FRETTING CORROSION AND CONTACT RESISTANCE
OF
EDGE-CARD CONNECTORS
by
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ABSTRACT

The price of gold has stimulated a great demand in
industry to replace gold with base metals that perform
equally well. However, base metal contacts in edge-card
connectors, which are subjected to mechanical vibration and
differential thermal expansion develop high contact resis-
tance due to fretting corrosion.

In this work, friction, wear and contact resistance of
base metal contacts such as Sn-Pb, Cu, Ni and their coatings
under fretting were studied. The behavior of Au-Co alloy
was also investigated for comparison.

It was found that the oxide debris is generated either
by the wear of oxide film or by the oxidation of metallic
wear particles. The rate of oxidation and the rate of wear
determine which mechanism dominates. The increase of con-
tact resistance of base metal contacts under fretting was
found to be essentially due to the accumulation of the oxide
wear debris at the contact interface.

A modulated contact surface which provides surface cav-
ities for trapping the oxide debris was tested and the
contact resistance was found to be low. The modulated base
metal surfaces could be substitutes for noble metals. The
concept of modulated contact surface for trapping the wear
particles can also be applied to reduce friction coeffi-
cient.

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1. INTRODUCTION

Edge-card connectors are widely used in computers and electronic instruments. The feature of the equipment can be varied by changing or adding the printed circuit (PC) boards. Furthermore, the repair work can be done by just replacing the PC boards. However, the plug-in and pull-out of the PC boards result in wear at the contact interface.

Moreover, although seemingly stationary during service, these separable connectors may be subjected to vibration from such mechanical devices as disk drives, blowers etc., and during transportation. The vibration can be transmitted to the contact interface and therefore result in fretting. In addition, differential thermal expansion and contraction may also cause the fretting motion.

Gold and its alloys are widely used as contact materials in edge-card connectors and PC boards because of the reliability and long life requirements. However, the high price of gold has stimulated economy measures across the electronics industry. Such measures include the use of thinner gold coatings or even base metals for the contact surfaces. However, both sliding and fretting at the interface degrade the contact and increase the electrical contact resistance, especially in the base metal contacts.

In this work, friction, wear and contact resistance of base metal contacts such as Sn-Pb, Cu, Ni and their coatings
under fretting were studied. The behavior of Au-Co, which is currently used in edge-card connectors, was also investigated for comparison. In addition, Scanning Electron Microscope (SEM), Energy Dispersive X-ray Analyzer (EDXA) and Auger Spectroscopy were used to characterize the contact surfaces before and after the wear tests.

It has been found that the contact resistance behavior strongly depends on material hardness, material transfer direction, the amount of oxide debris that accumulates at the contact interface. A modulated contact surface has been tested with promising results. The results suggest that the modulated base metal surfaces could be used as substitutes for noble metals.
2. REVIEW OF FRETTING CORROSION AND CONTACT RESISTANCE

2.1 Fretting Corrosion

Fretting is a small-displacement cyclic relative motion which occurs at the contact interface of solid materials. In contacts with noble-metals or base metals under inert atmosphere, there may only be fretting wear. When the base metal contacts are in a reactive atmosphere, fretting corrosion may occur.

This section will review the mechanisms of fretting corrosion first and then the effects of experimental variables. The role of oxidation on the fretting corrosion will be emphasized and briefly discussed. Finally, the ways of preventing fretting corrosion such as by coatings and lubricants are also presented.

2.1.1 Mechanisms

Fretting corrosion has been studied by many investigators since Tomlinson [1,2] who probably made the first systematic study of the phenomenon. Tomlinson suggested that fretting corrosion is caused by molecular attrition. The cohesion between molecules as they touch cause them to be detached from the surfaces and subsequently oxidized. Therefore fretting corrosion is not influenced by the normal load because molecular attrition is independent of the external forces.

Godfrey [4] proposed that fretting damage occurs due to
adhesion between the surfaces. The wear debris is extruded from the contact area and reacting with oxygen. However, good adhesion between two oxide-covered surfaces is questionable.

Feng and Rightmire [3] stated that fretting begins with adhesive wear, then goes through a transition period in which accumulation of the trapped wear particles gradually contribute to abrasive action. Eventually the damage is entirely caused by abrasion. They explained that the occurrence of loose wear particles is due to the plastic deformation at the contacting high spots.

Uhlig [5] interpreted that the mechanism of fretting corrosion includes a chemical factor and a mechanical factor. An asperity rubbing on a metal surface produces a track of clean metal which immediately oxidizes, or upon which gas rapidly adsorbs. The following asperity wipes off the oxide or initiates reaction of metal with adsorbed gas to form oxide. This is the chemical factor of fretting. In addition, asperities penetrate below the surface to cause wear by welding or shearing action by which metal particles are dislodged. This is the mechanical factor of fretting. Uhlig has derived an expression for the wear at different values of load, frequency and amplitude on the basis of the above model as
\[ W = \left( k_0 L^2 - k_1 L \right) \frac{c}{f} + k_2 \ell L c \]  \hspace{1cm} (2.1)

where

\( W \) = weight loss
\( L \) = normal load
\( c \) = number of cycles
\( f \) = frequency
\( \ell \) = displacement
\( k_0, k_1 \) and \( k_2 \) are constants.

Rabinowicz and Stowers [48, 49] identified two different regimes of fretting as a function of amplitude. In the low amplitude regime the volumetric wear per cycle is a function of the amplitude squared, whereas in the high amplitude regime it is directly proportional to the amplitude. They suggested that material loss resembles that produced by unidirectional adhesive wear much more closely than that produced by other types of wear. Moreover the amount of wear can be computed by the use of Archard's equation as

\[ V = \frac{k L x}{3p} \]  \hspace{1cm} (2.2)

where

\( V \) = wear volume
\( k \) = coefficient of wear
\( L \) = normal load
\( x \) = sliding distance
\( p \) = hardness of the worn surface
Waterhouse and Taylor [6,7] made an SEM study of fretting surfaces and showed that loose wear particles were produced by the propagation of subsurface cracks in a manner similar to the delamination mechanism proposed by Suh [8]. This results in the detachment of oxide coated plates of metal about 1.3 to 3.5 μm thick. The continuing fretting action grinds the initial wear particles down to particles of smaller size with a higher oxide content. They also divided the fretting corrosion process into two stages. Adhesion occurs in the early stage of fretting and it is more significant with noble metals or under inert environment. When this stage is passed the surfaces become smooth and removal of material from the surfaces occurs by delamination. The transition from adhesion to delamination is a function of the material and the nature of the environment.

Sproles et al. [9,10] concluded from the observed mode of metallic material removal that fretting wear by delamination mechanism, rather than by abrasive wear mechanism or by welding and material transfer mechanism, is the predominant form. They suggested that oxide debris is formed by the oxidation of metallic debris, or by the formation and subsequent scraping away of a thin oxide film from the metallic surfaces.

2.1.2 Experimental variables

Fretting corrosion is a complicated mode of wear which may involve adhesive, oxidative, abrasive and delamination
mechanisms. It is influenced by a large number of variables. The effects of experimental conditions on fretting corrosion have been investigated [11-16].

The effect of displacement has been studied most because fretting corrosion is the result of relative motion between two contacting surfaces. It is generally agreed that relative motion at the contact interface is a necessary requirement for fretting wear. However, opinions differ with regard to the effect of displacement. The conclusion that there is a critical amplitude above which wear rate increases by several orders of magnitude was made by Waterhouse et al. [11,12]. On the other hand, others, namely Feng, Uhlig and Rabinowicz didn't encounter this critical displacement. Their results show that wear rate is independent of displacement [14,48].

The effect of frequency was theoretically analyzed and a quantitative expression was derived by Uhlig [5]. He suggested that greater wear damage occurs at lower frequencies (for a given number of cycles) than at higher frequencies. The reason being the lower the frequency, the longer is each fretting cycle and therefore the longer is the time available for oxidation. If the formation of oxide debris is due to the breakdown of oxide film from the metal surface, it would be expected that the amount of such oxide debris produced would increase with decreased frequency of fretting for the same number of cycles.
Many investigators reported that an increase of load leads to an increase of the fretting damage [3]. However, others have determined that load has no influence on the damage [2], probably because fretting motion can be reduced or even suppressed by increasing the load.

Temperature and humidity were found to be sensitive variables in fretting. It was observed that greater damage occurs below room temperature compared with that above room temperature. Wear damage of fretting corrosion in dry air is found to be much more than that in moist air [5,14].

2.1.3 Oxidation

The formation of oxide films and oxide debris in fretting corrosion have also been studied [21-27]. The informations such as thickness, mechanical properties of the oxide film, oxidation rate and bonding strength of oxide to the substrate should be well understood in order to investigate the fretting corrosion behavior. Oxide film growth kinetics generally follow one of the following rates: logarithmic, parabolic, linear or cubic. For a given metal, the temperature determines which oxidation rate predominate and therefore the rate constant. As a consequence, the effect of temperature on the fretting corrosion has also been studied [21,27]. The results suggest that the mechanism of fretting corrosion depends on temperature and environment, i.e. the oxidation behavior.
2.1.4 Coatings

Several methods have been recommended for reducing or preventing fretting wear [17-20]. The first is to reduce the amount of relative displacement which was discussed before about the effect of displacement on the fretting corrosion wear. The second is to plate the contact surfaces with metal or non-metal coatings. The reason being the relative motion between contact surfaces may be taken up in the coating if the coating is soft and there would be less possibility for wear to occur [19]. Other explanation based on the delamination theory of wear is that if a thin layer of a softer metal is deposited on a harder substrate, large plastic deformation and wear of the substrate by delamination can be prevented because of the formation of a dislocation free surface layer.

The factors which have to be taken into consideration, in addition to hardness, for the coating materials are coating thickness and thermal conductivity. It was found [17] that the life of coating is proportional to the square of the thickness of the coating and a thickness between 75 and 125 µm is desirable.

