volume of deposition observed

   a. At 500 A, for both 10 and 30 MPa contact pressure, the size of deposition observed without SLIC is $10 \times$ more as compared to with SLIC (refer to Figure 4.15 and 4.16).
b. At 1100 A the size of deposition is higher as compared to that in 500 A both with and without SLIC and at both high and low contact pressures (refer to Figure 4.17 and 4.18)

c. At higher pressure and higher currents, we observe a crater instead of a deposition, we also observe a trend that craters are more often observed when the surface is preconditioned with SLIC (refer to Figure 4.17)

2. Number of spots observed
   a. Number of spots (either deposition or crater) observed in tests without SLIC are more as compared to there with SLIC (refer to Figure 4.14)
   b. Limitation of this comparison is that due to the excessive ploughing in case of plates without SLIC, some spots may have been missed.

3. Coefficient of friction
   a. The general trend is when the interface is preconditioned with a solid lubricant the coefficient of friction decreases.
   b. The force traces during spiral tests show variation in normal force over time, which decreases the confidence of any comparison across contact pressure.

4. Contact resistance
   a. At 10 MPa of normal pressure we observe an increase in the contact resistance when the interface is preconditioned with SLIC for both the currents of 500 and 1100 A (refer to Table 4.15).
   b. At 30 MPa of normal pressure we observe that the contact resistance is almost same with and without SLIC in case of 500 A, whereas we observe a slight decrease in the contact resistance in the tests at higher current of 1100 A (refer to Table 4.15)
c. The contact resistance increases with the increase in magnitude of ploughing at 30 MPa normal pressure which is substantially more in case of plates without any preconditioning.

d. We observe that the contact resistance almost remains constant with and without SLIC when the tests were done at 10 A of continuous current and 30 MPa of normal pressure (refer to Table 4.10)

e. The overall range of the contact resistance obtained in the Spiral test both with and without SLIC at the two normal pressures are lower as compared to the Ring tests done at the same current densities and normal pressures, the reason for which might be that less surface damage is done in case of Spiral tests as there is no repeated traversing of the tip through the same area.
CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Three types of tests have been developed and applied to study the effect of contact conditioners on the contact resistance, coefficient of friction and transfer of armature material to the rails. Static tests were done to establish the repeatability of contact resistance measure and to evaluate the effect of conditioner on the contact resistance. From the static tests, the range of contact resistance was found to vary from 408-452 micro-Ohms for the cyclic load tests. The contact resistance decreases by 10% when the contact pressure is increased from 10MPa to 40MPa. Stabilization values for the contact resistance are 630 and 402 micro-Ohms for contacts with and without SLIC, respectively. The pre-conditioning with SLIC increases the contact resistance by 220 micro-Ohm (~ 50% increase). The test data for repeatability concludes that the statistical variation in contact resistance under nominally the same contact conditions is within 40 micro-Ohms. If smaller changes need to be resolved, data from multiple repetitions of the tests need to be average.

Circular tests were done to determine the effect of number of passes, sliding distance and time on the contact resistance and coefficient of friction, with and without pre-application of SLIC. From the circular test at 10 A current, we find that the SLIC acted as a good solid lubricant, reduces the friction in half with SLIC as compared to that without SLIC and number of passes to failure is an order of magnitude higher. We saw an increase of about 15% in contact resistance (about 160 micro-ohms) with the use of SLIC.

Circular test at 500 A at 10 MPa, we found that SLIC reduced the friction to half and the number of passes to failure is larger than without SLIC by a factor of 5. Contact resistance was
higher with SLIC by 180 and 80 micro-Ohm in consecutive tests. At higher contact pressure tip wear was found to be several times (about 4×) faster at higher contact pressure. SLIC decreases the wear rate by a factor of 5 at 10 MPa and 10 at 30 MPa.

In the Circular test at 1100 A at 10 and 30 MPa, it was found that the wear of the tip is faster, when compare to the wear rate of 500 A, by a factor of about 1.8 (on the average). The effect or current is independent of whether SLIC is applied. At high melting current SLIC is effective in decrease the wear rate of the tip and reduces the wear rate by a factor of 4.5 at 10 MPa and 8.5 at 30 MPa. For contact without SLIC, the wear rate is higher by 4.3× when the pressure is increased from 10 MPa to 30 MPa, when with SLIC the wear rate increases only by 2.3×.

Spiral tests were done to evaluate the effect of varying surface velocities and sliding distance on the contact resistance and coefficient of friction, with and without SLIC.

At 500 A for both 10 and 30 MPa contact pressure, the size of deposition observed without SLIC is 10× more as compared to with SLIC. At 1100 A at both 10 and 30 MPa the size of deposition was a higher as compared to 500 A both with and without SLIC. The number of spots observed in tests without SLIC was more as compared to with SLIC. In general, the trend when the interface was pre-conditioned with SLIC, the coefficient of friction decreases. At 10 MPa contact resistance increased when the interface was pre-conditioned with SLIC for both the currents of 500 A and 1100 A. At 30 MPa normal pressure, contact resistance is almost same with and without SLIC in case of 500 A whereas there is slight decreases in the contact resistance at higher current of 1100 A. The depth of the wear groove observed in spiral tests with plate pre-conditioned with SLIC is less as compared to the plate without any condition.
5. 2 Future Work

- Use of other contact conditioner as a lubricant in Cu-Cu interface to evaluate the effect on coefficient of friction, material transfer, contact resistance

- To study the effect of higher sliding velocities on the coefficient of friction and contact resistance with intermittent high current pulsing, a high speed lathe can be used for the future work.
REFERENCE


APPENDICES
Procedure for measurement of contact resistance:

Methodology:

Contact resistance measurement is an important part of the experiment which evaluates the contact resistance between the Tip-Plate interfaces. Use of SLIC as a solid lubricant is instrumental in decreasing the friction between the interface while sliding and the tip wear is reduced. The conductivity of the interface is an important factor of consideration which is vital to ensure that the interface is still conducting after the application of SLIC. A data logger is used to measure the interface resistance at approximately 9 scans/second (5.5 digit accuracy). A data logger is primarily used to measure the temperature of the interface and then it converts the difference of temperature into voltage and is calibrated to display result in Degree Celsius. The data logger is also equipped for the direct measurement of the contact voltage. The approximate range of the voltage expected can be set in order to increase the accuracy of the measurement of the interface voltage. The data logger has two wires which are typically called hot and cold junction: the polarity of the hot junction is positive and that of the cold junction is negative. The wires from the interface are connected according to the polarity, where in the Tip is negative and the plate is positive.

