ARCHIVE 2012

FUNDAMENTAL PROPERTIES OF ELECTRICAL CONTACTS

by

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President

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__World renowned electrical contact expert__, Dr. Roland Timsit, returns to BiTS with a renewed and freshened course that builds on his very popular 2006 BiTS Tutorial. This seminar addresses how contact force and the mechanical properties of contact materials affect both contact resistance and the electrical/mechanical integrity of an electrical contact device.

Dr. Timsit usually teaches this material in a multi-day course, so this tutorial is packed with information for professionals seeking a broad, yet comprehensive understanding, of electrical contacts.

ABSTRACT

An interface between two solids is generated by contact between protruding surface asperities on each of the contacting bodies, so that mechanical contact is actually established at a discrete number of contact spots. Because these spots are tiny, the area of true contact is very small and electrical current passing through the interface is highly constricted at these spots. Constriction of the current gives rise to contact resistance.

The seminar addresses how contact force and the mechanical properties of contact materials affect both contact resistance and the electrical/mechanical integrity of an electrical contact device. Selected contact properties of materials and electroplates such as gold, tin and silver are reviewed. The deleterious effects of contaminant and corrosion surface films, and other mechanisms such as mechanical wear and fretting corrosion, that conspire to eliminate electrical contact spots, are described. The nefarious effects of these mechanisms can often act rapidly, with ensuing catastrophic failure, in devices where the contact force is small such as in MEMS. The effect of signal frequency on contact resistance will also be addressed.

Fundamental Properties of Electrical Contacts

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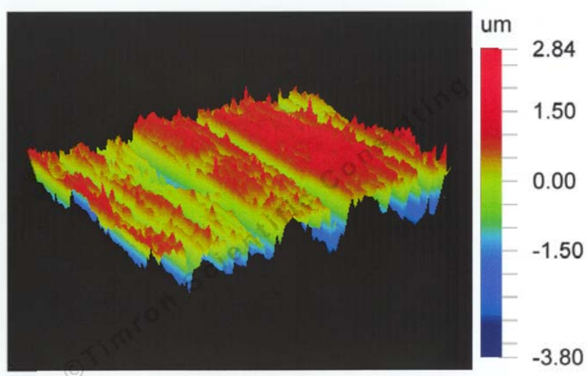
Extruded Surface



Mag: 5.1 X
Size: 368 X 238
Sampling: 3.31 um

Surface Stats:
Rq: 1.03 um
Ra: 829.65 nm
Rt: 6.64 um

Terms Removed:
Tilt

Because all solid surfaces are rough on the microscale, two mating solid surfaces make contact only where the peaks of small surface asperities (roughness) touch one another.

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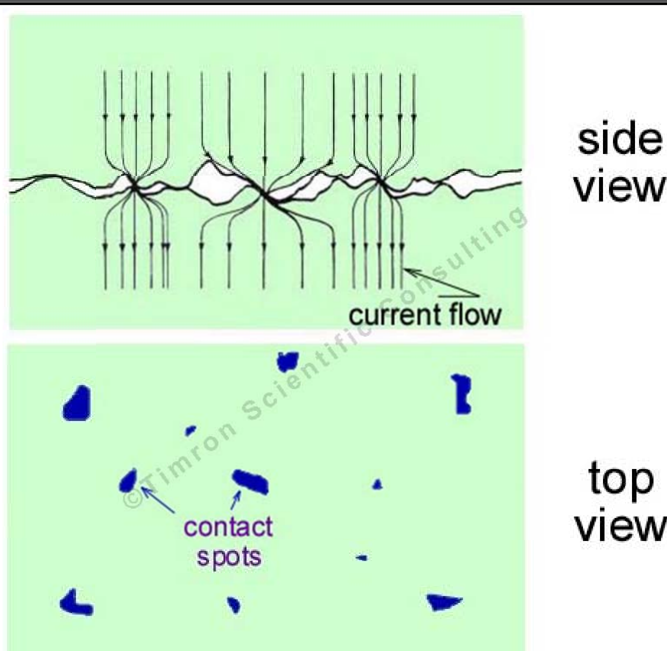

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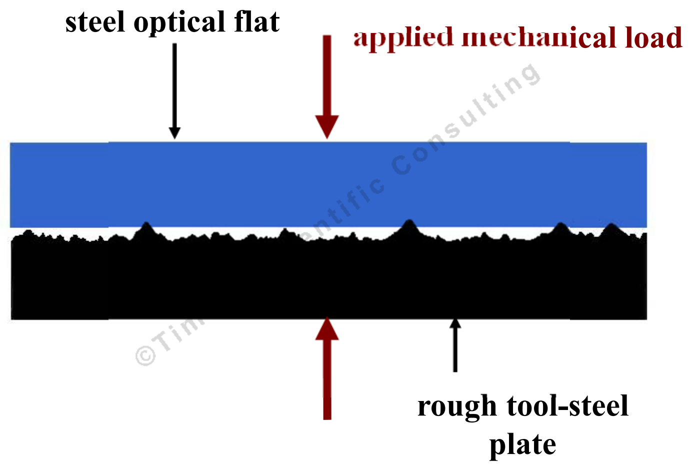
TRUE AREA OF MECHANICAL CONTACT



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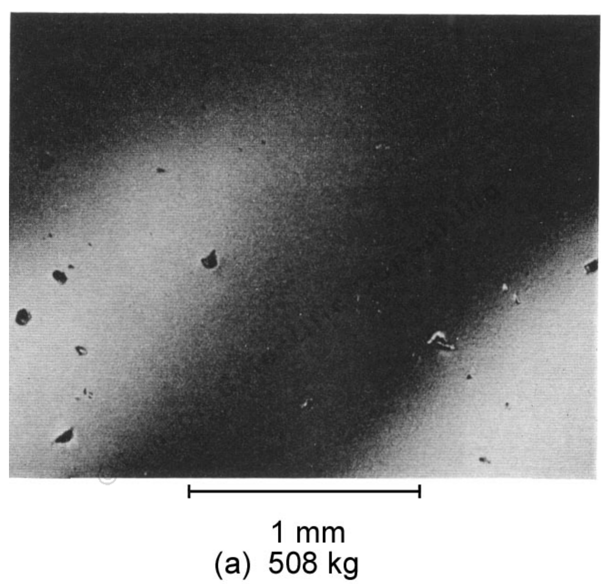

Steel optical flat after contact with sand-blasted tool-steel, under various loads.

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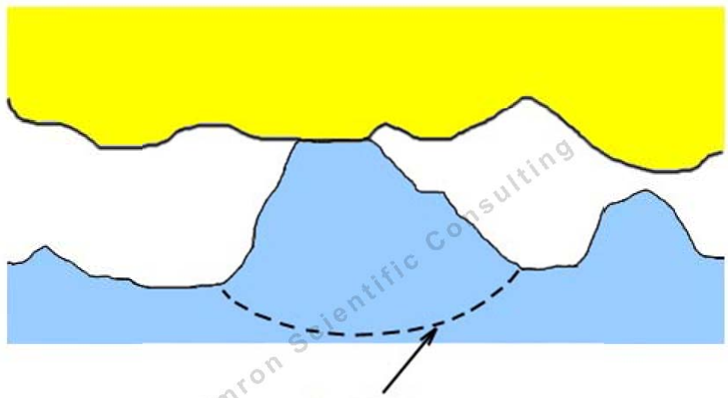
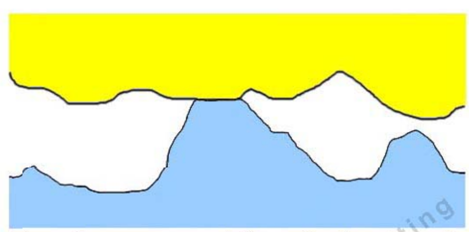


all micro-asperities deform plastically

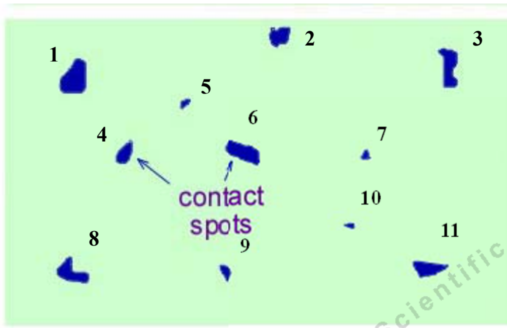


Since all contacting asperities deform plastically, then the contact force F_j acting on the surface A_j of the jth asperity is

$$F_j = K A_j$$

where K = **"some" yield stress of contact material [kg mm^{-2}]**

It turns out $K \rightarrow H$ = **Vickers' or Knoop microhardness [kg / mm^2] (~ 3 Y, Y = yield strength)**



top view

$F_1 = H A_1$
$F_2 = H A_2$
$F_3 = H A_3$
.
.
.
$F_{11} = H A_{11}$

$F = H A$

$F = F_1 + F_2 + F_3 + \ldots. + F_{11}$ = *Total Contact Force*
$= H(A_1 + A_2 + A_3 + \ldots.+ A_{11}) = H$ x total true Contact Area A