The generation of heat at the interface during fretting leads to a local temperature rise which will accelerate oxidation. A metal coating with high thermal conductivity will help dissipate this heat and reduce the oxidation rate. It is concluded [17] that the most effective metals for
increasing the fretting life are those which are relatively soft, have a high thermal conductivity, and which can be plated from baths of high cathode efficiency, for example, silver and copper.

Work done for prevention of fretting by ion-plated film [18] have proved to have higher bonding strength for the coating than that by sputtered film or vacuum evaporated film. However, ion-plated base metal film is not effective in preventing fretting because of the oxidation of base metal in the fretting process. It appears that this method can only be effective with noble metal films, not with base metal films.

2.1.5 Lubrication

The use of lubricants as a means of preventing fretting corrosion has been shown to be effective [28-33]. The effects of lubricants are postulated to be the reduction of friction and wear, flushing of wear debris from contacts and exclusion of oxygen from the contacts. A number of potential lubricants have been evaluated for reducing fretting corrosion. The important properties of lubricant to have good performance in electric contacts have been evaluated as high lubricity, low volatility, low creep and inactivity [31]. The performance of lubricated gold depends both on the lubricant composition and the viscosity [32]. Lubrication is especially necessary for contacts with thin coatings of gold or base metals. Lubricants with a liquid
phase are generally more desirable than solid lubricants on smooth surfaces, and the viscosity of the liquid should be as high as possible. It was found [32] that lubricants with high halogen content had better boundary properties, while silicon-containing fluids were poorer.

It is necessary to apply lubricants on both contact surfaces, except when there is a large difference in the surface area, such as in the edge-card connectors. In this case, the lubricant must be applied to the board contacts surface; it is less effective applying lubricant to the connector [47].

2.2 Electric Contact Resistance

In this section, electric contact resistance theory will be briefly reviewed. Then the contact behavior of noble metals, specifically gold, will be discussed. Finally, non-noble metals such as Sn–Pb and Cu will be scrutinized as substitutes for noble metals.

2.2.1 Contact resistance theories

An understanding of contact resistance theory is important to the study of contact resistance under fretting. An equation for contact resistance at the interface of two contact materials can be given as
\[ R_t = R_C + R_f + R_b \] (2.3)

where

- \( R_t \) = total contact resistance
- \( R_C \) = constriction resistance
- \( R_f \) = film resistance
- \( R_b \) = bulk resistance

Constriction resistance is due to the convergence of current flow in a very small area at the contact interface. Film resistance arises when there is oxide or tarnish film on the surface. Although metallic surfaces have adsorbed gas layers, they do not contribute to the contact resistance. The bulk resistance is generally small, however, any measurement will include a small bulk resistance of the contact materials as well.

The constriction resistance for a single contact spot due to Holm [65] is given by

\[ R_C = \frac{\rho_1 + \rho_2}{4a} \] (2.4)

where

- \( \rho_1 \) = resistivity of the first material
- \( \rho_2 \) = resistivity of the second material
- \( a \) = effective contact radius

Holm indicates that an entire asperity may not conduct elec-
tricity due to oxide and tarnish layers. Therefore, the variable "a" in Equation 2.4 refers to the "effective" radius of the asperity contact area.

This derivation of constriction resistance is based on a single contact. The normal mode of contact in practice, however, is not a single asperity contact. Greenwood [66] derived an equation for the constriction resistance of multiple contacts. It is basically the sum of the parallel resistances of the contacts, and an interaction term based on the spacing of the asperities. He simplified the equation by assuming a large number of contact spots uniformly distributed over a circular area of radius "R". The resistance is given by

$$R_C = \bar{\rho} \left( \frac{1}{2\ n\ \bar{a}} + \frac{16}{3\pi^2 R} \right) \quad (2.5)$$

where

- $\bar{\rho}$ = average resistivity of the contacting materials
- $\bar{a}$ = mean effective contact radius
- $n$ = number of conductive contact spots
- $R$ = radius of the apparent area,

If an oxide layer stays on the contact interface and it is thick enough to prevent electron flow, the film resistance could be much higher than the constriction resistance. However, electrons can also pass through thin layers of
insulating material by the quantum tunnel effect [67-68]. Insulating layers thicker than a few tens of angstroms are not penetrable. The probability of the electrons passing through the insulating layer by the electrical tunneling effect falls off exponentially with thickness. If tarnish film of the metal is thick enough to prevent the current from flowing through, current can only go through those areas where the film is broken and metal to metal contact is established. Film breakage can occur either mechanically or electrically. The possibility of film breakage mechanically depends on contact geometry, materials used and the environment. The film thickness and applied electrical field decide whether electrical breakdown will occur.

Experiments have been done on the effect of relative humidity on contact resistance for sliding contacts [71]. High resistance was developed rapidly under 20% to 55% relative humidity, whereas low resistance was found between 55% and 80%. Severe corrosion was observed when the relative humidity was over 80%.

2.2.2 Noble metal contacts

Noble coatings, especially gold, are widely used for electric contacts because they have the necessary oxidation and corrosion resistance. These coatings are generally very thin, 0.25 to 2 μm. However, gold platings are usually porous in this range of thickness which leads to an insulating film covering the surfaces. It has been shown that gold
is less porous when plated on smooth rather than on rough substrates [44]. The reliability of contacts made of thin gold plate on corrodiible substrates can be markedly improved if the substrate is prepared to be smooth.

The wear of a number of gold deposits has been investigated and concluded that the acid cyanide deposits have the best wear resistance [45]. A hypothesis involving a polymer lubrication mechanism was proposed to explain the low wear of the acid golds.

Wear tests on electrodeposited gold coatings on a smooth substrate show that hard golds (140-200 knoop) have good wear resistance when lubricated [46]. A plating consisting of a very thin gold (0.125 μm) over rhodium (0.5 μm) over nickel (7.5 μm) was found to prevent brittle fracture wear of the rhodium substrate and showed excellent wear resistance.

Nickel underplate for gold plating is an effective load bearing layer because it is harder than the gold coating [47]. Thus, it often reduces the wear of gold contacts. Diffusion barriers are generally necessary for operation above room temperature or when the gold coatings are thin. Nickel underplate also acts as a good diffusion barrier.

2.2.3 Non-noble metal contacts

The high price of gold has motivated the electronics industries to investigate the use of base metal in electrical contacts. Sn-Pb alloy has been mostly studied
concerning corrosion, penetrability, contact resistance and durability. In corrosion aspect, Sn-Pb is not much degraded by sulfur vapor, $O_2$, $SO_2$, $H_2S$, CO, and NH$_3$. However, films can grow to large thickness under NO and Cl, and corrosion of Sn-Pb can be promoted by a synthetic dust and by salt spray [51].

It was found that the bright Sn-Pb plating is as good as gold plating over Ni substrate in electric contacts except durability [52]. Accordingly, 100 sliding cycles of connector life for Sn-Pb and 500 sliding cycles for gold plating over nickel were recommended.

The contact properties of electroplated coatings such as Sn-Pb, Sn-Ni, sulphite gold and cobalt-hardened gold have been evaluated as functions of contact geometry, contact load and the plating thickness [53]. It was concluded that substrate hardness and the contact geometry have little effect on the contact resistance, but an increase in contact load leads to a decrease in the resistance. The Sn-35Ni electroplated layers give stable resistance and friction force during continuous sliding.

The heat treatment of Sn-Pb coating has shown that an intermediate layer of high wear resistance was formed although contact resistance was not decreased [54].

The so-called gas tight high pressure contacts [57] with soft metals as contact materials which produce large contact area are insensitive to load variations and have
metal-to-metal contact due to readily ruptured tarnish films. The contact area must be gas tight which means it was sealed by easily deformed metal against the environment.

The intermetallic growth of contact plating materials such as In and Sn has been studied over a range of temperature with and without a plated nickel barrier layer [58]. In general the Sn platings react more slowly than the In platings when applied directly on the copper alloy substrates. With a Ni barrier layer the reaction rates are greatly reduced for both, while it appears that Sn is less reactive than In above 383 K and more reactive below this temperature.

Aging of Sn platings at 323 K for 7 years shows the conversion of 5 μm coatings to such intermetallic compounds as Cu₆Sn₅, Cu₃Sn or Ni₃Sn₄ depending on the substrate. Dull tin platings show low contact resistance after aging even though there is a large proportion of intermetallic phases at the surface. Bright tin plating shows high contact resistance after aging. Sn-Pb might offer better contact properties than bright tin because lead is not soluble in Cu₅Sn₆ and Cu₃Sn and is not consumed by the diffusion processes. The Pb phase insures the coating to be soft. Dull Sn and Sn-Pb (at least 40% Pb) have been suggested as the best non-noble contact materials [59].

Sn-Pb alloys are extensively used in the electronic industry as contact materials. Electroplating of Sn-Pb
coatings on surfaces provide good solderability. However, Sn can develop whisker growth under adverse conditions [70,71]. This Sn whisker formation may result in short circuiting especially in closely spread contacts. The formation of whiskers can be prevented by an appropriate choice of the Sn-based alloys. Sn-40Pb was found without the tendency of whisker growth.

2.3 Fretting Corrosion of Electric Contacts

Although much work was done on fretting corrosion and electric contact separately, few studies have focused on the effect of fretting corrosion on electric contact resistance. A summary of experimental conditions and materials tested on fretting corrosion of electric contacts is shown in Table 2.1 [35-43].

Base metal contacts under fretting corrosion result in an increase in contact resistance due to the accumulation of oxide debris at the interface. Gold plated contacts may also fail by fretting corrosion if the gold wears out exposing the base substrate. Thin gold platings on nickel substrate maintain low contact resistance when the counterface material is solid gold, because nickel promotes adhesive transfer of gold. However, gold alloys (for example Au-30Ag) transfer less well [38].