The contact voltage is obtained as a raw data from the test with the help of the data logger. This raw voltage can be converted into contact resistance value as the current through the interface is known and is constant at 10 A. Knowing the current through the interface and the voltage, the resistance of the interface can be estimated using Ohm’s law. The contact resistance
value is averaged over number of readings which improves the accuracy of the readings. The minimum resolvable contact resistance is of the order of 4 micro-ohms for static contacts. The interface voltage data points are obtained at 9 scans/second, which is adequate to obtain data even for the sliding tests done.
Calibration of the force setup for the cross talk

Set up:

Procedure:

The tip is held on a high impedance load cell arrangement which is capable of measuring both the Normal and the Frictional components of the force. Depending on Frictional and Normal forces charge is developed in high impedance load cells (Piezo). The force measurement system is a bilinear system which consists of two piezo which are calibrated for both the normal and frictional force and equations are derived for converting the raw voltages given by the
amplifiers to forces. This error analysis aims at calculating the crosstalk over and above the calibration equations.

The whole setup of the force measuring system is mounted on the dynamometer with the help of two studs screwed in the threaded holes provided on the dynamometer. A special pulley system is used to load the force system in the desired load steps of 1-2-3-4 kg’s and the response of the dynamometer is noted.

The dynamometer used in this experiment is highly precise and noted to be having very less cross talk between the axes. Numerous experiments conducted on the dynamometer reveals high degree of preciseness for measurement of the applied forces and negligible cross talk.

Detailed experiment is as follows, the pulley is used to load the piezo with a load step of 1-2-3 and 4 Kg’s. LabVIEW is used to acquire the data from both the piezo arrangement as well as the dynamometer. The time of application of the load is carefully planned such that the voltage reading on the LabVIEW is constant without any variation. The data processing consists of averaging the voltage data obtained form the Piezo arrangement and the dynamometer for different loads and converting the same into Force (N). A graph is plotted which indicates the response of the two force measuring setups as shown in the graph below.

![Graph showing Load applies Vs Piezo Forces (N)](image-url)
This procedure is repeated to check the repeatability of the response and to analyze the error magnitude. From these experiments, it is concluded that the force read by the 2 piezo in the setup is comparable to that read by the dynamometer. From the above observation, we can conclude that the theory of super-position of force holds good in the experimental setup. The small deviation observed in the readings of the Fy of dyno and fx of the piezo is due to force acting on it due to the moment of the applied force. This error analysis plays an important role in analyzing the force system and to prove that the theory of super-position of forces holds good.
APPENDIX C

Procedure for calibrating piezo

In the above pictures, Piezo # 67 is frictional piezo and the Piezo # 66 is Normal piezo.

Procedure for the calibration of normal and frictional Piezo in horizontal and vertical position:

1. Set the arrangement in horizontal position/frictional position as shown in picture 1
2. In labVIEW software Column No. 3 shows the readings of piezo # 67 which is a frictional and Column No. 4 shows the reading of piezo # 66 which is a normal piezo.
3. Start the labVIEW software. Put the amplifier in operate mode.
4. Start from the no load condition that is prior to load application. Apply a load of 1 kg. Retain this load for 3 to 4 seconds. Release the load and stop the software.
5. Open the labVIEW output file and convert it into excel format. Delete the first column which is forth component and the second column i.e. Fz component.
6. Plot a graph of load (lb) Vs voltage in the same excel file which shows the two curves for frictional and normal force.

7. Take the voltage readings from load Vs voltage graph for the following three instances

   Reading 1: Voltage prior to the load application (zero load condition),
   Reading 2: Voltage at full load condition
   Reading 3: Voltage after load removal.

9. Take the average of first and third readings. Record it in the forth column

   Difference between this average value and the value of voltage at full load condition is to be recorded in the fifth column.

Follow the same procedure for Normal and frictional curves.

1. Repeat the same procedure for all the four loads i.e. 1 Kg, 2 Kg, 4 Kg, 6.5 Kg.

2. In final output sheet, plot the graphs of Load Vs Voltage for frictional as well as normal piezo readings. Fit a linear trend line with linear equation in both the plots and set intercept is zero.

3. Repeat the same procedure for the vertical arrangement as per picture 2.

4. After getting equations, solve them to find the values of two unknown’s i.e. F and N.

<table>
<thead>
<tr>
<th>In picture 1</th>
<th>In picture 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>When only F is applied</td>
<td>When only N is applied</td>
</tr>
<tr>
<td>F=F, N=0</td>
<td>N=N,F=0</td>
</tr>
<tr>
<td>(V_1F=A_1 F +Ao)</td>
<td>(V_1N=C_1N+Co)</td>
</tr>
<tr>
<td>(V_2F=B_1 F +Bo)</td>
<td>(V_2N=D_1 N+Do)</td>
</tr>
<tr>
<td>When both F and N are applied</td>
<td></td>
</tr>
</tbody>
</table>
\( \text{V1 Total} = A_1 F + C_1 N + C_0 \)

\( \text{V2 Total} = B_1 F + D_1 N + B_0 \)

\( A_0 = C_0 \) Similarly \( B_0 = D_0 \)

Given \( \text{V1 Total} \) and \( \text{V2 Total} \), decomposition to find \( F \) and \( N \)

By setting intercept = 0 \( (A_0, C_0, B_0, D_0) \)

\( \text{V1 Total} = A_1 F + C_1 N \)

\( \text{V2 Total} = B_1 F + D_1 N \)

By putting an actual value we will get \( F \) and \( N \) in terms of \( \text{V1Total} \) and \( \text{V2Total} \)
**APPENDIX D**

**Profilometry and high resolution pictures:**

Profilometry and high resolution pictures are vital to study the wear tracks (Circular test) and to study the material transfer (intermittent high current pulsing). Profilometry technique was used to quantify the groove depth and the amount of material transfer on the Cu-plate. Profilometer is a 3D surface scanning microscope which is equipped with piezo base which can scan the Z height accurately. The Cu plate is kept under the profilometer, and the spots of interest can be aligned with the objective of the profilometer using the motorized stage. The scanning fringes of the profilometer is adjusted such that the whole area of the spots can be scanned, if needed Map Stitching application can be used which would scan different regions of interest and would stitch the scans to obtain the final profilometric image where by covering large area of interest. The profilometric image would be useful in quantifying the average Z height added to the nominal plane of the Cu-plate. The ‘Z’ height above the nominal surface can be converted into volume added on the surface of the Cu-plate.

