Developments in Fretting Studies applied to Electrical Contacts

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The paper is primarily a review of studies undertaken at the University of Southampton over the last 5 years.

With important contributions from;
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- Liza Lam
- Christian Maul
- TaiCaan Technologies Ltd
Developments in Fretting Studies

1. Introduction to Fretting
2. Recent Fundamental Studies, Area of contact.
3. Defining The Fretting Process
4. Fretting Wear
5. Intermittency during Fretting
6. NEW Applications,
   - In-Body Electronics and PV systems
7. Conducting polymer interfaces
8. Observations
Part 1. Introduction to Fretting

- Fretting is defined as a low level relative movement between mated contacts (μm), caused by either differential thermal expansion of materials or forced movement for example by vibration.
- Fretting motion can be low or high frequency.
- Fretting is known to be a major cause of contact deterioration and failure; commonly exhibited as the contact resistance increases from a few mΩ to Ω.
- Classical Fretting studies are well documented. (ASTM)
- The aim of the review is to provide insight into recent studies, with particular emphasis to intermittency and wear, and new materials. (NEW DIRECTIONS)
Plated surfaces, (for example Sn-Sn) where the plated surface is worn by the fretting action to expose the base (Cu) material. The process is then governed by both wear and fretting corrosion, as the worn particles interact with the environment.

The traditional method is to use a forced fretting apparatus, where the contacts are cycled over 10-100’s microns, at typically below 1Hz.

The contact resistance is then monitored again at low frequency for example 10Hz.
The Loaded Surface Profile:
A new technique for the investigation of contact surfaces
Recent Fundamental Studies

- The aim is to investigate the relationship between contact force and measured contact area.
- Most investigators investigate the relationship between force and secondary phenomena such as contact resistance.
- The problem is how to measure the area of contact.
- There are a number of models of the interaction summarised in the paper.
- For the initial study defining the method a standard new Ag based electrical contact was selected, with hemispherical form.
- Recent advanced in surface metrology have allowed the development of the process used.
Experimental System:

- TaiCaan Technologies Ltd.
- XYRIS4000LT
- Confocal Laser
- Laser Sensor range 0.6mm
- Sensor Resolution 10nm
- Light spot size 2µm
- X,Y system
  - Resolution 0.1µm
- Optical Flat Ra=30nm
- Force Resolution 10mN
TaiCaan Technologies Ltd.
XYRIS4000LT
Confocal Laser
Allows for Multiple surface detection.
Film Thickness (micron)
Metallic surface can be detected through glass.
Measurement System

Laser Scanner

Contact
Force sensor

Adjustable screw support

Transparent flat surface
Contact Materials

- Contact Materials: The contact surface selected is a hemispherical Ag/SnO contact rivet, with a nominal radius of 6.422mm.
- All surfaces were cleaned prior to testing.
- The system is mounted upon an anti-vibration work station in a temperature controlled clean room (20°C +/- 0.5°C).
- The results are presented in a 3 stage process.
Stage 1. Initial tests without the glass surface. To determine the nature of the contact surface a series of scans were conducted on the electrical contact surface without the glass.

Stage 2. Initial study of the surface under a fixed contact force, to identify the contact areas.

Stage 3. The study of the contact areas as a function of the contact force.
Surface Measurement
The unloaded surface- No glass

- 3mmx3mm (30µm grid spacing) contact surface with the spherical form removed.

- 2D section, with sphere removed. R=6.422mm.

- Pa = 0.992um (Red Line),
- Ra = 0.172um (Blue Line) with
- 0.25 Gauss filter (Green)
Central Region of Surface

Details of the surface of the contact, 0.21mm x 0.21mm (301x301) grid 0.7µm
Res 1 = 0.6mm x 0.6mm, 2µm grid. As shown in previous slide, allow for the centering of the measurement, based on the ring structure.

Res 2 = 0.3mm x 0.3mm, 1µm grid, to identify the structure of the peaks within the contact region.

Res 3 = 0.21mm x 0.21mm, 0.7µm, for the evaluation of the surface area.