Palladium contacts have high contact resistance under fretting because of the formation of frictional polymers from organic pollutants; the contact resistance increases
Table 2.1. Fretting Corrosion of Electric Contacts: Summary of Experimental Conditions and Materials Tested.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Sn, Sn-Pb, Sn-Ni, Ni, Ag, Au</td>
<td>Sn, Au</td>
<td>Tin Alloy</td>
</tr>
<tr>
<td>Geometry</td>
<td>1/4&quot; sphere on center of flat disc</td>
<td>Card Connector</td>
<td>1/8&quot; ball on center of flat disc</td>
</tr>
<tr>
<td>Displacement</td>
<td>11° (rotation)</td>
<td>50µm</td>
<td>± 5° (rotation)</td>
</tr>
<tr>
<td>Load</td>
<td>50 ~ 600g</td>
<td>60g</td>
<td>50g</td>
</tr>
<tr>
<td>Frequency</td>
<td>11/60 Hz</td>
<td>----</td>
<td>11/60 Hz</td>
</tr>
<tr>
<td>Duration</td>
<td>2 hr or ~ 5Ω</td>
<td>Until Failure</td>
<td>660 cycles</td>
</tr>
<tr>
<td>Temperature</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Humidity</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Lubricant</td>
<td>White Mineral Oil</td>
<td>Monsanto OS-124 U.S.P. Petroleum Jelly</td>
<td>Mineral Oil</td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Wear Coefficient</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Contact Resistance</td>
<td>5mΩ ~ 10Ω</td>
<td>10mΩ ~ 2Ω</td>
<td>5mΩ ~ 10Ω</td>
</tr>
</tbody>
</table>
(continued)

<table>
<thead>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>Cu-Sn Cu-Al-Si-Co Cu-Ni-Sn, Au</td>
<td>Al, Sn, Ag, Cd, Zn, Ni</td>
<td>Al Cu</td>
</tr>
<tr>
<td>Geometry</td>
<td>Rider (D = 1/2&quot;) Wire on Flat on center of flat disc</td>
<td>Crossed Rod</td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>11° (rotation) 10µm</td>
<td>0.4 ~ 18µm</td>
<td></td>
</tr>
<tr>
<td>Load</td>
<td>50g 10g, 100g, 500g</td>
<td>20-160N</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>11/60 Hz 10⁻³ Hz</td>
<td>1/6 ~ 10⁻⁶ Hz</td>
<td></td>
</tr>
<tr>
<td>Duration</td>
<td>13200 Cycles 550 Cycles</td>
<td>10³ Cycles</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Humidity</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Lubricant</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Wear Coefficient</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Contact Resistance</td>
<td>1mΩ ~1Ω</td>
<td>1Ω ~60Ω</td>
<td>0.1mΩ ~ 100mΩ</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------------------------</td>
<td>-----------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>Materials</td>
<td>Au, Pd, Sn, Ag, Cu, Ni</td>
<td>Au, Au Alloy, Cu, Be-Cu, Ni, SnPb</td>
<td>Pd, Au, Au-Co, Ni, Cu, 60Sn-40 Pb</td>
</tr>
<tr>
<td>Geometry</td>
<td>Card, Connector</td>
<td>Hemisphere Rider (D = 3.2mm) on Flat</td>
<td>Hemisphere Rider (D = 3.2mm) on Flat</td>
</tr>
<tr>
<td>Displacement</td>
<td>$\sim \pm 0.2\text{mm}$</td>
<td>$20\mu\text{m}$</td>
<td>10, 20, 40, 80, 160$\mu\text{m}$</td>
</tr>
<tr>
<td>Load</td>
<td>100g</td>
<td>50g</td>
<td>50g, 100g</td>
</tr>
<tr>
<td>Frequency</td>
<td>1/2 Hz</td>
<td>4 Hz</td>
<td>1-8 Hz</td>
</tr>
<tr>
<td>Duration</td>
<td>$\sim 10^5 \text{ Cycles}$</td>
<td>$\sim 3 \times 10^5 \text{ or } 10^6 \text{ Cycles}$</td>
<td>$10^5 \text{ Cycles}$</td>
</tr>
<tr>
<td>Temperature</td>
<td>22-26°C</td>
<td>20-25°C</td>
<td>20-25°C</td>
</tr>
<tr>
<td>Humidity</td>
<td>25-40%</td>
<td>20-50%</td>
<td>20-50%</td>
</tr>
<tr>
<td>Lubricant</td>
<td>----</td>
<td>Polyphenyl ether OS-124</td>
<td>1. Polyphenyl ether OS-124</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Synthetic Hydrocarbon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. Microcrystalline wax</td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Wear Coefficient</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Contact Resistance</td>
<td>$10m\Omega$</td>
<td>$5m\Omega$</td>
<td>$2m\Omega$</td>
</tr>
<tr>
<td></td>
<td>$\sim 1\Omega$</td>
<td>$\sim 100\Omega$</td>
<td>$\sim 10\Omega$</td>
</tr>
</tbody>
</table>
are greatest at or near the ends of the track due to the accumulation of the polymer [39,43]. A study conducted under fretting with palladium mated with different noble metals and alloys shows that soft and low-polymer forming metals give low contact resistance because of the transfer of materials to palladium so that both surfaces are identical eventually.
3. EXPERIMENTS

3.1 Experimental Setup

In fretting tests, it is necessary to use an apparatus which can accurately produce small-displacement cyclic relative motion at the interface of two contacting bodies. In addition, the apparatus should be able to measure and control normal load, displacement, frequency, number of cycles and the friction force. Moreover, the apparatus must be rigid, and adequately instrumented in order to measure and control such small displacements. The fretting apparatus fabricated for this study had these capabilities. But it had a few drawbacks which will be described later.

A schematic diagram of the fretting apparatus is shown in Figure 3.1. The block diagram of experimental setup is illustrated in Figure 3.2. Figure 3.3 shows the photographs of experimental setup including a closeup of the contact. An electromagnetic shaker was used to drive one of the test samples. The shaker was driven by a function generator and a 20W power amplifier. A sinusoidal wave was used. The frequency and displacement of the fretting motion were set by the frequency and voltage of the function generator, respectively.

The board and pin to be tested are shown in Figure 3.4. The board was clamped to a table which was driven by the shaker. The pin and its housing were clamped in a holder
Figure 3.1 Schematic Diagram of the Fretting Apparatus.

1. SHAKER
2. DEAD WEIGHT
3. LVDT
4. PIN HOLDER
5. PIN
6. PC BOARD
7. VIBRATING TABLE
8. FORCE TRANSDUCER
9. RIGID ARM
10. MICROMETER
11. COUNTER WEIGHT
Figure 3.2 Block Diagram of the Experimental Setup.
Figure 3.3 The Experimental Setup (a), and a Closeup of the Apparatus (b).
Figure 3.4  Fretting Test Specimens:  (a) Pin and (b) Board.
which was connected to a rigid arm through a piezoelectric force transducer which has a compliance of 0.001 μm/N and can measure both tensile and compressive dynamic forces. The friction force was measured by this transducer, with power supplied and output coupled by a coupler. The output of the coupler was fed to an oscilloscope for visual monitoring, and it was also fed through a rectifier and averaging filter in order for the friction force to be recorded to a chart recorder. The force transducer was calibrated by the application of tensile and compressive static loads. The measured oscilloscope and recorder deflections for several loading conditions were used to obtain the calibration factor for the transducer. A normal force of 1.96 N (200g) was directly applied by a dead weight over the holder of the pin after the apparatus had been balanced by a counter weight.

The relative reciprocating motion was measured by a Linear Variable Differential Transformer (LVDT) which was attached to the pin holder and the vibrating table. A signal conditioning module supplied power to the LVDT and also converted its AC output to DC. The LVDT was calibrated by a micrometer which carried the core of the LVDT and was fixed to the shaking table while the coil of the LVDT was fixed to the pin holder. The output of the module was fed to an oscilloscope for monitoring, and to a frequency meter and an electronic counter for measuring frequency and the total
number of cycles. Figure 3.5 shows the waveforms of displacement and friction force shown in the oscilloscope. The waveform of displacement was sinusoidal, while that of friction force is close to a square wave.

The circuit used for measuring the contact resistance, both static and during the fretting test, is shown in Figure 3.6. A Wheatstone bridge circuit was used to measure the contact resistance. A signal conditioning module provided constant voltage to the bridge and acted also as an amplifier and filter for the output of the bridge. The output of the module was again fed to an oscilloscope for monitoring the dynamic contact resistance and to a chart recorder for recording the contact resistance. The bridge was balanced by the 10 kΩ potentiometer and then calibrated with 10, 20, 50 and 100 mΩ resistors.

Because the relative motion in fretting is very small, the displacement measured by the LVDT could be the sum of the relative displacement at the interface and the deflection of both the apparatus and the specimens between the interface and the point where the displacement is finally measured by the LVDT. An optical measurement should have been used to measure exactly the interface displacement. However, the displacement measured by the LVDT was found to be approximately the same (within 20 %) as that measured on fretted surfaces.

Care was exercised to operate the fretting apparatus at
Figure 3.5  Displacement (a), and Friction Force (b) from an Oscilloscope.
Figure 3.6 Wheatstone Bridge Circuit Used for Contact Resistance Measurement.
a frequency away from the resonant frequency of the apparatus, because the fretting motion resulted in up-and-down motion of the pin and the contact was lost when the apparatus was run at the resonant frequency. The friction force and contact resistance cannot be measured under this condition.

Table 3.1 lists the test conditions. It was found [39] that the number of cycles to attain a given increase in contact resistance decreases with increasing displacement of fretting. Displacements in the range of 20-200 µm were used in fretting corrosion of electric contact study (Table 2.1). A displacement of 200 µm was used in order to have reasonable test duration and make the evaluation of contact more conservative.