High resolution images are taken with the help of a Digital camera which is equipped with special attachments, which would allow direct mounting of it on the microscope. The images so obtained are of high clarity, with the help of which the wear direction, wear width, material deposited and color of the wear track can be evaluated. The images can be used to fruitfully compare between the two conditions (with and without SLIC) and pictorially make important inferences.
Volumetric analysis

Volumetric analysis done by exporting data from the Profilometry and the steps are as follows.

Step 1: Make sure that the pin is aligned in the Y axis of the profilometer and use the formulae given below. If map stitching in X axis use X in place of Y and vice versa. Save the data with deposition and without deposition using data masking to get a clean surface.

Step 2: Export the data form the Profilometer in UFD format and open in Winword and edit it for the character values

Step 3: Go to Preference option from the file menu and hit the tab for Text Import and Export, there uncheck the “Tab” and “Comma” options in the Import settings and Check all the options in the End of the line menu.

Step 4: In the other option, at end of line menu give a space in the box so that it recognizes the space in the data

Step 5: In export settings uncheck the option Export column headings, then open the word file from the Hard disk.

Step 6: All the data would appear in the first column, note the value of X scale, Y scale, Z scale also the number of rows and column.

Step 7: \{Modulo(Row() - 1, number of rows) * X scale\} for the values of X

\{Floor((Row() - 1) / number of rows) * Y scale\} for the values of Y

\{If( :Column1 == 32767, Empty(), :Column1 * Z scale)\} for value of Z

Step 8: For the column of Z fit use the formula
If( :z == Is Missing(Empty()), Empty(), (r^2 - ( :x - (m 1 * :y + c1))^2)^0.5 + m 2 * :y + c2)  

Where  m1= 0 (slope), m2= 0 (slope), c1= (number of rows* X scale)/2  

C2= Approximate radius of the pin, r= radius of the pin  

Step 9: Now we have the column of Zfit with the user defined parameters, to fit the data well and to get the exact values of the parameters fit a nonlinear fit and get the optimized parameters. After the iterations are done and the values converge, save the estimates.  

Step 10: Now plot a spinning plot with the column we would get a cylindrical profile.  

Step 11: Now we have the Z fit equation to fit a cylinder for the data with deposition.  

Step 12: Import the data for pin with deposition in similar manner and create the columns X, Y and Z as described above.  

Step 13: Prepare the column of Z equation using the formula  

If( :z == Is Missing(Empty()), Empty(), (r^2 - ( :x - (m 1 * :y + c1))^2)^0.5 + m 2 * :y + (c2))  

Note that in this formula we use the optimum parameters obtained from the Zfit in the above processing, also the fact that the data would be blank where there is blank in the actual data.  

Step 14: Now the material removed and added can be found out by using the formula  

Removed: If( :z - :zequation < 0, :z - :zequation, 0)  

Added: If( :z - :zequation > 0, :z - :zequation, 0)  

Note that the basic concept behind these equations is Z above the Zequation is material added and Z below Zequation is material removed.  

Step 15: Now we find the total material added and removed
Step 16: We find the number of elements where material is removed and added using following formula

Removed: \( \text{If(} \text{material removed} == \text{Is Missing(Empty())}, 0, \text{If(} \text{material removed} == 0, 0, 1)) \)

Added: \( \text{If(} \text{material added} == \text{Is Missing(Empty())}, 0, \text{If(} \text{material added} == 0, 0, 1)) \)

Step 17: We find the total number of elements where material is added/removed by summing the previous columns.

Step 18: To find the average Z height above/below the reference cylinder we divide the total material added/removed by the total number of elements above/below the Zequation.

Findings and cautions for correct analysis:

1. Ask the question “which way the pin is aligned?” that is in X or Y axis
2. Keep units of X, Y and Z same (microns or mm)
3. Do not lock any of the value when doing a non linear fit
4. Do not filter out the “No Data” points otherwise the X coordinates and positions would be lost
5. Keep a close eye on the SSE for the fit
6. Make sure that scanning is done on the part which has both clean and deposition on it.
7. Make sure that tilt and Cylinder is not removed before/after scanning.
8. Make sure that the fringes stabilize before the scan begins.

Modification done in Volumetric analysis

Cause of change:
Volumetric analysis done by scanning the areas of the pin which had both clean surface and deposition yielded no meaningful results as the streaks in the beginning are very meager and it is not a representative of the actual deposition on the pin due to the test. It showed less height of material added; also due to less deposition it could not fit good cylindrical fit on the data and considered some regions as material removed where actually there is less deposition.

**Correction steps:**

Step 1: View the deposition under the microscope and determine the approximate regions where we find deposition, which can be considered as the representative of the whole band of deposition.

Step 2: Carefully locate the pin under the profilometer such that the region selected is in focus and that the scanning bands of the profilometer passes through them.

Step 3: Here we set the profilometer to EX-precision mode and adjust the gain of the same; this is to ensure that there is no data loss after scanning the pin for deposition.

Step 4: This step is important to ensure that profilometer is set well; the gist of this step is we ensure that the best focus of the profilometer is when the fringes reaches half way mark. If this is not the case adjust the objective ring located at the bottom. Please do this after reading the directions in the manual of the profilometer.

Step 5: This step involves deciding between the alternatives available for scanning that is 10X or 50X zoom, by experience it is recommended to use 10X objective. Note that changing the zoom to 50X would lead to change in the values of C1, C2 and r in the volumetric analysis details of which is provided in the above procedure.