Fundamental Law of Contacting Surfaces

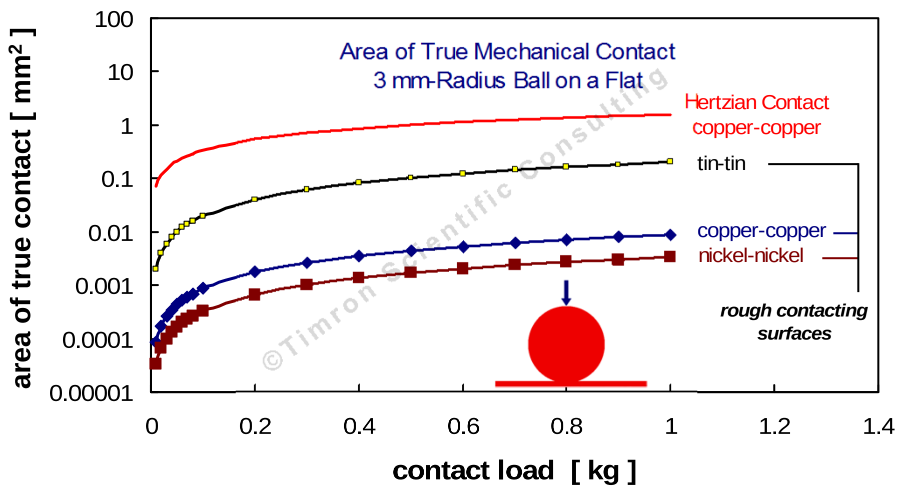
$$F = H A$$

or $$A = F / H$$

True Contact Area = Applied Contact Load / Hardness

irrespective of contact geometry !

EXAMPLES OF TRUE CONTACT AREA



CONSTRICTION RESISTANCE: MULTISPOT CONTACTS

For a multispot contact, the constriction resistance is well approximated as

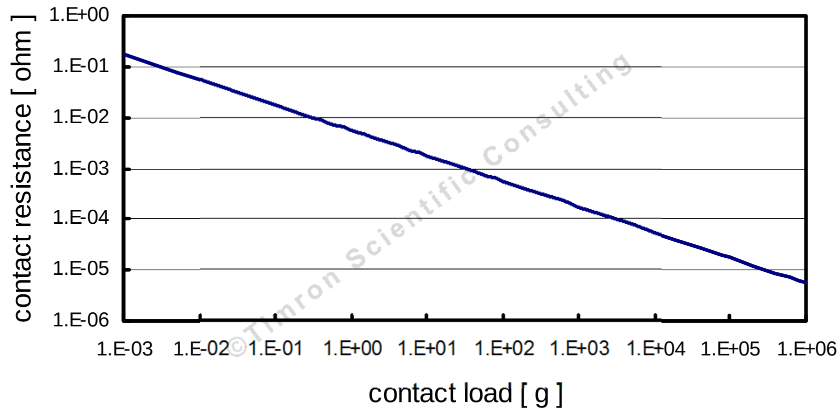
$$R_C = (\rho / 2)\,[\pi H / F]^{1/2}$$

where H = Vickers' or Knoop microhardness [kg / mm²]

ρ = average resistivity of contacting materials

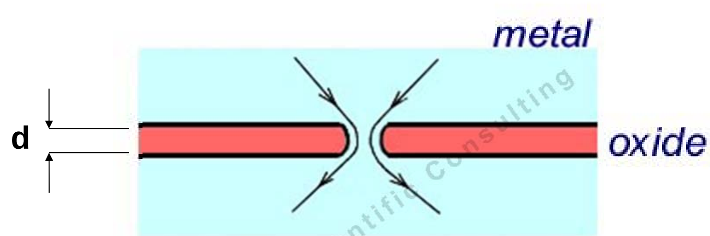
F = contact load [kg]

CONSTRICTION RESISTANCE



Contact resistance versus contact load for a copper contact with $H = 120\ kg\ mm^{-2}$. Resistivity $\rho = 1.65 \times 10^{-8}\ \Omega\ m$.

CONTACT RESISTANCE



There is also a contact resistance R_F due to the presence of oxide or other contaminant films on the mating surfaces :

$$R_F = \rho_{cont}\, d / A$$

where A = **area over of surface film**

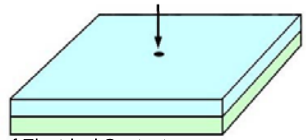
CONTACT RESISTANCE: METAL-TO-METAL VERSUS FILM-TO-FILM

OXIDE FILM THICKNESS = 2 nm

Type of Metallic Junction	Resistance of Metal-to-Metal *a*-Spot (Ω)	Film Resistance (Ω)	
		Cu_2O	Al_2O_3
copper-copper	1.7×10^{-3}	0.18	
aluminum-aluminum	2.6×10^{-3}		23.2

Total contact area = 1 cm^2
Radius of *a*-spot = 10 µm

location of contact spot



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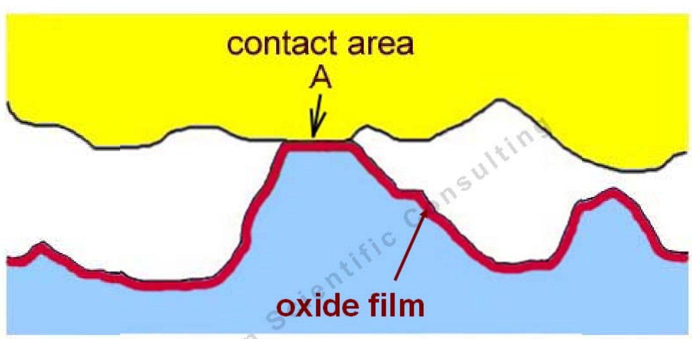

Total contact resistance

$$R_T = R_C + R_F$$

$$R_T = (\rho / 2) [\pi H / F]^{1/2} + \rho_{cont}\, d / A$$

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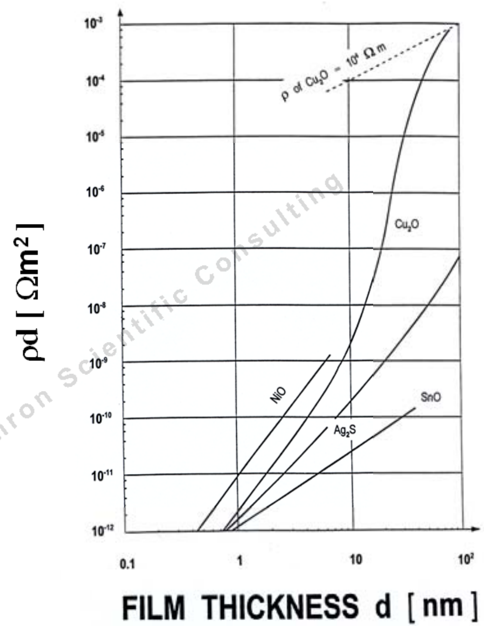
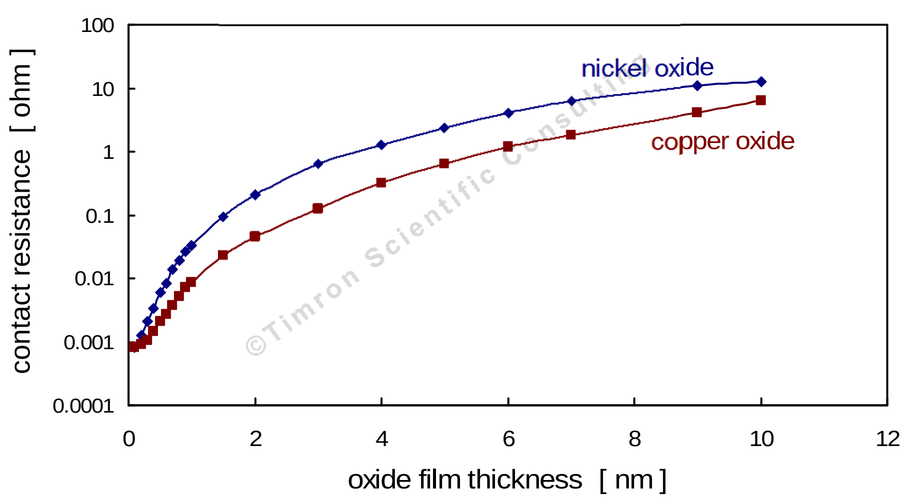
$$R_F = \rho_{cont}\, d / A$$