A limit of $10^5$ cycles was set for the duration of the test because at this stage severe damage was observed on the Au-Co alloy which is currently used in computers without any serious problem. The distance of fretting for 200 µm displacement at $10^5$ cycles is 40 m.

The frequency of fretting used was 30 Hz, on the assumption that the mechanical vibrations from disk drives, blowers, etc. cause the fretting motion in computers. The excitation voltage for the Wheatstone bridge circuit was set at 2 V in order to have a contact current of 20 mA which is about what is used in the edge-card connectors. The tests were conducted in laboratory air. A thermometer and a
<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>Normal Load</td>
<td>1.96 N (200 g)</td>
</tr>
<tr>
<td>Displacement of Fretting</td>
<td>200 µm</td>
</tr>
<tr>
<td>Frequency of Fretting</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Total Fretting Cycles</td>
<td>$10^5$ cycles</td>
</tr>
<tr>
<td>Distance of Fretting</td>
<td>40 meters</td>
</tr>
<tr>
<td>Contact Current</td>
<td>20 mA</td>
</tr>
<tr>
<td>Temperature</td>
<td>$293 \sim 298$ K</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>$55 \sim 65%$</td>
</tr>
</tbody>
</table>
hygrometer were used to measure the temperature and relative humidity during test.

3.2 Materials

Electroplated Sn-34Pb, Cu and electroless Ni were chosen for study because of their low resistivities and wide range of hardmesses. The hardmesses and resistivities are listed in Table 3.2.

Both bulk materials and their coatings were tested. Au-Co, which is currently used in printed circuit boards, was also tested for comparison. Finally, modulated Cu surfaces with coatings of Sn-Pb and Ni were studied as substitutes for the Au-Co alloy. Table 3.3 is a list of tested material combinations.

The pin was a Au-30Ag alloy of diameter 0.7 mm spotwelded on a phosphor-bronze wire. The specimens tested are shown in Figure 3.4. The pin was cut from a molded block to 8 mm wide while the board was cut into small piece of 70 mm x 60 mm.

3.2.1 Base metals

Electroplated Sn-Pb, Cu and electroless Ni on boards with 100 μm thickness were prepared for test. Thick platings were used to avoid the substrate effects.

3.2.2 Coatings on Cu laminates

Au-Co/Ni/Cu and Sn-Pb/Ni/Cu were used for study. Au-Co/Ni/Cu is currently used in printed circuit board. The
### Table 3.2 Experimental Materials

<table>
<thead>
<tr>
<th>Material*</th>
<th>Resistivity (µΩ - cm)</th>
<th>Hardness MPa (kg/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn - 34 Pb</td>
<td>$9.6 \pm 0.2$</td>
<td>$108 \pm 20$ ($11 \pm 2$)</td>
</tr>
<tr>
<td>Cu</td>
<td>$1.74 \pm 0.1$</td>
<td>$1009 \pm 88$ ($103 \pm 9$)</td>
</tr>
<tr>
<td>Ni</td>
<td>$8.3 \pm 0.6$</td>
<td>$4978 \pm 314$ ($508 \pm 32$)</td>
</tr>
<tr>
<td>Au - 1Co</td>
<td>$10.4 \pm 2.0$</td>
<td>$1597 \pm 196$ ($163 \pm 20$)</td>
</tr>
<tr>
<td>Au - 30 Ag</td>
<td>$13.8 \pm 0.5$</td>
<td>$1546 \pm 82$ ($158 \pm 8$)</td>
</tr>
</tbody>
</table>

* The composition is in weight percent.
Table 3.3 Material Combinations

1. Base Metals

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-34 Pb</td>
<td>100</td>
</tr>
<tr>
<td>Cu</td>
<td>100</td>
</tr>
<tr>
<td>Ni</td>
<td>100</td>
</tr>
</tbody>
</table>

2. Coatings on Cu Laminates

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-34 Pb</td>
<td>1/3.75/35</td>
</tr>
<tr>
<td>Au-1 Co</td>
<td>1.25/3.75/35</td>
</tr>
</tbody>
</table>

3. Coatings on Modulated Cu Surfaces

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-34 Pb</td>
<td>1/3.75/Modulated</td>
</tr>
<tr>
<td>Sn-34 Pb</td>
<td>1/30/Modulated</td>
</tr>
</tbody>
</table>
Au-1Co alloy with 1.25 μm (50 μin) thickness was electroplated on a hard Ni layer of nominal thickness of 3.75 μm (150 μin). The Ni in turn was plated over a 35 μm thick Cu laminate.

Sn-Pb/Ni/Cu was with Sn-34Pb alloy coating instead of Au-Co. The materials and thicknesses underneath were the same as those for Au-Co/Ni/Cu. The thickness of Sn-34Pb coating was 1 μm (40 μin).

3.2.3 Coatings on modulated Cu surfaces

A modulated surface, which is shown in Figure 3.7, was used for study. Ni with 3.75 μm (150 μin) thickness was plated on modulated Cu surface with pattern which was processed by etching. The sides of the "pad" and the cavity were 100 μm. The depth of the cavity was about 50 μm. Sn-34Pb alloy, 1.0 μm, in turn was plated on Ni. Thicker Ni, 30 μm thickness instead of 3.75 μm, was also used.

3.2.4 Lubricant

A lubricant provided by a vendor of Digital Equipment Corporation was used in this study. The composition is not described because it is proprietary. The lubricant was applied on the boards of selected specimens and exposed to air for 20 hours before test.

3.3 Microscopy

Scanning Electron Microscope (SEM) was used to investigate the wear tracks of the pins and boards after tests. In
Sn – 34 Pb (1 \mu m)

Ni (3.75 \mu m)

Figure 3.7  Geometry of the Modulated Surface.
addition, optical microscope was also used for observing the contacts. For a magnification of 100, the depth of focus for SEM is 1 mm, while for optical microscope it is only 1 μm.

Energy Dispersive X-ray Analyzer (EDXA) was used along with the SEM to determine the composition of the contact areas qualitatively. However, it cannot determine the exact composition of the surface because the depth of analysis for EDXA is about 1.5 μm. Micrographs were taken in the backscatter mode because better contrast was obtained in that mode. Both 10 and 45 degree tilts were used in the SEM photography.

3.4 Auger Electron Spectroscopy

Auger Electron Spectroscopy (AES) was used to determine the surface composition and to detect whether the substrate had been exposed. The surfaces were examined before and after 3 minutes of argon ion sputtering. The specimens had been tested at different number of cycles of fretting before surveying by AES in order to see when the subsurfaces had been exposed. In some selected specimens Auger mappings were done to determine the surface composition.
4. RESULTS

4.1 Bulk Base Metals

In this section, the friction coefficient and contact resistance of electroplated Sn-Pb, Cu and Ni are presented. The SEM micrographs of the specimens are also shown. The data plotted are from tests which illustrate average and typical results.

Figure 4.1 shows the friction coefficient vs. number of cycles for these materials. The friction coefficient of Sn-Pb ranges from an initial value of 0.34 to a steady value of 0.72. The data show an increase in friction coefficient as number of cycles increases up to $50 \times 10^3$ cycles. Thereafter a steady value of 0.72 is maintained. The friction coefficient of Cu starts at an initial value of 0.26 and reaches a maximum value of 0.74 at about $20 \times 10^3$ cycles. Then it decays to a steady value of 0.70. For Ni the friction coefficient is initially at 0.22 and rises to a maximum of 0.68 at about $20 \times 10^3$ cycles of fretting. The steady state value of friction coefficient is about 0.6.

The contact resistance vs. number of cycles for Sn-Pb alloy is shown in Figure 4.2a. The static contact resistance is about 7 mΩ. The dynamic contact resistance starts to increase after only a few hundred cycles of fretting. It rises over 100 mΩ after several thousand cycles. Figure 4.2b is the micrograph of Sn-Pb alloy after $10^5$
Figure 4.1 Coefficient of Friction vs. Cycles of Sn-34Pb, Cu and Ni.
Figure 4.2a  Dynamic Contact Resistance vs. Cycles of Bulk Sn-34Pb Alloy.
Figure 4.2b Bulk Sn-34Pb Alloy (a), and Pin (b) after $10^5$ Cycles.
cycles. The contact area shows severe plastic deformation and wear. Some of the material is even extruded from the contact area. Furthermore, some cracks are found in contact area although Sn-34Pb alloy is very ductile. The X-ray analysis of the pin shows the transfer of Sn-Pb alloy from the board to the Au-Ag pin. Both contact areas are covered with black oxide debris as was observed in an optical microscope. This debris may cause the high contact resistance.

The contact resistance of Cu is given in Figure 4.3a. The static contact resistance is about 10 mΩ. The dynamic contact resistance decreases to 5 mΩ immediately after the fretting motion begins and stays at this value till 60x10^3 cycles. After this stage, the contact resistance starts to increase and exhibits noise during fretting. The micrograph of Cu is shown in Figure 4.3b. Heavy plastic deformation and wear are observed at the contact area. It also shows extrusion. However, the wear is less severe than that of Sn-Pb alloy. The X-ray analysis of the pin shows transfer of Cu from the board. Some of the oxide and metallic debris accumulates at the wear area for both pin and board.

The contact resistance of Ni vs. number of cycles is plotted in Figure 4.4a. The static contact resistance of Ni is high, more than hundred milliohms. However, the resistance decreases to 9 mΩ after a few tens of fretting cycles. It then stays at this values during the test, although there are small deviations.
Figure 4.3a  Dynamic Contact Resistance vs. Cycles of Bulk Copper.
Figure 4.3b  Bulk Copper (a), and the Au-30Ag Pin (b) after $10^5$ Cycles.
Figure 4.4a Dynamic Contact Resistance vs. Cycles of Bulk Nickel.
Figure 4.4b shows the micrographs of Ni and the matched Au-Ag pin after test. No severe plastic deformation has occurred on the surface. Much Au-Ag alloy has been transferred from the pin on the Ni surface, which is shown by the X-ray analysis. Both contact surfaces at the interface are of the Au-30Ag composition eventually. The Au-30Ag to Au-30Ag contact keeps the contact resistance low and constant till the end of the test. Ni surface is little worn. Wear debris is mainly Au-Ag.