Res 4 = 0.02mm x 0.02mm, 0.2µm grid, for the evaluation of a single asperity.
Contact Force 0.35N

- Res 3 = 0.21mm x 0.21mm, 0.7µm, for the evaluation of the surface area.

- Close up of the surface, showing low number of peaks

Res 4, The profile of a single asperity 20µm x 20µm, with a grid spacing of 0.2µm
Determining the Contact Area

Histogram of loaded contact surface

RES 3.

Magnified section of the peaks where there are clearly low number of peaks above the 10 micron level.
BODDIES Software: Data below datum.
Surface Properties above datum

Number of cells: 445
Average Height [mm]: 0.006012
Average Area [mm²]: 3.448169e-06
Average Volume [mm³]: 9.483786e-09
Slice level definition: To determine the surface area in contact with the glass, the slice level is defined as that level at which there are a minimum of 3 clearly defined areas of contact, which are separated by a reasonable distance.
Stage 3: Contact area v Contact force

![Graph showing the relationship between Area of Contact (um$^2$) and Contact Force (N). The graph displays a linear trend with data points and a regression line.]
Continued Studies

- New Apparatus being designed to improve force measurement control.
- New material surfaces to be investigated are Au coated surfaces.
- The selected surface peaks will be investigated with SEM.
- Nano-Indenter to be used to investigate local surface hardness properties.
- Conducting Transparent surface of InSnO will be used to investigate the link with contact resistance.
- System to be used to investigate the contact phenomena of conducting polymer surfaces.
The X,Y grid resolution for the data presented in this paper is 0.7µm over a measurement area of 0.21mm x 0.21mm.
The slice level used is defined as follows;
Slice level definition: To determine the surface area in contact with the glass, the slice level is defined as that level at which there are a minimum of 3 clearly defined areas of contact, which are separated by a reasonable distance.
Part 3. Defining The Fretting Process

- Stick, where the movement between the contact surfaces is accommodated by the elastic deformation in the near surface regions.
- Mixed Stick-Slip, where there is a central stick area surrounded by an annular slip region.
- Gross Slip, where asperities are broken during each cycle, movements between 10-100µm.
- Reciprocating sliding, where the movements are more than 100-200µm.
Defining The Fretting Process

- A critical Driving Force in recent studies has been the advances in automotive electronics.
- There have been a number of recent studies into this application.
- The main focus here will be on the work trying to identify real fretting magnitudes insitu.
Defining The Fretting Process

Connector housing

A
B
C

Brake sensory system

Behind bumper

Near engine
Defining The Fretting Process

- A In-Situ Position Sensor has been developed using thick Film Techniques.
- This allows real displacement measurements to be made in the automotive system.
Defining The Fretting Process

- A Single Thermal Cycle, generated from an environmental chamber.
- Resulting pressure changes on a sealed connector leads to 17µm, of movement. (Gross Slip).
Defining The Fretting Process

Field Test Data, with 14um of Gross Slip
Part 4. Fretting Wear Studies

- Advances in 3D surface Metrology allow the accurate evaluation of surface wear.
- However there are a number of potential errors that need to be understood.
- The key issue is how to define a datum surface when the measured has 3D form, for example a cylinder connector surface, or a hemispherical contact.
The Evaluation of Wear During Fretting
The important question here is: should the form removal method be applied before the wear analysis?

- **Method A** Form removal applied to the wear region.
- **Method B** Wear region removed before form removal.

<table>
<thead>
<tr>
<th>Method</th>
<th>Volume below the datum surface, after form removal, (mm$^3$)</th>
<th>Volume above the datum surface, after form removal, (mm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method A</td>
<td>11.4 x10^{-5}</td>
<td>5.45 x10^{-5}</td>
</tr>
<tr>
<td>Method B</td>
<td>14.7 x10^{-5}</td>
<td>4.47 x10^{-5}</td>
</tr>
<tr>
<td>Error in A</td>
<td>-3.3 x10^{-5}</td>
<td>+0.98 x10^{-5}</td>
</tr>
</tbody>
</table>
Part 5. Intermittency

- The traditional fretting experiments measure the contact resistance at low frequency, eg 1Hz.
- This sampling method misses high frequency resistance changes often exhibited at the interface. Events have been monitored at the ns level.