Step 6: Select region where some regions are without deposition which would be later masked and used to fit a cylinder and calculate the average Z height of material removed and added.
Step 7: Process the data as explained in above procedure. Note that the data points would be less in the data without deposition due to the masking done, so the formula in the volumetric analysis should be changed accordingly.

Step 8: After the analysis calculate the average thickness of the band under consideration and find the deposition on the pin; for correct analysis it is necessary to perform step 2 with extreme caution.

Findings and general cautions:

1. By using this approach good results are obtained and we get a good estimate of the deposition on the pin.
2. Using 10X objective gives good results as compared to 50X objective.
3. We do not find any volume removed from 52100 pin, which is expected as the pin is hard.
4. Using this methodology we could get good estimates of the volume deposited even in regions of meager deposition.
5. If the deposition is very meager then use of 50X objective may prove less effective.
6. When using 50X objective make sure that it does not bump into the fixture or any other such obstructions.
7. Make sure that the regions with big spots are masked before exporting data from profilometer for fitting the cylinder.

Some of the non trivial problems faced during the analysis (Practical)

Problem1:
When we do the scanning of the pin with 50X zoom the resultant scan covers a very small region of the band we are interested in. We need to scan the band in various places in order to get an accurate solution. It would be an error to average out the deposition considering a very small patch of data.

Remedy:

When we scan with 50X objective, we should really be taking scans at different positions of the band and average it only for that small region, this would reduce the over estimation of the deposition.

Problem 2:

When we compute the deposition on the pin by using the cylinder equation, we are really finding the data points above and below the nominal cylinder. The deep groove on the pin due to the super finishing process comes out as the volume removed. When we fit the cylinder with the data obtained without any deposition we carefully remove these groves by using a technique called data masking.

Remedy:

We can use one of the three methods:

i. We can neglect the volume removed from the analysis and consider only the volume added, this would lead to the problem of assuming that the surface is perfectly flat without any undulation. This assumption would say that we do not consider any volume added due to the random variation in the surface of the pin.

ii. In this approach we can deduct the random error from the volume added by subtracting the Z height fit error of the surface which is indicated in JmPin when a
linear fit is done. We can see clearly the random error in the surface when we plot the
3D plot of the data points.

iii. This method involves masking the groves on the pin even when we export the data
with deposition; this would lead to the case wherein the deposition over the groves is
neglected. This is not a bad assumption as only the soft material would be deposited
in the grove for example a test with rulon as the conditioner would lead to deposition
of rulon in the grove and not the comparatively harder Al. Since we are interested in
the deposition of Al on the pin this assumption is by far the most accurate
assumption.

Note that we are now using the method ii. in our analysis and subtracting the volume
removed to compensate for the randomness of the surface of the pin. We would try method iii. to
find out whether it would result in substantial difference in the analysis.
APPENDIX F

Calibration of ‘Falex’ machine piezo

Frictional and Normal piezo calibration:

Configuration of loading arms:

Calibration of “Normal Force” Piezo

Approach: Apply different “normal forces” (F1) and read the corresponding jaw forces (F2)
From the slope of the correlation between $F_2$ and $F_1$ in the graph below, it can be seen that $F_2/F_1 = 6.64$

![Graph showing the correlation between $F_1$ and $F_2$ with the equation $y = 6.6403x$ and $R^2 = 0.9979$.]

- The calibration can be verified by measuring the distances approximately.

- Picture with ruler marked

- Schematic sketch with distances marked

- Ratio $L_1/L_2$ from geometry = $8.07/1.22 = 6.61$.

Number from geometry is consistent with number from force ratio.
Procedure for calculating torque from measured force F3 (“Friction force”)

- Approach
  - An approach similar to that adopted for calibration of the “normal force” piezo would have been to apply torques and compare the reading of the torque gage with that of the “friction force” piezo. We are not able to do so because the piezo is in the position of the torque sensing element and both cannot be used simultaneously.
  - The approach is to apply an external moment about the centerline of the pin (which is the pivot for the friction measurement, see schematic figure in the previous slide)

\[ T = F_4 L_4 = F_3 L_3 \]

where, \( F_4 \) is the applied load and \( F_3 \) is the measured force. From the geometry of the setup \( L_4 = 6.85 \) inches and \( L_3 = 2.6 \) inches.
The correlation between the applied Torque (F4*L4) and the measured “frictional force” F3 is plotted in the graph below. It can be seen that T/F3 = L3 = 3.1

Slightly different from measured L3 = 2.6. May be attributable to a slight error in alignment causing the load F3 to be non-collinear with the axis of the piezo.

Offsets in friction torque:

- While performing the experiments, we realized that there could be an offset torque if the machine is not perfectly horizontal, arising due to gravity. To check this, experiments were carried out without any pin in the spindle.
- A finite torque is detected, as shown in the graph below.
- Tests were performed to check the offset frictional torque and its consistency.

Tests performed to check the offset frictional torque and its consistency.
Note that the friction torque is nearly constant in time and consistent across trials. Initial spike may be due to the initial inertia of vee-block tester.

**Mean value of offset torque 0.15 lb-in**

Origin of offset torque due to friction

When the spindle rotates, even without the pin in place, the loading arms also tend to rotate due to friction in the journal bearing between the spindle and the loading arms.
• The system was leveled using a spirit level so that the effects of gravity on torque are minimal.
Superfinishing

Setup for super finishing pins:

- Clean the pin by acetone and hold it in a 5C collet on the lathe.
- Hold the cuboidal part of the mounting bar rigidly on the tool post.
- Slide the superfinishing attachment onto the cylindrical part of the mounting bar, and hand tighten the bolts at the base of attachment.
- Hardness of the 52100 pin is 58 HRC.

Procedure for superfinishing pins

- Super finish by using the diamond paste/alumina powder in the sequence from 45 micron to 3 micron. Use the diamond paste on a felt pad and super finish for 10
seconds of interval with one abrasive till we get the steady state surface roughness value.