It can be concluded from these results that the number of fretting cycles for the contact resistance to increase decreases with the increase of wear. decreases with the increase of wear. Ni has the least wear and the contact resistance under fretting is about 10 mΩ till the end of the test. However, the static contact resistance is about hundreds of milliohms. Sn-Pb has low static contact resistance, but the resistance under fretting increases after only a few hundred cycles. In order to have low static contact resistance and little wear it was proposed to have soft Sn-Pb thin coating on hard Ni substrate. Soft Sn-Pb coating assures low static contact resistance. Less wear than that of bulk Sn-Pb is expected because Ni substrate supports the normal load while Sn-Pb coating takes over the shear strain.

4.2 Coatings on Cu Laminates

The result for friction coefficient and contact resis-
Figure 4.4b Bulk Nickel (a), and the Au-30Ag Pin (b) after $10^5$ Cycles.
tance of Sn-Pb coating on Ni substrate, which in turn was plated on Cu laminates, are presented in this section. The Au-Co alloy coating, which is currently used in computer industry, was also tested for comparison. The micrographs of the wear tracks and X-ray analyses of the selected areas on the wear tracks are also shown.

The coefficient of friction vs. number of cycles of Au-Co/Ni/Cu and Sn-Pb/Ni/Cu is plotted in Figure 4.5. The friction coefficient of Au-Co alloy coating is initially at 0.35 and rises to a maximum value of 0.77 at $10 \times 10^3$ cycles. It then stays at this value till the end of the test, $10^5$ cycles.

The friction coefficient of Sn-Pb alloy coating starts at an initial value of 0.27 and rises rapidly to 0.62 at $10 \times 10^3$ cycles. The rate of increase of friction coefficient slows down from $10 \times 10^3$ to $50 \times 10^3$ cycles. It reaches the maximum and steady state value of 0.72 at $50 \times 10^3$ cycles.

Figure 4.6a is the contact resistance vs. number of cycles of Au-Co alloy coating. The static contact resistance was 8 mΩ. The dynamic contact resistance under fretting motion was constant at 9 mΩ throughout the test.

The micrographs of the Au-Co coating and the matching Au-Ag pin are presented in Figure 4.6b. Much wear has occurred at the contact area. As evidenced from the energy dispersive X-ray analysis, much Au-Ag has been transferred to some areas of the wear track on the board. At some other
Figure 4.5  Coefficient of Friction vs. Cycles of 1.25 μm Au-1Co and 1.0 μm Sn-34Pb Coatings, Both on 3.75 μm Ni Substrate and Cu Laminate.
Figure 4.6a Dynamic Contacts Resistance vs. Cycles of 1.25 \mu m Au-1Co Coating and 3.75 \mu m Ni Substrate on Cu Laminate.
Figure 4.6b 1.25 µm Au-1Co Coating and 3.75 µm Ni Substrate on Cu Laminate (a), and the Au-30Ag Pin (b) after $10^5$ Cycles.
areas, the Au-Co alloy coating is partially or completely removed. The Ni signal from X-ray analysis at these areas indicates either a very thin Au-Co coating left, or the exposure of Ni. The micrograph of the pin shows Au-Ag has been transferred to the board. The X-ray analysis of one area of the pin shows signals of Sn and Pb which are due to the wear of Sn-Pb outside the spotwelded area, which is Sn-Pb coating on phosphor-bronze.

The contact resistance vs. cycles of Sn-34Pb alloy coating is shown in Figure 4.7a. The static contact resistance is 10 mΩ. However, the dynamic contact resistance starts to increase after fretting motion begins and shows noise under fretting motion throughout the test.

Figure 4.7b shows the micrographs of Sn-34Pb coating and pin after test. Much wear has occurred in the contact area. Sn-34Pb seems to have been worn out before 10⁵ cycles. X-ray analyses show exposure of Ni. Some areas are covered by Au-30Ag alloy which has been transferred from the pin. The micrograph of the matching pin is shown at the bottom of Figure 4.7b. The X-ray analysis indicates the transfer of Ni from the board to the pin.

In summary, Sn-Pb coating on Ni substrate assures low static contact resistance and less wear than that of bulk Sn-Pb. However, the contact resistance starts to increase after fretting begins. It is assumed that the accumulation of generated oxide debris at the contact interface is
Figure 4.7a Dynamic Contact Resistance vs. Cycles of 1.0 μm Sn-34Pb Coating and 3.75 μm Ni Substrate on Cu Laminate.
Figure 4.7b 1.0 μm Sn-34Pb Coating and 3.75 μm Ni Substrate on Cu Laminate (a), and the Au-30Ag Pin (b) after 10⁵ Cycles.
responsible for the increase in contact resistance.

In order to have low contact resistance under fretting, it is necessary to remove the accumulating oxide debris from the contact interface. A modulated contact surface, which provides new contact geometry for trapping the oxide debris, is proposed.

4.3 Coatings on Modulated Cu Surfaces

Sn-34Pb alloy and Ni coatings on modulated Cu surfaces with pattern were used to trap the oxide debris which was postulated to be responsible for the increase in contact resistance. Figure 4.8 shows the coefficient of friction of these modulated surfaces. The friction coefficient of 1.0 μm Sn-Pb coating on 3.75 μm Ni coating which in turn was plated on a modulated Cu surface is initially at 0.28 and rises to a steady value of 0.68. The contact resistance, which is shown in Figure 4.9a, maintains at 5 mΩ till the end of the test. The micrograph is shown in Figure 4.9b. The transfer of Au-Ag has occurred as evidenced from the X-ray analyses. The wear particles were trapped into the cavities. The trapping of wear debris leads to a low and constant contact resistance. However, much wear was observed. Therefore it was decided to increase the thickness of Ni substrate to reduce the wear.

The same combination of materials except with thick Ni coating (30 μm) instead of 3.75 μm was used to reduce the wear. The results show much difference in friction coeffi-
Figure 4.8  Coefficient of Friction vs. Cycles of 1.0 \( \mu m \) Sn-34Pb Coatings and Ni Substrates (3.75 and 30 \( \mu m \)) on Modulated Cu Surfaces.
Figure 4.9a Dynamic Contact Resistance vs. Cycles of 1.0 µm Sn-34Pb Coating and 3.75 µm Ni Substrate on Modulated Cu Surface.
Figure 4.9b 1.0 μm Sn-34Pb Coating and 3.75 μm Ni Substrate on Modulated Cu Surface (a), and the Au-30Ag Pin (b) after $10^6$ Cycles.
icient and contact resistance. The friction coefficient for this with 30 μm Ni, which is also plotted in Figure 4.8, ranges from an initial value of 0.25 to a steady value of 0.50. After 40x10³ cycles the friction coefficient is more or less steady. The contact resistance data, which is presented in Figure 4.10a, shows low static contact resistance but the dynamic contact resistance increases rapidly to more than 100 mΩ at 15x10³ cycles. Figure 4.10b is the micrograph after test. It is clear that the wear debris is trapped into the cavities. The debris consists of Au-Ag, Sn-Pb and Ni as seen from the X-ray analysis. X-ray analyses of the pads show either a very thin Sn-Pb layer was left or Ni was exposed. The micrograph of the pin is shown in Figure 4.10C. The transfer of Ni from the board to the pin has occurred. This leads to an increase in contact resistance because Ni to Ni contact has taken place.

4.4 Auger Electron Spectroscopy

Auger surface survey was performed on specimens of Au-Co/Ni/Cu and Sn-Pb/Ni/Cu(M) which had been tested at different number of cycles in fretting to determine when the substrate had been exposed. In addition, Auger mappings were done on samples which showed initial exposure of subsurface. The samples were analyzed before and after 180 seconds of argon sputtering. Oxygen, sulfur, chlorine and carbon were present as adsorbed layer on the coating before sputtering. The results are shown in Appendix A.
Figure 4.10a Dynamic Contact Resistance vs. Cycles of 1.0 μm Sn-34Pb Coating and 30 μm Ni Substrate on Modulated Cu Surface.
Figure 4.10b 1.0 μm Sn-34Pb Coating and 30 μm Ni Substrate on Modulated Cu Surface after 10^5 Cycles.
Figure 4.10c Au-30Ag Pin Fretted with 1.0 μm Sn-34Pb Coating and 30 μm Ni Substrate on Modulated Cu Surface.
4.5 Lubrication

The lubricant was applied on selected specimens and exposed to air for 20 hours before test. The coefficients of friction are plotted in Figure 4.11. The friction coefficients for all the materials are low, ranging from 0.20-0.23. There appeared to be no run-in period, the period from the beginning of test till a steady state value of friction coefficient is reached. The contact resistances are low (less than 10 mΩ) and constant throughout the test as shown in Figure 4.12.

Figure 4.13 is the micrograph of Au-Co/Ni/Cu for lubricated test. Au-Co still stays on the surface. The Ni signal in the X-ray analysis means either exposure of Ni or a very thin layer of Au-Co stays at the dark areas. As evidenced from the X-ray analysis of the pin, Au-Co has been transferred to the pin.

The micrograph of Sn-Pb/Ni/Cu is in Figure 4.14. Sn-Pb still stays on the surface although at some areas it may be thin. As evidenced from the X-ray analysis of the pin, no Sn-Pb has been transferred to the pin.

Figure 4.15 shows the micrograph of Sn-Pb/Ni/Cu(M). Oxide debris has been generated and has fallen into the cavities. Some are rolled by the fretting motion into cylinders. There is plowing on the surfaces of the pads and the pin. Sn-Pb still stays on most of the areas.