CONTACT RESISTANCE:

Cu-Cu Contact Spot 10 μm radius covered with Oxide Film

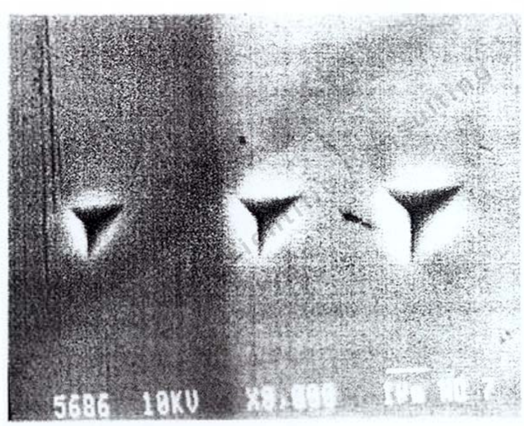


SURFACE OXIDE FILMS

To enhance electrical contact reliability

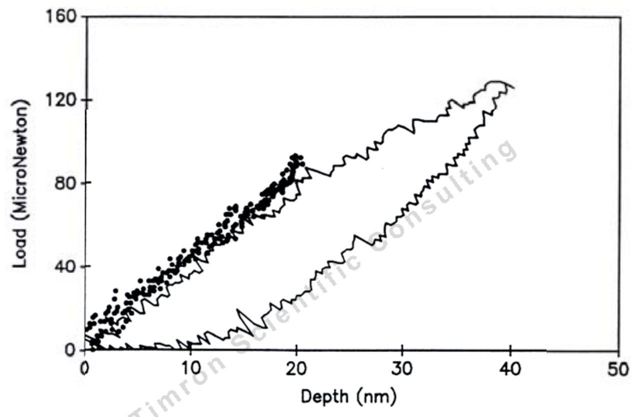
- ***do not tolerate** surface contaminant films i.e. do not expect conduction though them*
- ***abrade/remove all surface films, in particular oxide layers***

ELECTRICAL CONTACT RESISTANCE : SMALL CONTACT LOADS

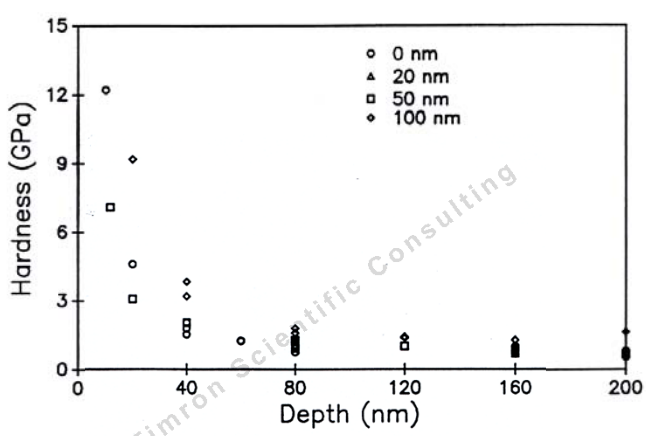


Recall $R_C = (\rho / 2)\,[\,\pi H / F\,]^{1/2}$

For small contact loads, H is the nanohardness

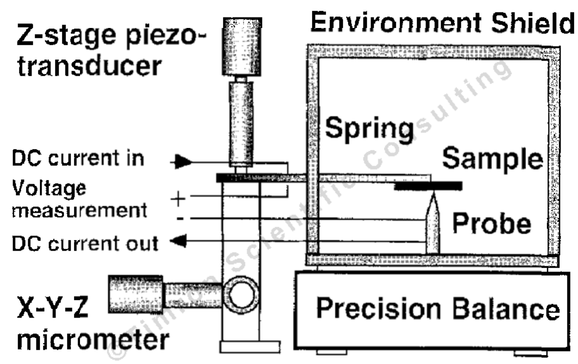


Load depth data for super purity Aluminum with 100nm anodic oxide coating showing deviation from the elastic response at the depth of 20nm.

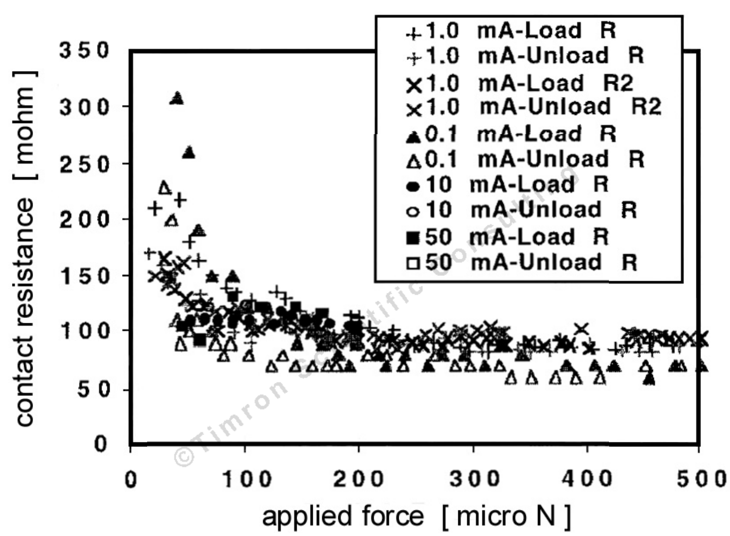


Effect of anodic oxide coating thickness on the variation in the hardness with the total depth of penetration at the peak load.

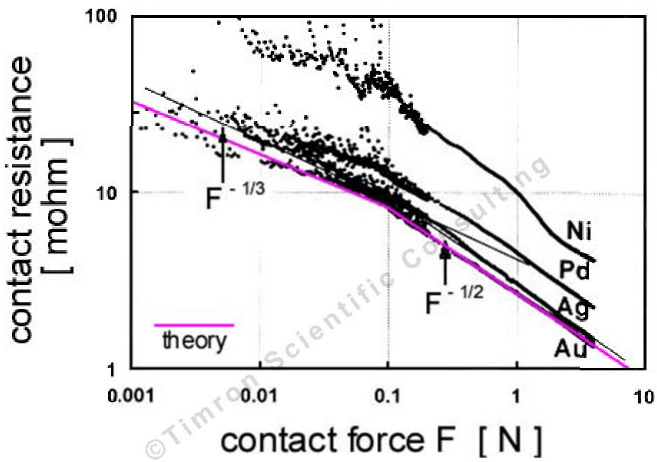
Contact Materials : Silicon Micro Springs



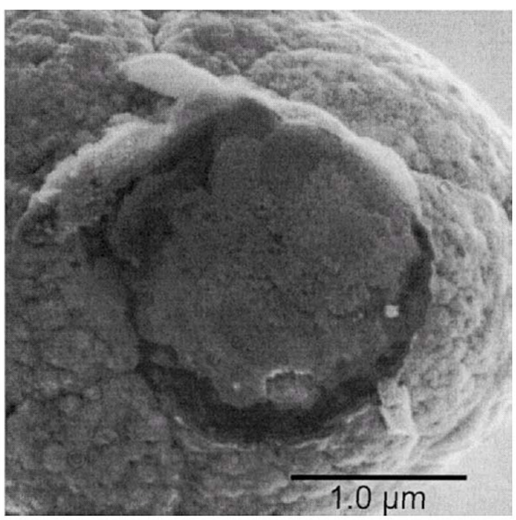
Example of apparatus used for the measurement of contact resistance between gold layers on Si (Hyman et al, IEEE Trans. CPT, p. 357, vol. 22 1999).



Contact resistance vs. applied force for pure gold micro-contacts using gold layers on Si (Hyman et al 1999).