- 45 grit diamond paste (grit size=325, grit type= micronized metal bond)
- 15 grit diamond paste (grit size=1200, grit type= micronized metal bond)
- 9 grit alumina powder (grit size=1800)
- 3 micron : (grit size=8000)

Test Parameters:

- Values of vibration amplitude and pressure are.
  - Vibration amplitude (B) for all steps = 3.3mm;
  - Air pressure in cylinder applying normal force (P) is 2 bar
- Contact area (A) is approximately 3.0 mm wide x 20 mm long. (from wear scar on stones)
- RPM of lathe = 300 ; Surface speed 99 (πDN) mm/sec

To establish the process conditions for super finishing we have changed the values of vibration amplitude and pressure as per the below matrix. Which help us to find out the best sequence of superfinishing where we get desire surfaced roughness values with less time.

**Result:**

<table>
<thead>
<tr>
<th></th>
<th>Before Superfinishing</th>
<th>After Superfinishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Amplitude</td>
<td>3.3 mm</td>
<td></td>
</tr>
<tr>
<td>Air Pressure</td>
<td>2 bar</td>
<td></td>
</tr>
<tr>
<td>Contact Area</td>
<td>Approximately 3.0 mm wide x 20 mm long.</td>
<td></td>
</tr>
<tr>
<td>RPM of Lathe</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>Surface Speed</td>
<td>99 (πDN) mm/sec</td>
<td></td>
</tr>
</tbody>
</table>
Time (seconds) needed to get a steady state surface finish (microns) by each diamond paste

<table>
<thead>
<tr>
<th>Pressure 2 bar :</th>
<th>Pressure 2 bar :</th>
<th>Pressure 3.5 bar :</th>
<th>Pressure 3.5 bar bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>Amplitude</td>
<td>Amplitude</td>
<td>Amplitude</td>
</tr>
<tr>
<td>3.3 mm</td>
<td>4.4 mm</td>
<td>4.4 mm</td>
<td>3.3 mm</td>
</tr>
<tr>
<td>Grit size</td>
<td>Steady state</td>
<td>Grit size</td>
<td>Steady state</td>
</tr>
<tr>
<td></td>
<td>time (sec.)</td>
<td></td>
<td>time (sec.)</td>
</tr>
<tr>
<td>45</td>
<td>30</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time (seconds) Vs surface finish (microns)
Surface roughness values for test matrix

<table>
<thead>
<tr>
<th>Pressure 2 Bar: amplitude 3.0 mm</th>
<th>Pressure 2 Bar: amplitude 4.0 mm</th>
<th>Pressure 3.5 Bar: amplitude 4.0 mm</th>
<th>Pressure 3.5 Bar: amplitude 3.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rp 0.22</td>
<td>Rp 0.35</td>
<td>Rp 0.43</td>
<td>Rp 0.71</td>
</tr>
<tr>
<td>Rv -0.36</td>
<td>Rv -0.41</td>
<td>Rv -0.48</td>
<td>Rv -0.88</td>
</tr>
<tr>
<td>Rq 0.069</td>
<td>Rq 0.074</td>
<td>Rq 0.08</td>
<td>Rq 0.08</td>
</tr>
<tr>
<td>Ra 0.056</td>
<td>Ra 0.062</td>
<td>Ra 0.069</td>
<td>Ra 0.062</td>
</tr>
<tr>
<td>Pv 0.58</td>
<td>Pv 0.75</td>
<td>Pv 0.91</td>
<td>Pv 1.58</td>
</tr>
</tbody>
</table>

Conclusion:

Low pressure (2 bar) and high amplitude (4.0 mm) give the surface roughness value \(Ra: 0.062\) and \(Rq: 0.074\) in time 110 seconds. This is less than other combinations.
APPENDIX H

Tests conducted at 500 A:

Circular tests done at high intermittent current pulses of 500 A with a normal pressures of 10 and 30 MPa, with the tip repeatedly traversing a circle of constant radius, to determine the effect of number of passes, sliding distance and time on the contact resistance and coefficient of friction, with and without pre-application of SLIC.

Spiral tests done at high intermittent current pulses (500 A) at 10 and 30 MPa to evaluate the effect of varying surface velocities and sliding distance on the contact resistance and coefficient of friction, with and without SLIC.

Results of Circular Tests:

Circular tests were carried out with 500 A intermittent current pulses with and without pre-application of conditioner. In these tests the tip was loaded to nominal contact pressures of 10 and 30 MPa at a predetermined radius from center, and the plate was rotated at 550 rpm to form a ring of constant diameter. The contact resistance and coefficient of friction were tracked and the test stopped when audible squealing was heard, which corresponded to a sudden increase in friction coefficient. The time to failure of the contact was also noted.

Tests carried out:

Tests were carried out at three ring diameters of 14, 40 and 60mm on each of four plates (two each with and without SLIC). The sliding velocities at ring1, ring 2 and ring 3 are 0.4, 1.15 and 1.72 m/s, respectively.
**Tests with SLIC at 10 MPa:** The results of the tests at 10 MPa and 500 A intermittent current pulses at the three diameters on the first plate are given in Figure 1 and results for the second set of three tests are given in Figure 2.

![Figure 1: Comparison of the evolution of coefficient of friction for the three sliding tests on the first plate with SLIC.](image1)

![Figure 2: Comparison of the evolution of coefficient of friction for the three tests on the second plate with SLIC.](image2)

Figures 3, 4 and 5 show comparisons of the coefficient of friction at rings 1, 2 and 3, respectively of test 1 and 2 done with SLIC as a solid lubricant to check the repeatability of the test. The trend of coefficient of friction Vs Sliding distance was also noted.
Test A: Ring 1

Figure 3: Comparing the evolution of coefficient of friction of ring 1 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

Test B: Ring 2

Figure 4: Comparing the evolution of coefficient of friction of ring 2 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.
Test C: Ring 3

Figure 5: Comparing the evolution of coefficient of friction of ring 3 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

Figures 6 and 7 show comparison of the contact resistance of the three rings of the test 1 and 2 with SLIC as a solid lubricant

Test 1:

Figure 6: Comparison of the evolution of contact resistance for the three tests on the first plate with SLIC.
Test 2:

Figure 7: Comparison of the evolution of contact resistance for the three tests on the second plate with SLIC.

**Test without conditioner**: Circular test done without pre-conditioning of the interface with solid lubricant.

Figures 8 and 9 shows the trend of coefficient of friction and contact resistance, respectively for the three tests on the plate without any pre-application of solid lubrication on the interface.