The micrograph of Sn-Pb/Ni(30µm)/Cu(M) is in
Figure 4.11  Coefficient of Friction vs. Cycles of Selected Specimens. Lubricated Tests.
Figure 4.12 Dynamic Contact Resistance vs. Cycles of Selected Specimens. Lubricated Tests.
Figure 4.13 1.25 μm Au-1Co Coating and 3.75 μm Ni Substrate on Cu Laminate (a), and the Au-30AG Pin (b) after $10^5$ Cycles. Lubricated Test.
Figure 4.14 1.0 μm Sn-34Pb Coating and 3.75 μm Ni Substrate on Cu Laminate (a,b), and the Au-30Ag Pin (c) after 10^5 Cycles. Lubricated Test.
Figure 4.15 1.0 \( \mu m \) Sn-34Pb Coating and 3.75 \( \mu m \) Ni Substrate on Modulated Cu Surface (a), and the Au-30Ag Pin (b) after 10^5 Cycles. Lubricated Test.
Figure 4.16. Oxide debris has been trapped into the cavities and some are rolled into cylindrical shape. Transfer of Au-Ag has occurred. The Ni signal shows either exposure of Ni or a thin layer of Sn-Pb staying at the dark areas.
Figure 4.16 1.0 \( \mu \text{m} \) Sn-34Pb Coating and 30 \( \mu \text{m} \) Ni Substrate on Modulated Cu Surface (a), and the Au-30Ag Pin (b) after 10^5 Cycles. Lubricated Test.
5.1 Fretting Corrosion of Electric Contacts

5.1.1 Friction

The friction coefficients of Sn-Pb, Cu and Ni under fretting have a low initial value of about 0.3 and increase rapidly with the number of cycles to a maximum value (Figure 4.1). Then the friction coefficient for Ni decreases to a steady value. The others (Sn-Pb and Cu) stay at this maximum as the steady state value. This behavior can be explained by the genesis of friction proposed by Suh and Sin [64].

The initial rise of friction coefficient is due to an increase in adhesion, and in the number of wear particles entrapped between the fretting surfaces. The oxide debris entrapped between the surfaces causes plowing of the contact surfaces. A steady value is reached when the number of entrapped particles at the interface remains constant. (i.e., the number of the newly entrapped particles equal the number of entrapped particles leaving the interface). The adhesion contribution to friction remains constant at this stage.

In the case of Ni, the asperities are gradually removed, creating a smooth finish. The plowing is low because wear particles generally cannot penetrate the polished hard surface depending on the hardness of the wear
particles. The number of the entrapped wear particles at
the interface decreases due to less wear of Ni. This leads
to a decrease in friction force. However, the surfaces are
never perfectly smooth; there are always craters on the
surfaces due to the creation of delamination wear particles
(Figure 5.1). These craters provide trapping space for the
wear particles. Eventually when the number of entrapped
particles at the interface reaches constant again, the fric-
tion force levels off.

5.1.2 Wear

The wear behavior of the base metals under fretting
corrosion largely depends on the information of oxidation
such as oxidation rate, thickness and mechanical properties,
for example hardness, of oxide film, etc.

If the materials do not react with the environment,
then the wear particles will be transferred back and forth
from surface to surface and a lower wear rate will occur.
If the materials are reactive to the atmosphere, higher wear
rate will occur because generated oxide debris appears to
become separated and loose from the surface.

Oxide debris can be generated either by the wear of
oxide film or by the oxidation of metallic wear particles
[9, 10]. The rate of oxidation and the wear rate determine
which mechanism dominates. In materials such as Sn-Pb and
Cu in which much wear was observed, most of the oxide debris
comes from the oxidation of metallic wear particles. On the
Figure 5.1  A Hard Polished Surface, and Craters Due to Delamination Wear.
other hand for materials with little wear such as Ni, the wear of oxide film leads to most of the oxide debris.

The delamination of wear [8] states that the repeated cyclic stresses of fretting cause subsurface cracks to form and propagate to the surface with resultant loosening of sheets of metal. However, not all the wear debris is of sheet-like, which implies that debris is generated from the transferred materials or the breaking of sheet-like particles.

The wear particles from softer surface could be easily transferred to harder surface depending on the compatibility of the two surfaces. When the pin is Au-Ag and the plate is a hard base metal, contact resistance does not rise significantly because Au-Ag is transferred readily to the base metal resulting in Au-Ag to Au-Ag contact, as in the case of Ni (Figure 4.4a). If base metal is transferred to the Au-Ag surface, both surfaces become all-base and oxidize. Therefore contact resistance rises rapidly to high values, as with Au-Ag versus Sn-Pb (Figure 4.2a). In the intermediate case such as Au-Ag to Cu contact (Figure 4.3a) with less difference in hardness, metal transfer of each member occurs approximately to the same extent. However, Cu gets oxidized and the resulting contact surfaces, which consist of Au-Ag, Cu and Cu oxides, show increase of contact resistance after longer fretting cycles than that of Sn-Pb.

From the above mechanism of material transfer, it is
concluded that hardness and compatibility are important factors for material transfer. The relative hardness of the contact materials determines the dominant transfer direction. Furthermore, the contact resistance depends on the resulting composition of contact surfaces which is a function of material transfer direction.

5.1.3 **Contact resistance**

**A. Theory**

In general, two factors cause the high contact resistance of base metal contacts.

(a) An oxide film stays on the surface without being penetrated by surface asperities under contact load and fretting motion. This film prevents the surfaces from forming metal-to-metal contact and therefore increases the contact resistance due to the high film resistance.

(b) Oxide debris generated by fretting corrosion accumulates at the contact interface. This accumulating oxide debris reduces the number of metal-to-metal contact spots and increases the average resistivity, therefore increases the contact resistance because of high constriction resistance.

Holm derived the constriction resistance for a single contact spots as shown in Equation 2.4 [65]. However, the normal contact in practice is not a single asperity contact.
Greenwood's equation of constriction resistance [66] for multiple contact spots is given in Equation 2.5. It is basically the sum of the parallel resistances of the contacts and an asperity interaction term based on the closeness of the asperities. The constriction resistance changes, presumably as a result of a change in one or more of the variables in the equation. Since the radius "R" of the apparent area will not vary appreciably, the number "n" of conductive contact spot and mean effective contact radius "a" could possible be the changing variables. The average resistivity will also be changed because oxide is a poor conductive material.

This problem can also be simplified by assuming that the mean effective contact radius "a" is constant because it depends on the average asperity radius. Finally, the variation of constriction contact resistance possibly is a result of changes in the number "n" of conductive contact spots. The oxide debris accumulating at the contact interface reduces the number of conductive contact spots and increases the average resistivity. The constriction contact resistance, therefore, increases.

B. Model

A model for contact resistance under fretting with base metal contact is schematically illustrated in Figure 5.2. It is divided into three stages as function of fretting cycles.
Figure 5.2  Model for Contact Resistance of Base Metal Contacts under fretting.
In the first stage, immediately after static contact or fretting motion begins, surface asperities penetrate the oxide film providing a good metal-to-metal contact. The contact resistance decreases to less than 10 mΩ. It happens immediately after contact occurs when the substrate is softer than the pin. If the substrate is harder, oxide film will not be broken through before fretting motion begins.

The second stage is characterized by burnishing and increasing adhesion of the contact surfaces. The transfer of materials occurs, little oxide debris is generated and metal-to-metal contact still exists.

In the third stage, more oxide debris has been generated from the contact and accumulates at the interface. It reduces the number of metal-to-metal contact spots and increases the average resistivity, therefore increases the contact resistance due to a rise in constriction resistance.

This model is able to explain the contact resistance behavior of noble versus base metal contacts. The scheme fits the experimental results closely only with the modifications of the level of contact resistance and the number of cycles where the transitions occur.

In the case of bulk Sn-Pb (Figure 4.2a), breakage of the oxide film occurs at the presence of contact load because Sn-Pb is softer than Au-Ag pin. When the fretting motion begins, Sn-Pb is transferred to the pin resulting in Sn-Pb at both surfaces. This leads to fast generation and
easy penetration of oxide debris at the interface because Sn-Pb is very soft, therefore makes the second stage much shorter than that for Cu.

For Cu, based on the proposed model of material transfer, the transfer of Cu and Au-Ag occurs approximately to the same extent because their hardnesses are close. Therefore the resulting contact surfaces with mixture of Cu and Au-Ag have slower generation of oxide debris. This extends the second stage with low contact resistance (Figure 4.3a). The first stage occurs before the fretting motion begins because the oxide film has been broken through under contact load.

Because Ni is much harder than Au-Ag, the first stage, i.e., the breakage of oxide film, occurs only after fretting motion begins. The static contact resistance is several hundred milliohms due to the high film resistance. In the second stage, after the oxide is removed, only transfer of Au-Ag occurs and this makes the resulting contact surfaces with Au-Ag to Au-Ag. Almost no oxide debris has been generated and stage three did not happen up to the end of test (Figure 4.4a).

The contact resistance for Sn-Pb coating on Ni underplate over Cu laminate (Figure 4.7a) shows that there is a lower level of noise after $20 \times 10^3$ cycles. At this stage, Sn-Pb coating has been worn out and Au-Ag begins to be transferred to Ni surface to make Au-Ag to Au-Ag contact
which decreases the contact resistance. However, still some Sn-Pb oxide debris sticking at the contact surfaces causes the fluctuation in contact resistance.

In summary, contact resistance behavior of Au-Ag pin versus base metal contacts begin with the penetration of surface asperity into oxide film under contact load or fretting motion. Once the oxide film is broken through providing a metal-to-metal contact, the subsequent behavior depends on the direction of material transfer, the amount of oxide debris and the penetration of oxide debris on the contact surfaces.

C. Effect of displacement

It has been found [39] that the number of cycles to attain a given increase in contact resistance decreases with increasing displacement of fretting. It has also been proposed that there was a critical displacement below which wear rate decreased as displacement decreased [11,12].