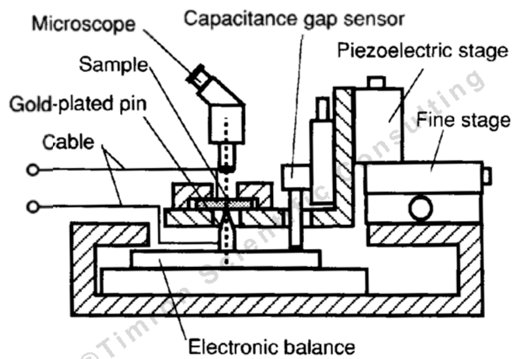


The data of Hyman et al suggests a higher level of surface contamination of the gold than is the case for the data shown above. The "$F^{-1/3}$" behavior at very low contact force may stem from adhesion ("stiction").



Contact spot on the gold-coated Si micro-lever after applying a contact force of 500 µN (Hyman et al 1999).

Contact Materials : Silicon Micro Springs



Another example of apparatus used for the measurement of contact resistance between gold and gold layers on Si (Hosaka et al, Proc. MEMS' 93, February 1993). Note that only total resistance was measured.

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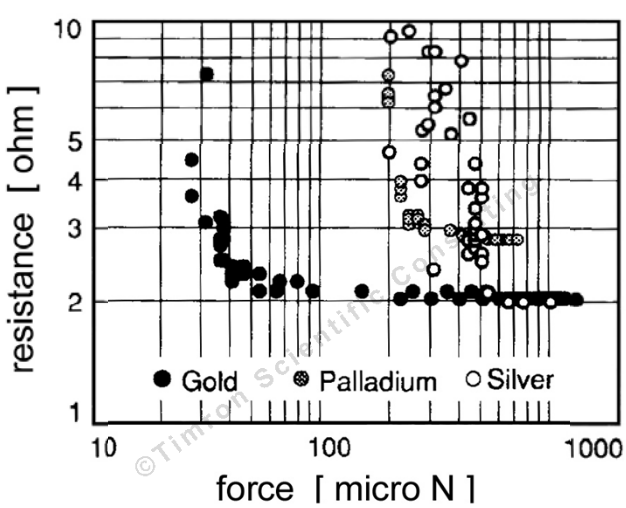

Total circuit resistance vs. applied force for a pure gold pin in contact with a sputtered layer of gold, palladium and silver on glass (Hosaka et al 1993).

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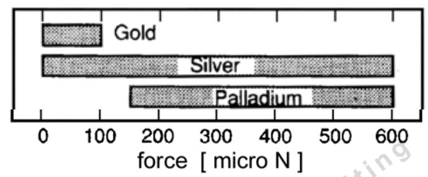
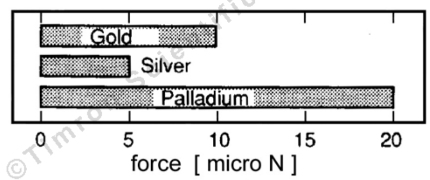


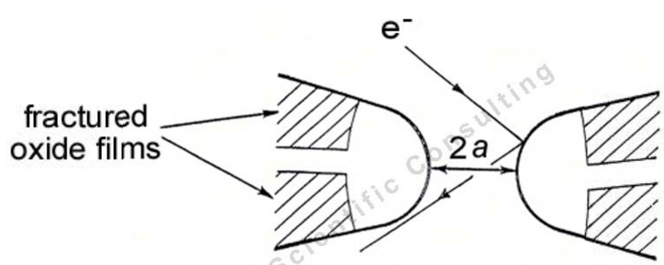
Contact force needed for stable contact resistance



Contact force needed for completely open contact

Minimum contact loads to achieve specified contact resistance conditions (Hosaka et al 1993).

BREAKDOWN OF CLASSICAL ELECTRICAL CONTACT THEORY



for *a* ~ electronic mean free path, classical electric contact theory breaks down

$R_C = \rho / 2a$ no longer holds!

- **electrons behave ballistically within the constriction**
- **little or no heating in the constriction**

BREAKDOWN OF CLASSICAL ELECTRICAL CONTACT THEORY

The expression for the resistance through a small constriction of radius "a" becomes

$$R_B = \Gamma(K)(\rho / 2a) + C / a^2$$

$\Gamma(K)(\rho / 2a)$: temperature dependent classical resistance

C / a^2: temperature independent Sharvin resistance

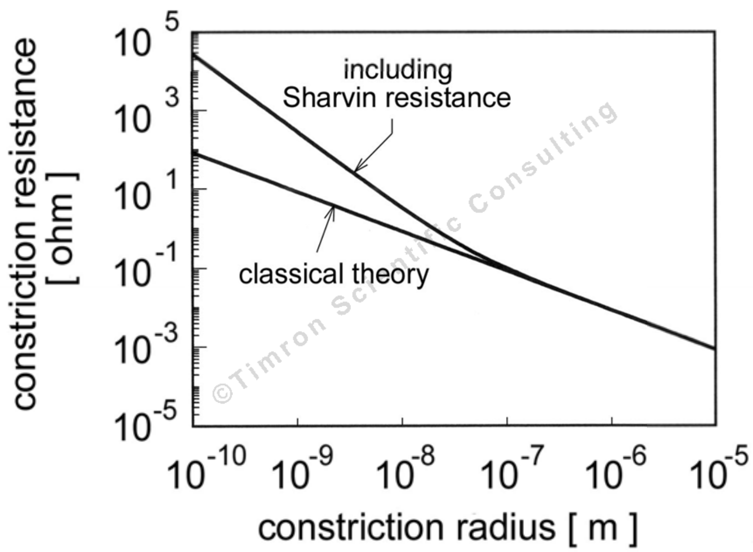
where

K = *l / a* (*l* = *electron mean free path*)

Γ (K) = varies from 1 to about 0.7 as K varies from 0 to ∞

C = a constant that depends on the contact material

Constriction Resistance for Cu



GROWTH OF INTERMETALLIC COMPOUNDS

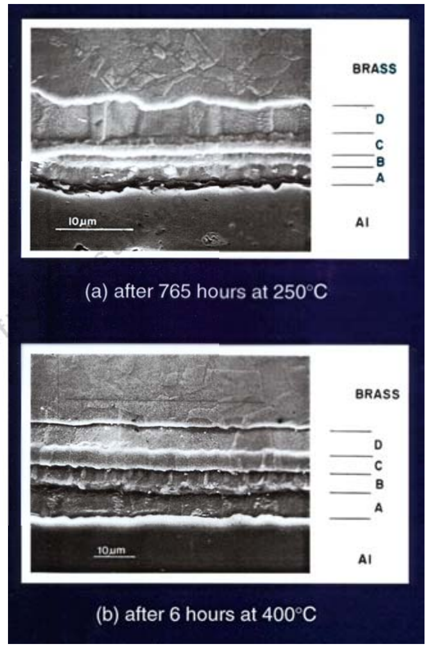
The width X of an intermetallic layer or an interdiffusion band increases with time t as

$$X^2 = kt$$

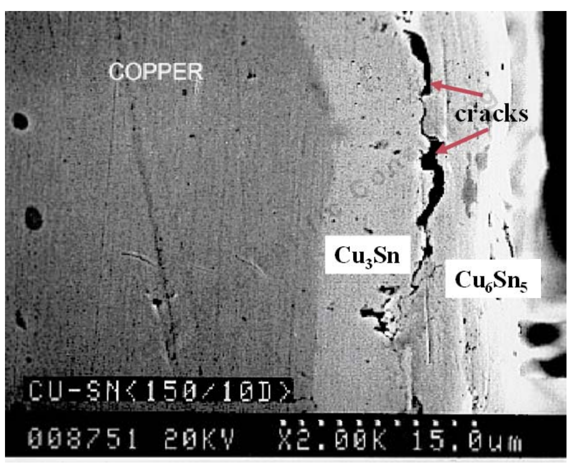
with k = interdiffusion constant

$$= k_0 \exp(- Q / RT)$$

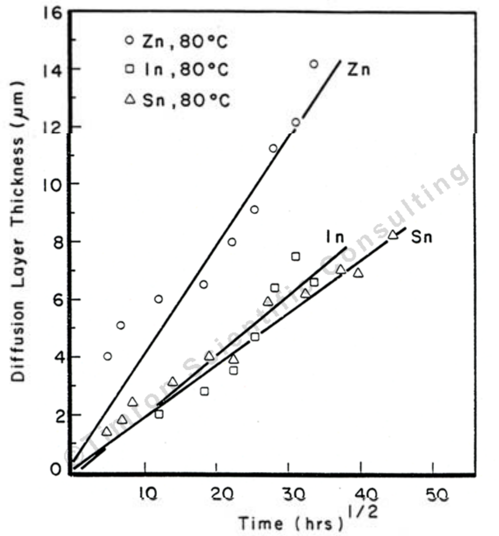
Q = activation energy
R = gas constant
T = absolute temperature



INTERMETALLICS FORMATION



Intermetallics growth at a copper/tin interface.