Test 1:

Figure 8: Comparison of the evolution of coefficient of friction for the three tests on the plate without any pre-application of solid lubricant.
Figure 9: Comparison of the evolution of contact resistance for the three tests on the plate without any pre-application of solid lubricant.

Test 2:

Figure 10: Comparison of the evolution of coefficient of friction for the three tests on the plate without any pre-application of solid lubricant.
Figure 11: Comparison of the evolution of contact resistance for the three tests on the plate without any pre-application of solid lubricant.

Figures 12 and 13 shows the evolution of the coefficient of friction and contact resistance with and without pre-application of solid lubrication in the interface.

Test: 1

Figure 12: Comparison of the evolution of coefficient of friction and the sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.
Figure 13: Comparison of the evolution of contact resistance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Test:2

Figure 14: Comparison of the evolution of coefficient of friction and the sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.
Figure 15: Comparison of the evolution of contact resistance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

In figure 16, 17 and 18 it shows that the comparison of sliding distance at different ring with and without pre-application of SLIC

Figure 16: Comparison of the evaluation of the sliding distance at ring 1 with and without application of SLIC

Figure 17: Comparison of the evaluation of the sliding distance at ring 2 with and without application of SLIC
Figure 18: Comparison of the evaluation of the sliding distance at ring 3 with and without application of SLIC

**Test 1:**

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.61</td>
<td>0.65</td>
</tr>
<tr>
<td>Contact resistance (u ohms)</td>
<td>492</td>
<td>562</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>42</td>
<td>68</td>
</tr>
</tbody>
</table>

**Test 2:**

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.67</td>
<td>0.8</td>
</tr>
<tr>
<td>Contact resistance (u ohms)</td>
<td>552</td>
<td>579</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>97</td>
<td>115</td>
</tr>
</tbody>
</table>

Table 1: Comparison of coefficient of friction, contact resistance and sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.
Observations:

1. We observe more oscillations in the force data in the tests done on the plate without pre-application of SLIC, which indicates that application of SLIC acts as a good lubricant and reduces the friction.

2. We observe that the coefficient of friction is almost constant for all the rings which indicate that the failure takes place due to wear of the tip which is significantly less when SLIC is applied to the interface.

3. We observe that the contact resistance in case of plate conditioned with SLIC is of the range of 600-700 micro-ohms and that without conditioning is of the range of 450-600 micro-ohms

4. We checked the repeatability in case of tests with SLIC and found that tests were repeatable

5. It is observed that contact resistance stabilizes after some sliding as the tip becomes conformal to the plate and the oxide layer (if present) is broken through.

6. The coefficient of friction decreases substantially from a high value of 0.6 to less than 0.3 when the interface was pre-conditioned with SLIC

7. Ploughing marks observed in case of plate pre-conditioned with SLIC is significantly less.

Conclusions:

1. SLIC acts as a good solid lubricant and reduces the friction which is also evident from the trend of coefficient of friction

2. We see a small increase in the contact resistance with the use of SLIC as a solid lubricant which may be attributable to visco-elastic behavior of PTFE, whereby it
behaves stiffer and maintains a higher separation between the surfaces during sliding contact as compared to static contact.

3. We conclude that wear of the tip considerably reduces when SLIC is used as a solid lubricant which is evident from the time the test takes to fail when compared with unconditioned plate.
APPENDIX I

**Tests conducted at 1100**

Circular tests done at intermittent high current pulses of 1100 A with a normal pressures of 10 and 30 MPa, with the tip repeatedly traversing a circle of constant radius, to determine the effect of number of passes, sliding distance and time on the contact resistance and coefficient of friction, with and without pre-application of SLIC.

Spiral tests done at intermittent high current pulses (1100 A) at 10 and 30 MPa to evaluate the effect of varying surface velocities and sliding distance on the contact resistance and coefficient of friction, with and without SLIC.

**Test Matrix for this series of test:**

**Results of Circular Tests:**

Circular tests were carried out with 1100 A intermittent current pulses with and without pre-application of conditioner. In these tests the tip was loaded to nominal contact pressures of 10 and 30 MPa at a predetermined radius from center, and the plate was rotated at 550 rpm to form a ring of constant diameter. The contact resistance and coefficient of friction were tracked and the test stopped when audible squealing was heard, which corresponded to a sudden increase in friction coefficient. The time to failure of the contact was also noted.

**Tests carried out:**

Tests were carried out at three ring diameters of 14, 40 and 60mm on each of the plates (With and without SLIC at 10 and 30 MPa). The sliding velocities at ring1, ring 2 and ring 3 are 0.4, 1.15 and 1.72 m/s, respectively.

**Tests with SLIC:**

Test done at 10 MPa normal pressure:
The results of the tests at 10 MPa and 1100 A intermittent current at the three diameters on the first plate are given in Figure 84 and results for the second set of three tests are given in Figure 85.

Figure 1: Comparison of the evolution of coefficient of friction for the three sliding tests on the first plate with SLIC.

Figure 2: Comparison of the evolution of coefficient of friction for the three tests on the second plate with SLIC.

Figures 3, 4 and 5 show comparisons of the coefficient of friction at rings 1, 2 and 3, respectively of test 1 and 2 done with SLIC as a solid lubricant to check the repeatability of the test. The trend of coefficient of friction Vs Sliding distance was also noted.
**Test A: Ring 1**

Figure 3: Comparing the evolution of coefficient of friction of ring 1 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

**Test B: Ring 2**

Figure 4: Comparing the evolution of coefficient of friction of ring 2 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

**Test C: Ring 3**

Figure 85: Comparing the evolution of coefficient of friction of ring 3 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

Figures 6 and 7 shows comparison of the contact resistance of the three rings of the test 1 and 2 with SLIC as a solid lubricant.
Test 1: Figure 6: Comparison of the evolution of contact resistance for the three tests on the first plate with SLIC.

Test 2: Figure 7: Comparison of the evolution of contact resistance for the three tests on the second plate with SLIC.

**Test without conditioner:** Circular test done without pre-conditioning of the interface with solid lubricant.

Figures 8 and 9 show the trend of coefficient of friction and contact resistance, respectively for the three tests on the plate without any pre-application of solid lubrication on the interface.
Test 1:

Figure 8: Comparison of the evolution of coefficient of friction for the three tests on the plate without any pre-application of solid lubricant.