It is generally agreed that the larger the relative displacement, the more is the fretting wear. However, the wear rate (wear volume per sliding distance) is independent of displacement. The reason why there was a critical displacement below which wear rate decreased as displacement decreased is that the transmission of relative motion to the contact interface was occasionally accommodated by the deflection of test samples and apparatus between the interface and the point where the displacement was measured.
Therefore, there was almost no relative motion at the contact interface on occasion although a low value of displacement was measured by the measuring device.

In addition to the wear volume and the wear rate, a new variable, the wear volume per unit wear area, may best characterize the contact resistance of base metal contacts. This is so because the contact resistance depends on the amount of the oxide debris distributed at the contact interface. The contact resistance of Sn-Pb, Cu and Ni (Figure 4.2-4.4) support this statement, assuming that the wear areas are about the same. The more the wear, the less is the number of cycles required for the contact resistance to increase.

It is generally agreed that the wear volume is proportional to the sliding distance. When the displacement "b" is much less than the length of contact "a" in the direction of fretting motion (Figure 5.3a), the wear volume of the board is given by

\[ V = k_2 b N \quad b \ll a \quad (5.2) \]

where "N" is the number of cycles, k is a constant.

If the displacement "b" is much larger than the length of contact "a" (Figure 5.3b), it is also given by

\[ V = k_2 b N \quad b \gg a \quad (5.3) \]
Figure 5.3 Two Cases of Reciprocating Sliding: (a) Displacement Much Smaller than Length of Contact and (b) Displacement Much Larger than Length of Contact.
If the wear volume is divided by the wear area, assuming that the area has unit width normal to the direction of motion, the wear volume per unit wear area for both cases is, therefore, given by

\[ \frac{V}{A} = K \frac{2N}{b} \quad b \ll a \quad (5.3) \]

and

\[ \frac{V}{A} = K \frac{2N}{b} = K \frac{2N}{b} \quad b \gg a \quad (5.4) \]

respectively.

Therefore, it can be clearly compared that for the same number of cycles the wear volume per unit area is proportional to the displacement if the displacement is much less than the length of contact. However, it is independent of displacement if the displacement is much larger than the length of contact.

From contact resistance point of view, the more the wear per unit wear area, the more is the oxide debris per unit wear area. Consequently, the contact resistance is higher. It is concluded by quantitative derivation (Equation 5.3, 5.4) that the number of cycles to attain a given increase in contact resistance (Wear volume per unit area is constant.) decreases with increasing displacement if
the displacement is much less than the length of contact in
the direction of motion. On the contrary, when the dis-
placement is much larger than the length of contact, the
number of cycles to attain a given increase in contact
resistance is independent of displacement.

Furthermore, because there are such different behaviors
of contact resistance with length of contact in the direc-
tion of motion as a critical value for the displacement,
this value may be used to characterize the transition from
fretting to sliding. As a matter of fact, the length of
contact for most tests done in the past with rider on plate
geometry is about the same order as the transition value,
200-300 μm.

5.1.4 Lubrication

It has been shown [28] that non-noble metal contacts
undergo accelerated oxidation when subjected to fretting
motion, and this oxidation can be postponed or prevented
when oxygen is excluded from the contact interface by the
application of a suitable lubricant. In noble metal con-
tacts, lubrication seems to reduce wear although these
materials give stable and low contact resistance values in
both the dry and lubricated tests.

In all lubricated tests the friction coefficient
remained essentially low and constant 0.22 through the test
period (Figure 4.11). That is, there was no run-in period,
the period from the beginning of test till a steady state
value of friction coefficient is reached. The rise in friction coefficient in the run-in period is due to an increase in adhesion and in the number of wear particles entrapped at the contact interface as explained in 5.1.1.

Therefore, it can be concluded that the major benefit of lubrication is the reduction of adhesion and wear particles. The friction coefficient decreases to 0.22 as compared with about 0.7 in dry test. The volume of wear particles is also reduced, specifically the oxide debris because the lubricant excludes oxygen from the contact surfaces. The contact resistance, therefore, has not increased.

It was found [32] that the friction coefficient curves for the poor lubricants usually have two regions, one of rising and one of falling. It means that the run-in period still exists. Apparently a poor lubricant has little ability to lower the extent of adhesion, metal transfer and wear debris generation.

Essentially, the lubricant provides environmental protection from fretting corrosion of base metal contacts. In the case of thin film lubrication, not reservoir lubrication, a good lubricant, from contact resistance point of view, should be able to seal out the atmosphere under fretting motion. The sealing ability results from the self healing properties of the film. Concerning the long term effects, the film retention life and the properties of
lubricant such as self healing and harmful polymer formation need to be evaluated.

5.1.5 Connector design to prevent fretting motion

What the LVDT measures is the relative displacement between the pin holder and the vibrating table to which the board is clamped. However, the pin itself can deform elastically in both vertical and horizontal directions as shown in Figure 5.4.

The vertical deflection allows the PC board to be plugged in and pulled out. The horizontal compliance can probably avoid or reduce the fretting motion at the interface of contact when there is relative motion between the board and the pin housing.

It was found that there was a critical displacement, above which the waveform of friction force was close to a square wave, under which to a sinusoidal wave. This critical value of displacement was about 30 μm for this specific connector design. The friction force with sinusoidal waveform implies that a spring element lies between the interface of the contact and the force transducer. This spring element is the flexible pin.

In order to eliminate or reduce the small relative motion in the contact interface, a design consideration in increasing the compliance of the pin in the direction of fretting motion is suggested to prevent transmission of relative motion to the contact interface. However, a com-
Figure 5.4 Horizontal and Vertical Compliances of the Pin.
promise between the compliance of the pin and the stability of the PC board after it has been plugged into the connector block should be considered, too.

The design of contact geometry of the pin is another way of preventing contact failure by fretting corrosion. Different contact geometries such as hemisphere, domed, wedge and cylindrical, etc. might show different contact performance. The oxide debris may be pushed out of the contact interface by these contact geometries.

5.2 Modulated Contact Surfaces

Frettion of base metals causes the generation of oxide debris at the interface. The accumulation of the oxide debris at the interface results in an increase in contact resistance, although some of the debris is pushed out of the interface by the fretting motion.

In order to have low dynamic contact resistance under fretting, it is necessary to remove the accumulating oxide debris from the contact interface. The modulated contact surfaces, which provide new contact geometry for trapping the oxide debris, are discussed below.

5.2.1 Friction and contact resistance

The object of using the modulated contact surface is to trap the oxide debris accumulating at the contact surface so as to assure metal-to-metal contact at the interface. This will result in low contact resistance for base metal con-
tacts under fretting.

The results prove this hypothesis. Most of the oxide debris is entrapped in the "cavities" of the modulated contact surface (Figure 4.9b) resulting in low contact resistance for base metal contacts under fretting up to 105 cycles (Figure 4.9a).

The results for the same materials with flat contact surfaces are shown in Figure 4.7a, 4.7b. The contact resistance starts to increase after the fretting motion begins. It is over 20 mΩ after 3x10³ cycles. The significance of modulated contact surface in reducing contact resistance can be clearly seen by comparing these results. Furthermore, the comparison of contact resistance between modulated base metal surface (Figure 4.9a) and Au-Co (Figure 4.6a) shows that the former is able to be a substitute for noble metal.

The coefficients of friction for the flat and modulated surfaces with the same materials (Figure 4.5, 4.8) have about the same values. The contributions of the three basic friction generating mechanisms (i.e., asperity deformation, plowing and adhesion) can be used to analyze the friction coefficients of flat and modulated surfaces.

The plowing component is expected to be lower for the modulated surface because the wear particles are entrapped in the "cavities". This leads to more metal-to-metal contacts so that contact resistance is low. However, more metal-to-metal contacts also increase the adhesion component
of friction. The total contributions of plowing and adhesion components could make the friction coefficient the same for flat and modulated surfaces.

The concept of modulated contact surface can also be applied to other areas where low friction coefficient is required. When two contact materials are incompatible, the adhesion component is negligible whether or not the wear particles stay at the contact interface. The plowing component will be lower for the modulated surface than that for the flat surface, while the adhesion component is negligible for both. The total friction coefficient, therefore, will be lower for modulated surface.

In order to decrease the adhesion component of friction coefficient, tests were done using an AISI 52100 steel slider instead of Au-Ag pin. A hemispheric slider, 1/4" diameter, was polished and oxidized at 423 K for 20 hours. Therefore, a coherent oxide film was generated on the surface of the slider. The adhesion between the oxide film and Sn-Pb coating was expected to be small.

Fretting tests were done on both flat and modulated surfaces. The friction coefficients are shown in Figure 5.5. The friction coefficient for the specimen without modulated surface increases from an initial value of 0.28 to a steady value of 0.63. However, the steady value for the modulated surface with pattern is only 0.36. The reduction of friction coefficient is due to a decrease in
Figure 5.5  Coefficient of Friction vs. Cycles of Sn-34Pb Coatings and Ni Substrates on Flat and Modulated Surfaces. Oxidized AISI 52100 Steel Sliders.
the plowing component because the wear particles are trapped in the cavities and also due to poor adhesion between the oxidized steel and Sn-Pb.

There is also another advantage of modulated surface when applying the lubricant on the contact surface. The application of lubricant on the fingers of the printed circuit board can be done by having the tips, which supply the lubricant, at the entry of connectors (Figure 5.6). Each time the PC board is plugged in or pulled out, the tips can sweep all over the surfaces of the fingers. However, the lubricant cannot be spread all over the surface without this in-and-out motion of the PC board for the flat surface. In order to have lubricant on the contact surface all the time, a regular in-and-out motion of the PC board is necessary. With the modulated surface, the regular in-and-out motion can be eliminated, because experiments have shown that the lubricant can be spread all over the modulated surface by the capillary effect even though the lubricant is applied by the tip at a spot far away from the contact.

5.2.2 Geometries and materials

The geometry and size of the pattern, which may affect the process of debris trapping, will be discussed in this subsection. The choice of materials for this modulated contact surface is also an important factor affecting the contact resistance.