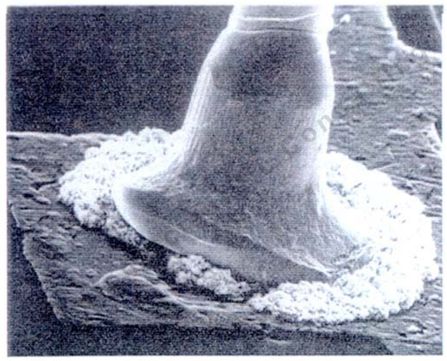


Growth of interdiffusion bands generated with Zn, Sn and In on brass at 80^{0}C.

Thickness of Interdiffusion Layers Produced by Zn, In and Sn Deposits on Brass

Time Interval	T (^{0}C)	Interdiffusion Layer Thickness (μm)		
		Zn	In	Sn
1 month	20	0.43	1.0	1.9
1 year	20	1.5	3.5	6.7
1 month	55	3.4	2.8	3.5
1 year	55	11.8	9.8	12.1

EFFECTS OF INTERDIFFUSION



An SEM photograph of Au-Al intermetallic compound formation (white and fluffy) around the perimeter of the bond and under the grossly deformed ball. Even with its poor appearance, the bond was mechanically strong and electrically conductive.

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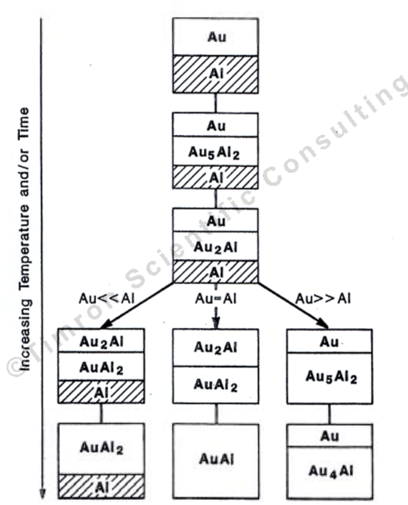
EFFECTS OF INTERDIFFUSION



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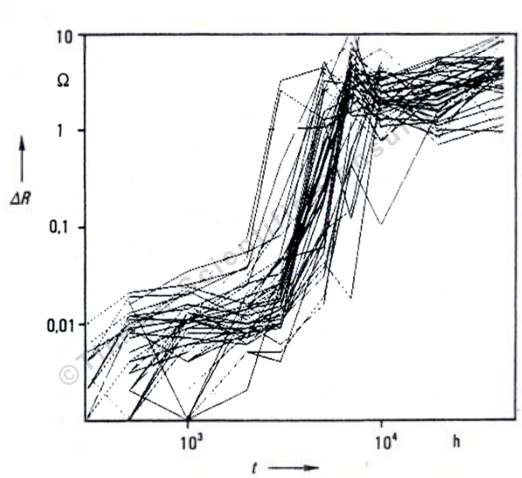
EFFECTS OF INTERDIFFUSION



The change in contact resistance of multiple Au ball bonds on 1.3 mm Al pads as a function of time at 200°C. The initial bond resistance was a few milliohms. (After Gerling [I-7].)

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TEMPERATURE IN AN ELECTRICALLY-HEATED CONTACT

a contact spot may be considered
a "thermally-insulated" resistor
of value R

1. if the resistor is made of copper and R = 10 x 10^{-6} ohm, it is found that the resistor melts at a current of 43,000 A
2. if the resistor is made of copper and R = 1 ohm, it is found that the resistor melts at a current of 0.43 A

What is the common factor describing melting of the contact spot ?

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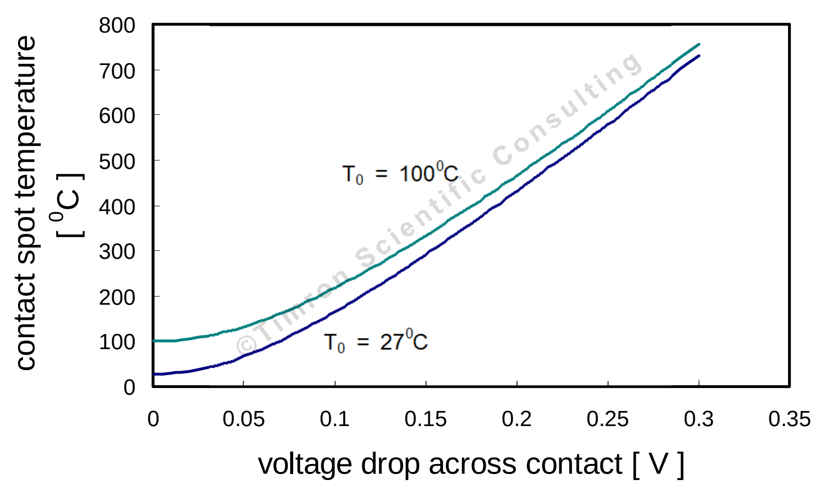
TEMPERATURE IN AN ELECTRICALLY-HEATED CONTACT

The contact spot temperature depends only on the potential drop across the contact.

CONTACT - SPOT TEMPERATURE



MAXIMUM VOLTAGE-DROP IN AN ELECTRICAL CONTACT

Melting of a contact spot is determined by the voltage-drop across the contact, not the electrical current

Metal	Softening Voltage (V)	Melting Voltage (V)
Al	0.1	0.3
Fe	0.19	0.19
Ni	0.16	0.16
Cu	0.12	0.43
Zn	0.1	0.17
Ag	0.09	0.37
Cd		0.15
Sn	0.07	0.13
Au	0.08	0.43
Pd		0.57
Pb	0.12	0.19
60Cu, 40Zn		0.2

TEMPERATURE IN AN ELECTRICALLY-HEATED CONTACT

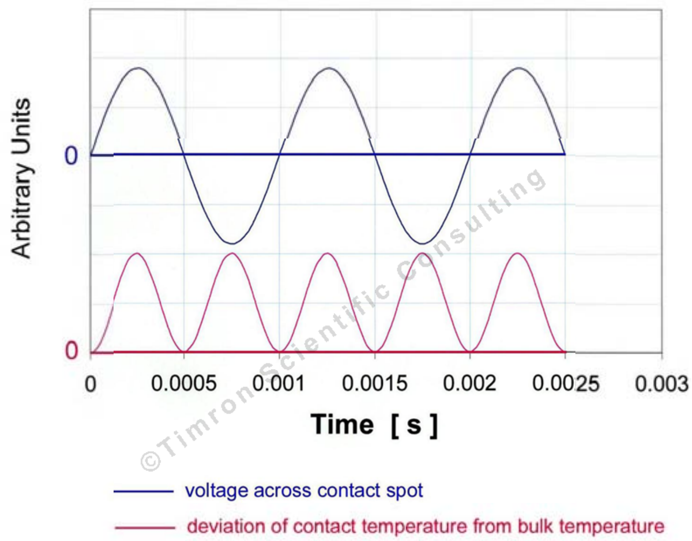
thermal risetime τ of a contact spot of radius "a"

$$\tau = C\,a^2/\,4\lambda$$

where C = conductor heat capacity
λ = thermal conductivity

For copper, $C = 3.44$ J cm^{-3} ^{0}C^{-1}
$\lambda = 4$ W cm^{-1} ^{0}C^{-1}

so that $\tau = 2.2 \times 10^{-7}$ s for a contact spot with $a = 10\ \mu$m



Schematic variation of contact spot temperature associated with variations in voltage-drop across the contact, at a signal frequency of 1 kHz.