Figure 9: Comparison of the evolution of contact resistance for the three tests on the plate without any pre-application of solid lubricant.

Test 2:

Figure 10: Comparison of the evolution of coefficient of friction for the three tests on the plate without any pre-application of solid lubricant.
Figure 11: Comparison of the evolution of contact resistance for the three tests on the plate without any pre-application of solid lubricant.

Figures 12 and 13 shows the evolution of the coefficient of friction and contact resistance with and without pre-application of solid lubrication in the interface.

Figure 12: Comparison of the evolution of coefficient of friction and the sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Figure 13: Comparison of the evolution of contact resistance for the three tests on the plate with and without pre-application of solid lubricant on the interface.
Test 2:

Figure 14: Comparison of the evolution of coefficient of friction and the sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Figure 15 Comparison of the evolution of contact resistance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Test done at 30 MPa

**Tests with SLIC:** The results of the tests at 10 MPa and 1100 A intermittent current at the three diameters on the first plate are given in Figure 1 and results for the second set of three tests are given in Figure 2.
Figure 16: Comparison of the evolution of coefficient of friction for the three sliding tests on the first plate with SLIC.

Figure 17: Comparison of the evolution of coefficient of friction for the three tests on the second plate with SLIC.

Figures 18, 19 and 20 show comparisons of the coefficient of friction at rings 1, 2 and 3, respectively of test 1 and 2 done with SLIC as a solid lubricant to check the repeatability of the test. The trend of coefficient of friction Vs Sliding distance was also noted.

Test a: Ring 1
Figure 18: Comparing the evolution of coefficient of friction of ring 1 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

Test b: Ring 2

Figure 19: Comparing the evolution of coefficient of friction of ring 2 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.

Test c: Ring 3

Figure 20: Comparing the evolution of coefficient of friction of ring 3 as a function of sliding distance with the interface pre-conditioned with SLIC as a solid lubricant.
Figures 21 and 22 show the comparison of the contact resistance of the three rings of the test 1 and 2 with SLIC as a solid lubricant.

Test 1:

![Graph showing contact resistance evolution for test 1 with SLIC](image1)

Figure 21: Comparison of the evolution of contact resistance for the three tests on the first plate with SLIC.

Test 2:

![Graph showing contact resistance evolution for test 2 with SLIC](image2)

Figure 22: Comparison of the evolution of contact resistance for the three tests on the second plate with SLIC.

**Test without conditioner:** Circular test done without pre-conditioning of the interface with solid lubricant.
Figures 106 and 107 shows the trend of coefficient of friction and contact resistance, respectively for the three tests on the plate without any pre-application of solid lubrication on the interface.

Test 1:

Figure 23: Comparison of the evolution of coefficient of friction for the three tests on the plate without any pre-application of solid lubricant.

Figure 24: Comparison of the evolution of contact resistance for the three tests on the plate without any pre-application of solid lubricant.

Test 2:
Figure 24: Comparison of the evolution of coefficient of friction for the three tests on the plate without any pre-application of solid lubricant.

Figure 25: Comparison of the evolution of contact resistance for the three tests on the plate without any pre-application of solid lubricant.

Figures 26 and 27 shows the evolution of the coefficient of friction and contact resistance with and without pre-application of solid lubrication in the interface. (Test 1)
Figure 26: Comparison of the evolution of coefficient of friction and the sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Figure 27: Comparison of the evolution of contact resistance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Test 2

Figure 28: Comparison of the evolution of coefficient of friction and the sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.
Figure 29 Comparison of the evolution of contact resistance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

Overall Observation:

For 10 MPa normal force

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.21</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>2.21</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>584</td>
<td>631</td>
</tr>
<tr>
<td></td>
<td>508</td>
<td>508</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>30</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 1: Comparison of coefficient of friction, contact resistance and sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.

For 30 MPa normal pressure

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ring 1</td>
<td>Ring 2</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.6</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.36</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>349</td>
<td>323</td>
</tr>
<tr>
<td></td>
<td>467</td>
<td>333</td>
</tr>
<tr>
<td>Sliding distance (meter)</td>
<td>4.5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 2: Comparison of coefficient of friction, contact resistance and sliding distance for the three tests on the plate with and without pre-application of solid lubricant on the interface.
Observations:

8. We observe more oscillations in the force data in the tests done on the plate without pre-application of SLIC, which indicates that application of SLIC acts as a good lubricant and reduces the friction.

9. We observe that the coefficient of friction is almost constant for all the rings which indicate that the failure takes place due to wear of the tip which is significantly less when SLIC is applied to the interface.

10. We observe that the average contact resistance in case of plate conditioned with SLIC is observed to be 520 micro-ohms and that without conditioning is observed to be 470 micro-ohms.

11. We checked the repeatability in case of tests with and without SLIC and found that tests were repeatable

12. Coefficient of friction in case of plate pre-conditioned with SLIC is of the order of 0.2-0.3 and that without any preconditioning is of the order of 0.35-0.45

13. Ploughing marks observed in case of plate pre-conditioned with SLIC is significantly less.

14. Sliding distance covered before failure in case of preconditioning with SLIC was 5-10 times that obtained with plate without any preconditioning

Conclusions:

4. SLIC acts as a good solid lubricant and reduces the friction which is also evident from the trend of coefficient of friction

5. We see a small increase in the contact resistance (about 50-100 micro-ohms) with the use of SLIC as a solid lubricant which may be attributable to visco-elastic behavior of
PTFE, whereby it behaves stiffer and maintains a higher separation between the surfaces during sliding contact as compared to static contact.

6. We conclude that wear of the tip considerably reduces when SLIC is used as a solid lubricant which is evident from the time the test takes to fail when compared with unconditioned plate.

7. The Sliding distance before tip fails improves 5 folds as compared to that without any preconditioner.
**Test C:**
Spiral tests were carried out with 10 A current with and without pre-application of conditioner. In these tests the tip was loaded to a nominal contact pressure of 30MPa, the current was turned on, and the plate was rotated at 550 rpm and at the same time moving the tip outwards to produce a spiral. This test would allow us to study the effect of variation of sliding velocities on the coefficient of friction and contact resistance. One of important objective of this test is to study the response of contact resistance and Coefficient of friction under influence of varying normal pressures.