An intermittency event in a Sn-Sn fretting study. The softening and melting voltages are often exceeded $F = 500 \text{ mN}, U = 14.0\text{ V}; I = 54 \text{ mA}; v = 0.1 \text{ mm/s}$
Intermittency Contact Configuration
Fretting Motion (200µm)
Intermittency

Maximum Contact Voltage, during intermittency events in a Sn-Sn fretting study, with 200µm fretting cycle.  \( F = 500 \text{ mN}, \ U = 14.0 \text{ V}; \ I = 54 \text{ mA}; \ v = 0.1 \text{ mm/s} \)
Part 6. New Applications

Intermittency Events in Bio-Compatible Electrical Contacts
INTRODUCTION

- Intermittency
  - The requirement for high sampling rates in fretting tests.
  - *An intermittence or discontinuity is the temporary disruption of metallic conduction in a closed electrical contact.*

- Examples of Connectors used for Body Implanted Electronics
  - In all cases multiple contact points are used. (4-40).
All materials have to be Bio-Compatible, excluding the use of Au, Ag, and other common electrical contact materials. The common materials used for this application are:

- Titanium (Grade 5). Ti-6Al-4V. Ti
- Stainless Steel. 316L SS
- MP35N Ni-Co-Cr-Mo Alloy MP
Power Supplies

- Power Supply 1: The 5V test, with 5mA current
- Power Supply 2: Bespoke regulated 20mV supply with maximum current of 100mA.

- The low voltage level generates a Non-Linear relationship between Contact Resistance and Contact Volt drop.
Event Definition

- 5V Power supply: Trigger Level, data logged every ½ cycle.
- 20mv Power supply: data logged every ½ cycle with statistical evaluation of intermittency events based on:

\[
\bar{U}_C\left(\frac{1}{20}\right) > \bar{U}_C \pm 2\sigma
\]
Exp. 1: SS v Ti (5V)
Typical Events for 5V and 20 mV

→ Exp 2 Ti-MP and Exp 3 Ti-MP
Max voltage per cycle (20mV)

![Maximum over Cycle](chart)

Voltage across Contact [V]

Cake

Cycle

Ti-MP
Part 7. Conducting Polymers

There are a number of developments with the application of conduction polymer surfaces to electrical contact applications.
There are 2 types of surface under development.

- ECP: Extrinsic Conducting Polymers.
- ICP: Intrinsic Conducting Polymers.

The interest for the fretting problem is the potential ability to reduce the influence of lateral motion.
Application of Conducting Polymers

- Initial study of fretting with an ECP.
- 1N contact Force

Contact Resistance / Ohms

<table>
<thead>
<tr>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>800</td>
</tr>
<tr>
<td>1000</td>
</tr>
</tbody>
</table>

Sn-Sn terminal

Sn-ECP terminal
Intrinsic Conducting Polymers.

The main characteristic of a conducting polymer is the conjugated backbone.

Figure 2. PEDOT/PSS structure

Figure 3. PANI (emeraldine salt) structure

The main characteristic of a conducting polymer is the conjugated backbone.
Application of Conducting Polymers ICP

The Fretting Characteristics of Intrinsically Conducting Polymer Contacts

- Material and structures
- Fabrication techniques

Laboratory tests and results

Field tests and results
Initial studies on novel conducting polymers

- Conductivity levels
- Thermal and mechanical property
- Processibility and stability
- Minimise influence of fretting
- Automotive applications
- Develop various structures for ICP contact
- Study various ICP coating process.
- Investigate thermal and forced fretting influences.
Application of Conducting Polymers ICP

- Copper metal
- Polycrystalline (doped with AsF₅)
- Polycrystalline (doped with I₂)
- Liquid mercury
- Polyp-phenylene doped with AsF₅
- Thiophene
- Polyaniline

Conductivity (S/cm)
Conduction Process ICP

Poly(3,4-ethylenedioxythiophene)/ poly(4-styrenesulfonate) [PEDOT/PSS]
Add *Dimethylformamide* (DMF) to increase conductivity

- Secondary solvent
- $\text{C}_3\text{H}_7\text{NO}$
- Screening Effect
- Influence of different amount of DMF doping
4 Wire Resistance Method