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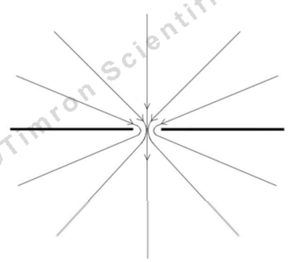
CONSTRICTION RESISTANCE:
Effect of Signal Frequency

Under conditions of DC current flow :

constriction resistance $R_C = \rho / 2a$

ρ = resistivity



constriction of radius *a*

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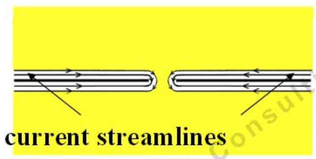
EFFECTS OF FREQUENCY: THE SKIN EFFECT



Under alternating current (AC) conditions, current penetrates into a conductor to an electromagnetic "penetration depth" δ

$$\delta = [\rho / \pi f \mu_0]^{1/2}$$

ρ = *resistivity*

μ_0 = *magnetic permeability of free space*

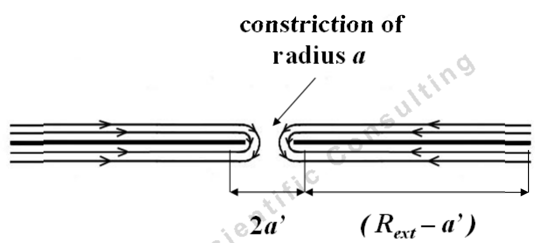
f = *excitation frequency in Hz*

EFFECTS OF FREQUENCY: THE SKIN EFFECT

Variation of Skin Depth with Frequency for a Metal of Resistivity 3 x 10^{-8} Ω m

f [Hz]	*Skin Depth* δ [µm]
60	11254
10^3	2757
10^4	872
10^5	276
10^6	87
10^7	28
10^8	8.7
10^9	2.8

EFFECTS OF FREQUENCY



R_{ext} = outer radius of "External" ring

a' = inner radius of "External" ring

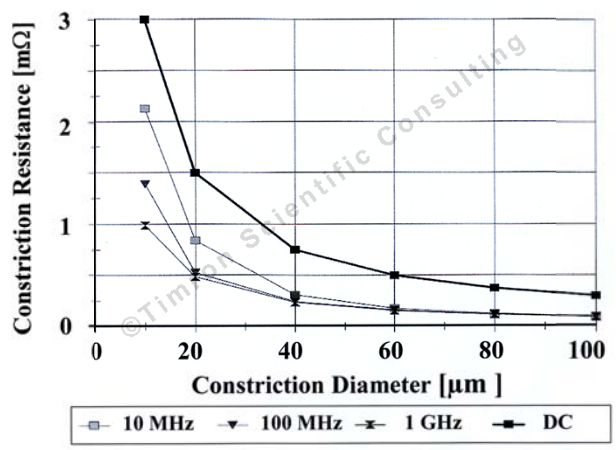
EFFECTS OF FREQUENCY

Total Connection Resistance = Constriction Resistance + Resistance of "External" Ring

Resistance of "External" Ring $= (\rho / 2\pi\,\delta)\ \ln\,(R_{ext} / a')$

δ = electromagnetic penetration depth
R_{ext} = outer radius of "External" ring
a' = inner radius of "External" ring
ρ = resistivity

CONSTRICTION RESISTANCE AT HIGH FREQUENCIES

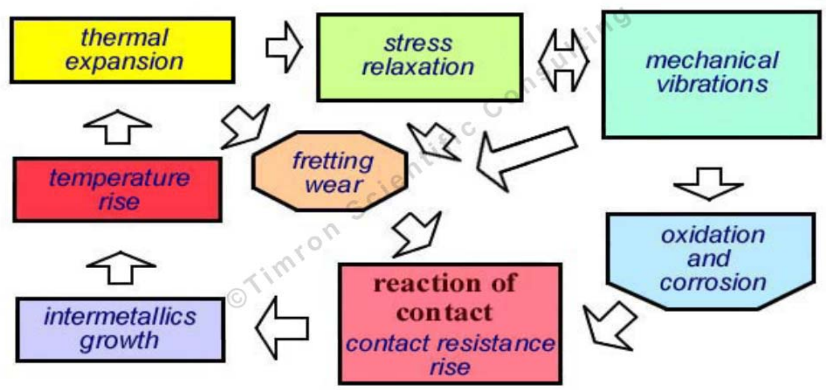


CONSTRICTION RESISTANCE VS. CONNECTION RESISTANCE AT HIGH FREQUENCIES

Signal Frequency f [Hz]	Constriction Resistance [mΩ]	Connection Resistance [mΩ]
10^7	2.2	3.2
10^8	1.4	4.7
10^9	1.0	11.2

$\rho = 3 \times 10^{-8}\ \Omega m$
$a = 5\ \mu m$
$R_{ext} = 100\ \mu m.$

Degradation Mechanisms



Tribology

Most common types of wear in metal sliding :

I. Abrasive Wear – relevant only to high power connectors

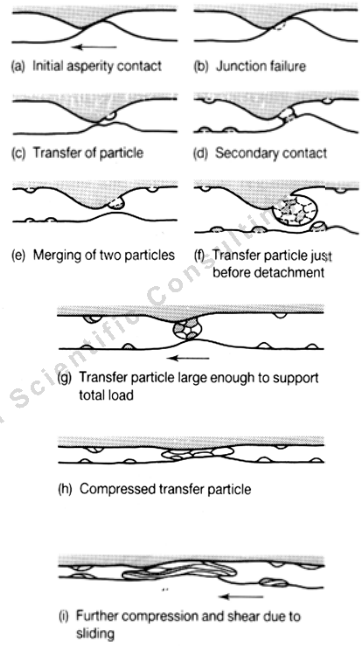
II. Adhesive Wear

III. Fretting Wear

IV. Erosion - generally not relevant to connectors

V. Lubricated Wear - not relevant to connectors

Adhesive Wear



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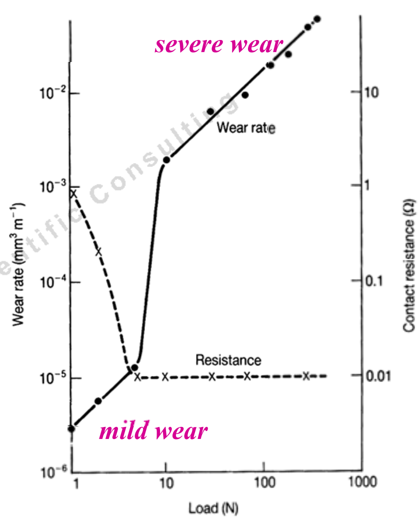
Tribology: Adhesive Wear

Wear rate and electrical contact resistance of a leaded α / β brass pin against a hard stellite ring. Note the sharp transition in wear rate.



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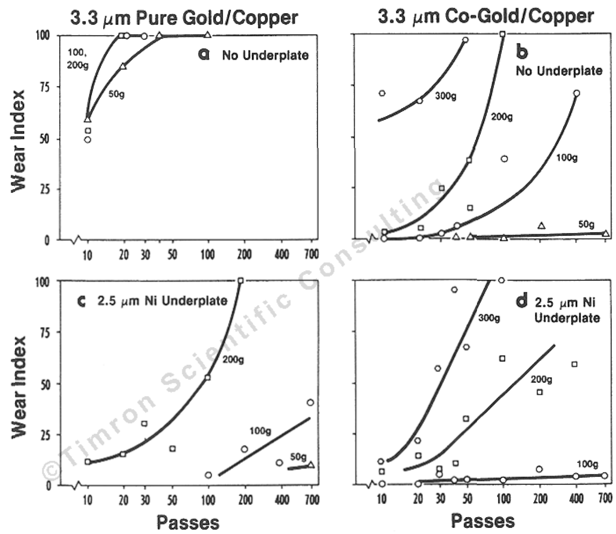
Tribology: Adhesive Wear

	Mild Wear	Severe Wear
Metal Transfer	small	large
Wear Debris	small	large
Contact Wear	relatively symmetrical, depends on sliding frequency	generally unsymmetrical
Effect on Surface	smoothing, subsurface deformation, little hardening	roughening subsurface deformation, increased hardness

Tribology: Adhesive Wear Transition Loads

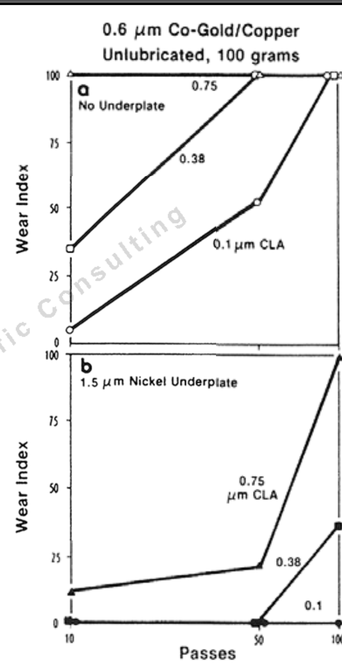
	Pure Gold	Hard Gold
Clean Surface	5 g	10 g
Contaminated	10 – 50 g	25 – 300 g
Lubricated	100 – 500 g	500 – 2000 g

Tribology: Adhesive Wear



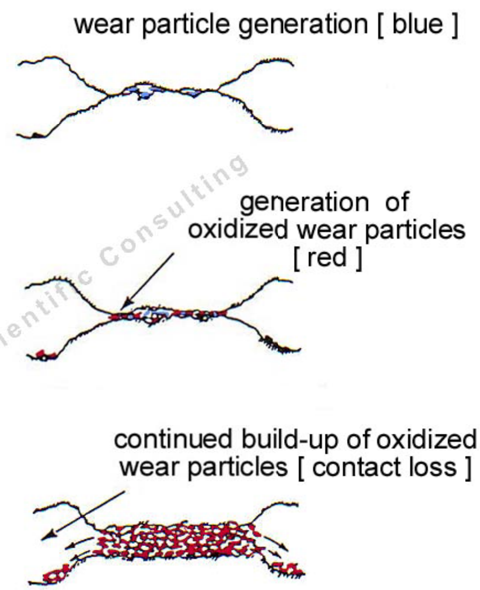
Wear indices from unlubricated adhesive wear runs: (a), (c) pure gold with and without 2.5 µm Ni underplate; (b), (d) hard cobalt gold, with and without 2.5 µm Ni underplate.