The geometry of modulated contact surface is shown in
Figure 5.6 Application of the Lubricant on the Contact Surfaces by the Tips at the Entry of the Connector.
Figure 3.7. The sides of the square pads and cavities are 100 µm long while the height of the pads is about 50 µm. It seems that a smaller pad might easily trap the wear particles depending on the displacement of fretting motion. When the displacement is larger than the side of the pads, all the wear particles will be trapped in the cavities. On the other hand, part of oxide debris might be left on the pads if the displacement of fretting motion is less than the side of the pads. However, in a test using a relative displacement of only 20 µm instead of 200 µm, the contact resistance was found to be about 6 mΩ throughout the test (Figure 5.7).

The geometry of the pattern may also affect the contact resistance behavior. If circular pads instead of square pads are used (Figure 5.8), it might be easier to trap the wear particles. However, these circular pads may indent the pin, especially if the diameter of the pads is small. The oxide debris, which is generated at the contact interface, will be left at the indentation instead of being trapped in the cavities. This leads to high contact resistance. Therefore, the indentation at the pin by the pads should be avoided. The square geometry of the pads was found to be optimum.

The hardnesses of the pin and pad materials are also critical. When the pin is much harder than the pads, the pads will be worn out quickly before $10^5$ cycles. Therefore, the contact resistance will increase because there is no
Figure 5.7 Dynamic Contact Resistance vs. Cycles of 1.0 μm Sn-34Pb Coating and 3.75 μm Ni Substrate on Modulated Cu Surface. 20 μm Displacement.
Figure 5.8  Geometries of the Modulated Surface:  (a) Square and (b) Circular.
more cavities to trap the oxide debris if the pads are worn out.

On the other hand, if the pin is much softer than the pads, the pads can possibly indent the pin. The oxide debris, which is generated at the contact interface, will be left at the indentation instead of being trapped in the cavities. This results in high contact resistance. It is concluded that the hardnesses of the pin and pattern materials should be about the same.

An attempt was made to reduce the wear and consolidate the pads by increasing the thickness of Ni underplate from 3.75 μm to 30 μm. Low contact resistance was found only up to $14 \times 10^3$ cycles (Figure 4.10a), although the friction coefficient decreased from 0.7 to 0.5 (Figure 4.8). The wear particles were also entrapped in the cavities (Figure 4.10b). However, some sheet-like wear plates of Ni sticking on the surface of Au-Ag pin were found. It is postulated that these Ni wear plates increase the contact resistance because this leads to Ni to Ni contact. The oxide films, which are not broken through, on the Ni surface prevent the metal-to-metal contact.

However, there was no Ni wear plate sticking at the Au-Ag surface for the specimen with only 3.75 μm Ni underplate. A hypothesis based on delamination mechanism [69] can be used to explain these different behaviors.

Sn-Pb coating was oxidized and worn out early at about
$15 \times 10^3$ cycles (Figure 4.10a) with the Ni plate left on the surface. If the thickness of Ni plate is less than the depth of low dislocation region, the plate will not be strain-hardened because the dislocations generated in the plate will escape through the free surface. On the contrary, if the Ni plate is thicker than this critical value, dislocations can accumulate in the plate and lead to strain-hardening and wear of the Ni plate by delamination.

Therefore, wear of 30 $\mu$m Ni plate by delamination mechanism has occurred resulting in the sticking of Ni wear plate on the Au-Ag surface. No such wear of Ni has occurred when the thickness of Ni was 3.75 $\mu$m.
6. CONCLUSIONS

As a result of this study the following conclusions can be drawn:

1. The relative hardness of the contacting bodies determines the direction of most material transfer under fretting. Different direction results in different behavior in contact resistance when one contact member is essentially noble and the other is non-noble.

2. The oxide debris is generated either by the wear of oxide film or by the oxidation of metallic wear particles. The rate of oxidation and the wear rate determine which mechanism dominates. In materials with high wear rate such as Sn-Pb, most of the oxide debris comes from the oxidation of metallic wear particle. On the other hand for materials with low wear rate such as Ni, the wear of oxide film leads to most of the oxide debris.

3. Two factors cause high contact resistance of base metals.

   (a) An oxide film, which stays on the surface without being penetrated by asperities of the counterface under the contact load and fretting motion, prevents the surfaces from forming metal-to-metal contact spots.

   (b) Oxide debris generated by fretting corrosion accumulates at the contact interface.
4. A major benefit of lubrication is the reduction of adhesion. The friction coefficient of lubricated surfaces is 0.22 as compared with about 0.7 in dry tests. In addition, the volume of wear particles is reduced, especially the oxide debris because the lubricant excludes oxygen from the contact surface. The increase of contact resistance, therefore, is prevented.

5. The number of cycles to attain a given increase in contact resistance decreases with increasing displacement if the displacement is much less than the length of contact in the direction of motion. On the contrary, when the displacement is much larger than the length of contact, the number of cycles to attain a given increase in contact resistance is independent of displacement.

6. The modulated contact surfaces, which have cavities for trapping the oxide debris, was tested. Most of the debris was entrapped in the cavities resulting in low contact resistance under fretting motion. The results suggest that the modulated base metal surfaces could be used as substitutes for noble metals.

7. This concept of modulated contact surface for trapping the wear particles can also be applied to reduce friction coefficient. The plowing component of friction coefficient of modulated surface will be lower than that of flat surface, because wear particles are entrapped in
the cavities. The total friction coefficient, therefore, will be lower for modulated surface if asperity deformation and adhesion components are the same for both cases.

8. In order to eliminate or reduce fretting motion in the edge-card connectors, a design consideration in increasing the compliance of pin in the direction of fretting motion is suggested to prevent transmission of relative motion to the contact interface.
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APPENDIX A: RESULTS FOR AUGER ELECTRON SPECTROSCOPY

AES survey was done on specimen with 1.0 μm Sn-Pb coating over 3.75 μm Ni which had been plated on modulated Cu surface, and on Au-Co alloy for comparison. Figure A.1 shows the results of untested samples.

The results for the Sn-Pb coating after $10^2$, $10^3$, $10^4$ and $10^5$ fretting cycles are shown in A.2. The Ni signal was first present after $10^3$ cycles. More Ni was exposed at $10^4$ cycles. At $10^5$ cycles, Cu was also exposed in addition to Ni. The corresponding results for the Au-Co coating are shown in Figure A.3. Ni first was exposed at $10^4$ cycles fretting. At $10^5$ cycles Cu was also exposed. Figure A.4a–A.4c show the micrographs of Sn-Pb alloy coating at $10^2$, $10^3$ and $10^4$ cycles respectively. The one with $10^5$ cycles is shown in Figure 4.9b. All show transfer of Au-Ag alloy from the pin to the board. Figure A.4d is the Auger mappings of Sn, Ag and Ni for Sn-Pb alloy coating at $10^3$ cycles which was found with initial exposure of Ni by Auger survey. The bright areas on the pads are the Au-Ag alloy, while the dark areas are the Ni. The gray areas show the existance of Sn-Pb alloy although some of them might be covered by carbon.

The graphs for the Au-Co alloy coating at $10^2$, $10^3$ and $10^4$ are in Figure A.5a–A.5c. For $10^5$ cycles, it is in Figure 4.6b. The transfer of Au-Co alloy from the board to the pin was observed as shown by the X-ray analyses at $10^2$ and
Figure A.1 Auger Electron Spectrum of Untested Au-1Co/Ni/Cu and Sn-34Pb/Ni/Cu(M) with 3 Minutes of Argon Sputtering.
Figure A.2  Auger Electron Spectrum of Sn-34Pb/Ni/Cu(M) with 3 Minutes of Argon Sputtering after $10^2$, $10^3$, $10^4$ and $10^5$ Cycles.
Figure A.3
Auger Electron Spectrum of Au–Co/Ni/Cu with 3 Minutes of Argon Sputtering after 10^2, 10^3, 10^4 and 10^5 Cycles.
Figure A.4a 1.0 µm Sn-34Pb and 3.75 µm Ni Substrate on Modulated Cu Surface (a), and the Au-30Ag Pin (b) after $10^2$ Cycles.
Figure A.4b 1.0 μm Sn-34Pb and 3.75 μm Ni Substrate on Modulated Cu Surface (a), and the Au-30Ag Pin (b) after $10^3$ Cycles.
Figure A.4c 1.0 μm Sn-34Pb and 3.75 μm Ni Substrate on Modulated Cu Surface (a-c), and the Au-30Ag Pin (d) after $10^4$ Cycles.
Figure A.4d Auger Mapping of Sn, Ag and Ni for Sn-34Pb/Ni/Cu(M) after $10^3$ Cycles.
Figure A.5a 1.25 μm Au-1Co Coating and 3.75 μm Ni Substrate on Cu Laminate (a), and the Au-30Ag Pin (b) after $10^2$ Cycles.
Figure A.5b 1.25 μm Au-1Co Coating and 3.75 μm Ni Substrate on Cu Laminate (a), and the Au-30Ag Pin (b) after 103 Cycles.
Figure A.5c 1.25 μm Au-1Co Coating and 3.75 μm Ni Substrate on Cu Laminate (a), and the Au-30Ag Pin (b) after 104 Cycles.
10^3 cycles. However, at 10^4 cycles much Au-Ag had been transferred from the pin to the board. Ni was exposed at this stage. Figure A.5d is the Auger mappings for Au, Ag and Ni for Au-Co alloy coating at 10^4 cycles which shows the initial exposure of Ni from Auger survey. Au, which comes from both the board and pin, was spreading all over the area. Much Au-Ag had been transferred to the board as can be seen in Figure A.5c. The dark areas shows the exposure of Ni.
Figure A.5d Auger Mappings of Au, Ag and Ni for Au-1Co/Ni/Cu after $10^4$ Cycles.