**Test 1:** Spiral test with interface pre-conditioned with SLIC as a solid lubricant

Force Trend:

![Force Trend Graph]

*Figure 114: Evolution of forces for the spiral test on the plate with pre-application of solid lubricant on the interface.*
Contact resistance:

![Graph showing contact resistance evolution](image)

**Figure 115:** Evolution of contact resistance for the spiral test on the plate with pre-application of solid lubricant on the interface.

**Test 2 (repeat):** Spiral test with interface pre-conditioned with SLIC as a solid lubricant

**Force Trend:**

![Graph showing force trend](image)

**Figure 116:** Evolution of forces for the spiral test on the plate with pre-application of solid lubricant on the interface.
Contact resistance:

**Figure 117**: Evolution of contact resistance for the spiral test on the plate with pre-application of solid lubricant on the interface.

**Test 2**: Spiral test without any application of solid lubricant on the interface.

**Force trends**:

**Figure 118**: Evolution of forces for the spiral test on the plate without application of solid lubricant on the interface.
Contact resistance:

Figure 119: Evolution of contact resistance for the spiral test on the plate without application of solid lubricant on the interface.

Test 2(repeat): Spiral test without any application of solid lubricant on the interface.

Contact resistance:

Figure 120: Evolution of contact resistance for the spiral test on the plate without application of solid lubricant on the interface.

Figure 121 and 122 shows the comparison of the coefficient of friction and the contact resistance on the plate with and without pre-application of SLIC on the interface.
Figure 121: Comparison of the evolution of coefficient of friction for the spiral tests on the plate with and without pre-application of SLIC on the interface.

Test repeat 2

Figure 123 and 124 shows the comparison of the coefficient of friction and the contact resistance on the plate with and without pre-application of SLIC on the interface.

Figure 123: Comparison of the evolution of coefficient of friction for the spiral tests on the plate with and without pre-application of SLIC on the interface.
Figure 124: Comparison of the evolution of contact resistance for the spiral tests on the plate with and without pre-application of SLIC on the interface.

Test 1 (30 Mpa): Spiral test with interface pre-conditioned with SLIC as a solid lubricant

Force Trend:

Figure 125: Evolution of forces for the spiral test on the plate with pre-application of solid lubricant on the interface.
Figure 126: Evolution of contact resistance for the spiral test on the plate with pre-application of solid lubricant on the interface.

**Test 2(repeat):** Spiral test with interface pre-conditioned with SLIC as a solid lubricant
Force Trend:

Figure 127: Evolution of forces for the spiral test on the plate with pre-application of solid lubricant on the interface.

Contact resistance:

Figure 128: Evolution of contact resistance for the spiral test on the plate with pre-application of solid lubricant on the interface.

Test 2: Spiral test without any application of solid lubricant on the interface.

Force trends:
Figure 129: Evolution of forces for the spiral test on the plate without application of solid lubricant on the interface.

Contact resistance:

Figure 130: Evolution of contact resistance for the spiral test on the plate without application of solid lubricant on the interface.

Test 2(repeat): Spiral test without any application of solid lubricant on the interface.

Force trends:

Figure 131: Evolution of forces for the spiral test on the plate without application of solid lubricant on the interface
Contact resistance:

![Graph showing contact resistance and current over time]

**Figure 132**: Evolution of contact resistance for the spiral test on the plate without application of solid lubricant on the interface.

Figure 133 and 134 shows the comparison of the coefficient of friction and the contact resistance on the plate with and without pre-application of SLIC on the interface.

![Graph showing coefficient of friction over time]

**Figure 133**: Comparison of the evolution of coefficient of friction for the spiral tests on the plate with and without pre-application of SLIC on the interface.
Figure 134: Comparison of the evolution of contact resistance for the spiral tests on the plate with and without pre-application of SLIC on the interface.
Test 2 repeat:

Figure 135 and 136 shows the comparison of the coefficient of friction and the contact resistance on the plate with and without pre-application of SLIC on the interface.

**Figure 135:** Comparison of the evolution of coefficient of friction for the spiral tests on the plate with and without pre-application of SLIC on the interface.

**Figure 136:** Comparison of the evolution of contact resistance for the spiral tests on the plate with and without pre-application of SLIC on the interface.
10 MPa Spiral test at 1100 A

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.53</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 1</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>485</td>
</tr>
</tbody>
</table>

Table 3: Comparison of coefficient of friction and contact resistance for the spiral tests done on the plate with and without pre-application of solid lubricant on the interface.

30 MPa Spiral test at 1100 A

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Unconditioned</th>
<th>Conditioned with SLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of friction</td>
<td>Test 1</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>0.45</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>Test 1</td>
<td>637</td>
</tr>
<tr>
<td></td>
<td>Test 2</td>
<td>592</td>
</tr>
</tbody>
</table>

Table 4: Comparison of coefficient of friction and contact resistance for the spiral tests done on the plate with and without pre-application of solid lubricant on the interface.

Observations:

1. The coefficient of friction in case of without preconditioning with SLIC was found to be 0.51 and is 0.33 in case of preconditioning with SLIC.
2. The average contact resistance in case of plate without any conditioning is 455 micro-ohms, where as that obtained in case of plate preconditioned with SLIC is 482 micro-ohms
3. It is observed that contact resistance shows an increasing trend without any conditioning on the plate, in contrast we observe that the contact resistance almost remains constant in case of plate pre-conditioned with SLIC.
4. We observe that the oscillation in the frictional and normal in case of plate conditioned with SLIC is minimal which indicates good lubrication at the interface.
Conclusions:

1. SLIC reduces the frictional force where by reducing the frictional co-efficient
2. Interface conditioned with SLIC maintains a low constant contact resistance of the order of 480 micro-ohms which is just 30 micro-ohms more as compared to test without any interface lubrication (Table 3 and 4.)
3. Spiral groove observed in the test with plate pre-conditioned with SLIC is less as compared to the plate without any condition
4. Tip maintains conformity with the plate even at the end of the test when conditioned with SLIC