Tribology: Adhesive Wear



Effect of surface roughness on Wear Index, using solid gold riders :
(a) no underplate
(b) 1.5 µm Ni underplate .

Tribology: Fretting Wear



— metal debris particles

— oxidized particles

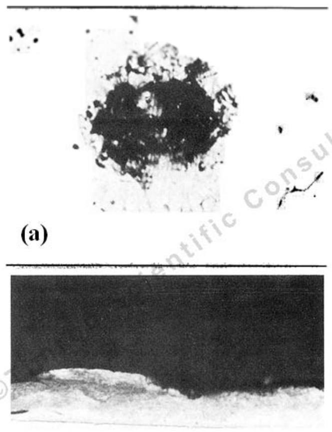
Tribology: Fretting Wear

***Fretting Wear** is generated by small-amplitude **movement** leading to the formation of small debris particles at a mechanical interface. In electronic connectors, the amplitude of this micromotion ranges from a few µm to about 100 µm.*

***Micromotion** is caused by external vibrations or by **changing temperature** due to differences in thermal **expansion coefficients** of the mating materials.*

***Oxidation** of fretting debris leads to increased electrical contact resistance.*

Tribology: Fretting Wear

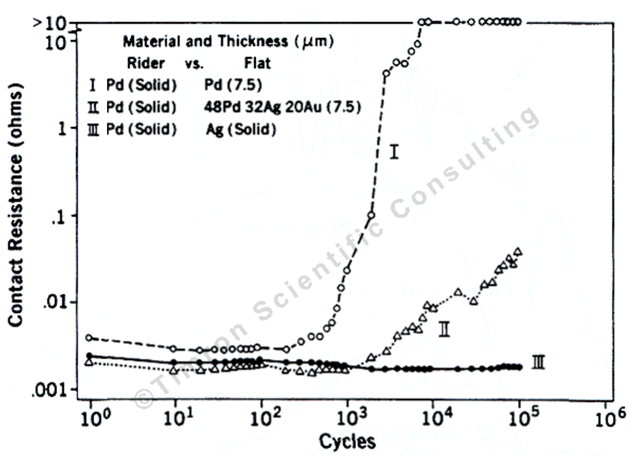


a) Fretting damage on a tin electroplate surface,

b) Cross-sectional view of (a).

(b)

Tribology: Fretting Wear



Typical contact resistance variations due to fretting at 50 g and 8 Hz with a 20 µm wipe. Curve I – unacceptable, curve II – acceptable, curve III – best.

Tribology: Fretting Wear

Silver

Silver is the most stable material in fretting, since it is relatively wear resistant, does not oxidize readily, and does not form frictional polymers. It displays excellent behaviour when mated to itself. Silver is prone to tarnish in the presence of even minute amounts of sulfur and chlorine compounds. This limits the use of silver in electronic connectors.

Silver is widely used as a finish on aluminum busbar contacts.

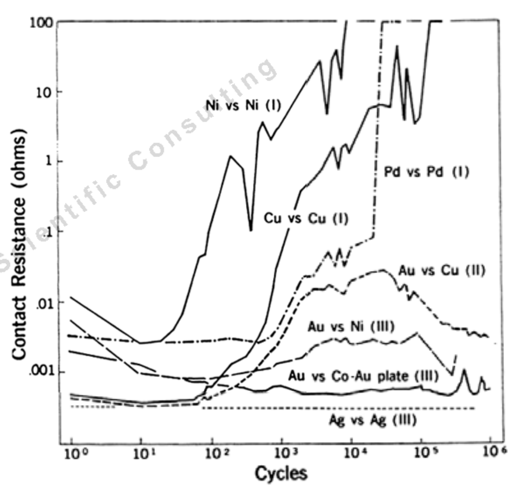
Tribology: Fretting Wear

Contact resistance behaviors due to fretting, in various materials. Load of 50 g, 20 µm displacement at 4 – 8 Hz.:

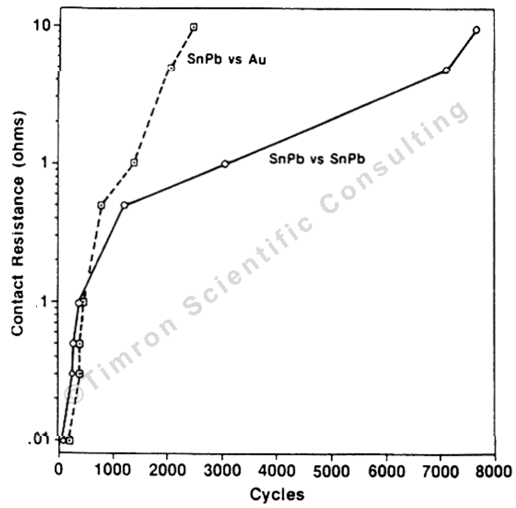
I - solid Ni on Ni-electroplate 2.5 µm thick on Cu
- solid Pd on Pd-clad 5 µm thick on Ni
- solid Cu on solid Cu

II - solid Au on solid Cu

III - solid Au on Ni-electroplate 2.5 µm thick on Cu
- solid Au on Co/Au-electroplate 0.6 µm thick on Ni electroplate on Cu
- solid Ag on solid Ag.

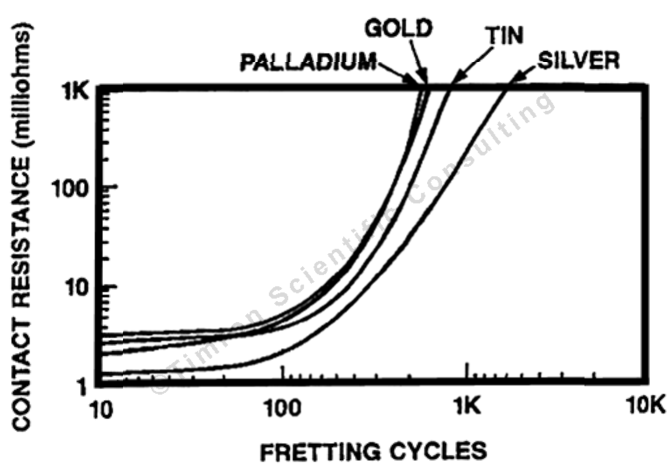


Tribology: Fretting Wear



Contact resistance versus fretting cycles, 150 g, 8 Hz, 10 µm wipe.

Fretting at Tin – Metal Interfaces



Results of fretting tests conducted on degreased tin, gold, palladium and silver surfaces mated to degreased tin surfaces.

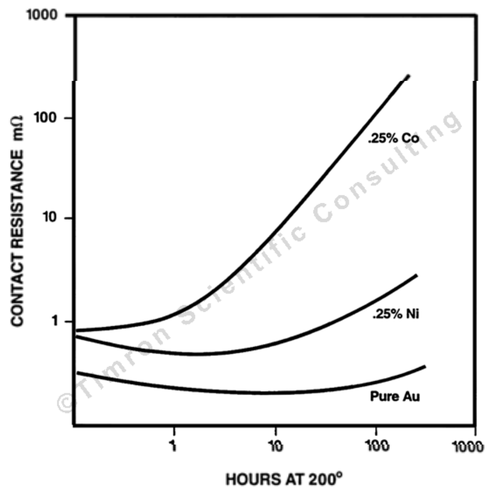
Tribology: Fretting Wear

Gold

Gold approaches silver in its stability. Although it is known that has organic materials, aerosols and other contaminant layers accumulate on gold surfaces to increase contact resistance, these contaminants are usually eliminated by rubbing.