R ≈ 500 Ω
**Processing Method. ICP**

*Drop coating*
- inject approximately 3 ml of ICP to cover contact surface
- leave to cure under ambient temperature conditions for 24 h

*Spin coating*
- an additional spinning procedure to curing process
- sample held onto a turn table and rotated at 600 rpm
Laboratory Tests

PEDOT/PSS:DMF = 3:1

- Normalised resistance = Actual resistance / Maximum resistance
  where max. $R_{\text{spin}} = 385$ ohms $R_{\text{drop}} = 2.9$ kohms
Forced Fretting Apparatus.

Fretting motion of 100 µm at 0.17 Hz
Fretting Tests (Spin Coated samples)

Unblended

First 1000 cycles with a 100 µm fretting amplitude

Normalised Resistance vs Number of cycle

Possible onset of rapid change in connector resistance to failure

Unblended

(R_{\text{max}} = 81 \text{ kohms})

3:1

(R_{\text{max}} = 820 \text{ ohms})

5:1

(R_{\text{max}} = 2.7 \text{ kohms})
First 1000 cycles with a 100 µm fretting amplitude

Fretting Tests (Drop Coated samples)

Normalised Resistance

Number of Cycle

(R_{max}=800 ohms)

(R_{max}=1.2 kohms)

(R_{max}=71 kohms)
Spin-coated samples

- Resistance reduces at a gradual rate of 35% and 25% from the original values at the end of 1000 cycles for the 5:1 and 3:1 samples respectively.
- Minimal fluctuations indicate stable outputs and can be associated with the degree of elasticity of the ICP materials.
- Different amounts of secondary doping change in malleability of blends.

Drop-coated samples

- Fail to have reliable responses after approximately 350 cycles.
- Possible reason the way ICP film was formed during the curing process. (To be further investigated).

Observation

- By spinning, water dispersion of PEDOT/PSS on the coated surface would have a higher level of homogeneity and upon curing, the film provides a more stable structure.
- More weakly structured drop coat brittleness of the film.
Field Test

Travel on any road surface for 40 mins
Rest period (with engine off) for 10 mins
Defining The Fretting Process

Connector housing
- Brake sensory system
- Behind bumper
- Near engine
Field Test data

![Graph showing normalised resistance over time](image)

- **3:1** (R\(_{\text{max}}\) = 250 ohms)
- **PEDOT/PSS** (R\(_{\text{max}}\) = 18 kohms)
- **5:1** (R\(_{\text{max}}\) = 16 kohms)

+ spin-coated
Discussion of Field Test data

Change of resistance averages at
- 15% for PEDOT/PSS:DMF of 3:1
- 80% for PEDOT/PSS:DMF of 5:1

Possible reason for the observed fluctuations for the measured resistance:
The elasticity of the epoxy core of the pellet would allow the contact surface to shrink or expand in some degree when vibration occurs. Compression forces acting on the ICP sample would therefore change the variations in resistance at the contact interface.

3:1 sample appears to
- be most stable for field test
- agree with lab test results
- have the lowest resistivity
Conclusions: Conducting Polymers

- Material, structure, fabrication
- Negative temperature coefficient of resistance
- Fretting influences
- Simple field test
- Spin-coated samples appear to give better results
- PEDOT/PSS:DMF of 3:1 – optimum blend

Different secondary dopant?
Various spin-coated thickness?
Structure improvement?
Observations: Electrical Contacts

- Although there is much repeated work in the R&D of electrical contact studies, the field is still very strong, and is still wide open in a number of new and exciting areas.
- To any new researcher working in the area, there are still many un-answered fundamental questions.
- As with all good research, it is important to define the question.
- There is still a very clear industrial demand for the field of study.
- ALWAYS READ THE LITERATURE FIRST.
Some Observations

- There is still much to be investigated in the area of fundamental mechanical and electrical contact. Particularly applied to Micro-and Nano devices.
- Fretting studies should be extended in investigate intermittency events, as this is increasing the main concern for electronic systems.
- Conducting Polymer contacts (ICP), are still some way from being used commercially.