It has been claimed that traces of polymer form when gold contacts are rubbed together in benzene vapor or immersed in an oil. No deleterious effect of this polymer on contact resistance has been detected.

Effects of Heating



Thermal stability of contact resistance of 50 µm gold electroplate on copper, aged at 200^{0}C. Effects of Co and Ni additions of 0.25 wt%.

OXIDATION / CONTAMINATION IN AIR

copper:- *oxide forms immediately*
- *thickness depends on temperature*

tin: - *oxide growth is initially slow*
- *depends on temperature*

	T^0C	THICKNESS (nm) 10^3 h	10^5 h
Cu	20	2.2	4
	55	3.5	17
	85	8.7	69
	100	15.0	130
Sn	20	4.2	6.1
	55	10.3	14.6
	85	18.8	26.0
	100	25.0	36.0

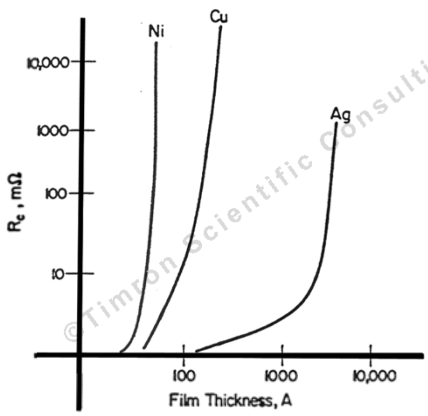
OXIDATION / CONTAMINATION IN AIR

	T^0C	THICKNESS (nm) 10^3 h	10^5 h
Ni	20	1.6	15.0
	55	2.1	21.0
	85	2.7	27.0
	100	3.4	34.0

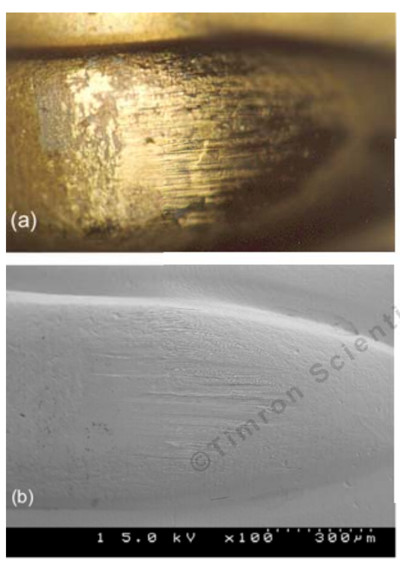
nickel:- *oxide growth is self-limiting*
- *weak dependence on temperature*

silver:- *Ag_2S formation*
- *formation of Ag_2O in presence of ozone*

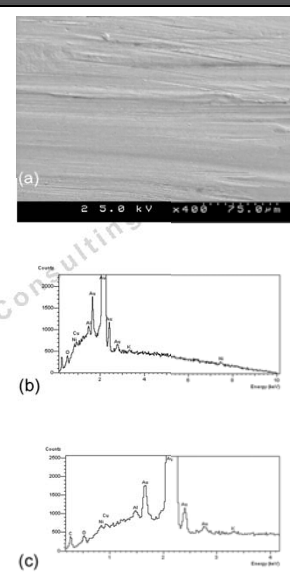
Film Formation in a Harsh Environment



Contact resistance due to formation of surface films on Ag, Cu and Ni in N_2-O_2-SO_2-S_8-H_2O mixtures at 30^0C.

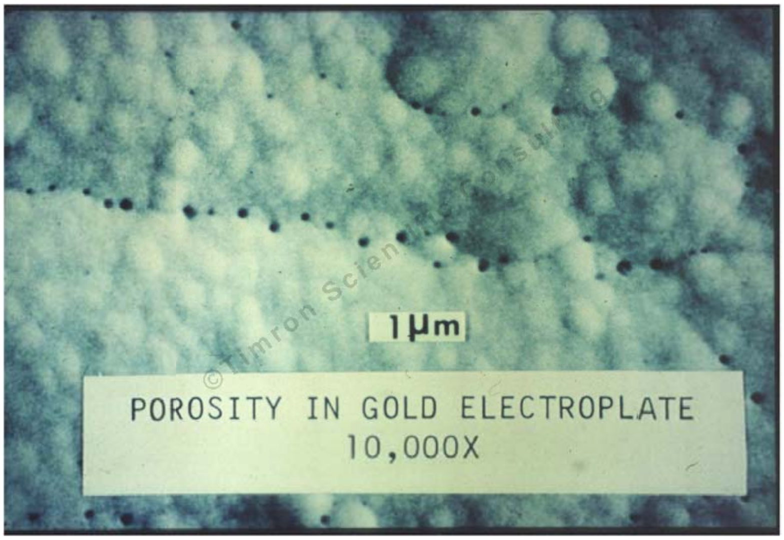


(a) Optical micrograph
(b) SEM micrograph.



(a) SEM micrograph of scratch marks,
(b) EDX spectrum from entire region shown in (a),
(c) region of EDX spectrum of (b) showing only the 0 - 4.4 kV region.

Pore Corrosion



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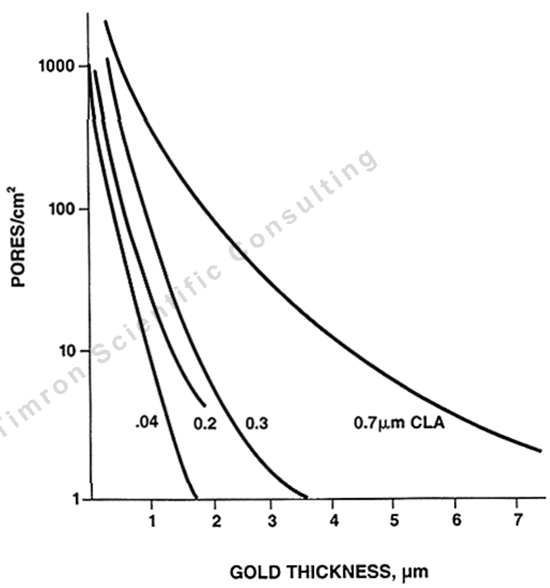
Electroplate Porosity

Dependence of pore density on electroplate thickness, for various CLA (Center Line Average) values of Substrate roughness. Pure gold on 1.5 µm thick Ni underplate on copper.



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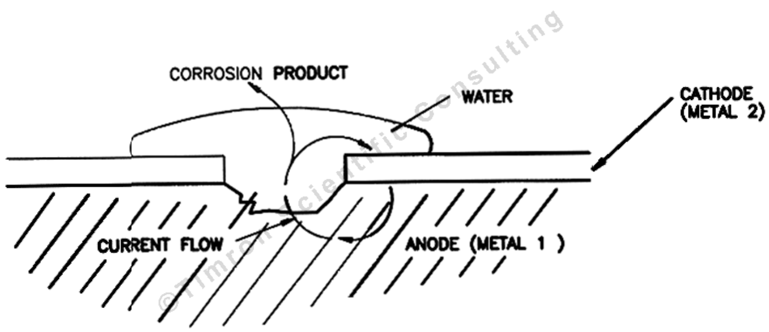
Galvanic Corrosion



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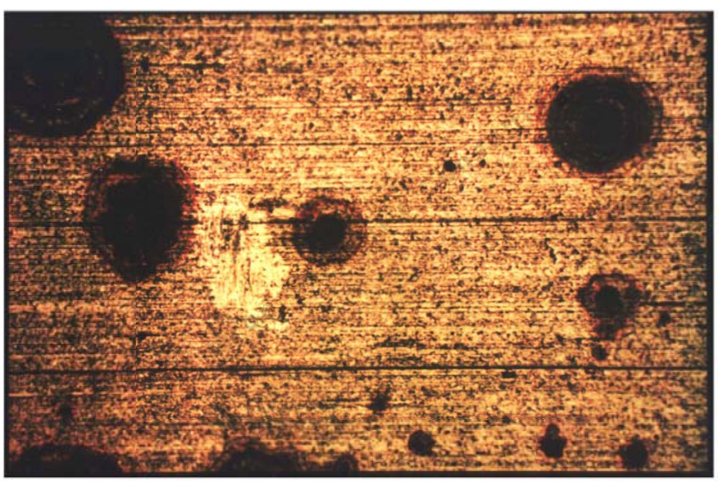
Pore Corrosion



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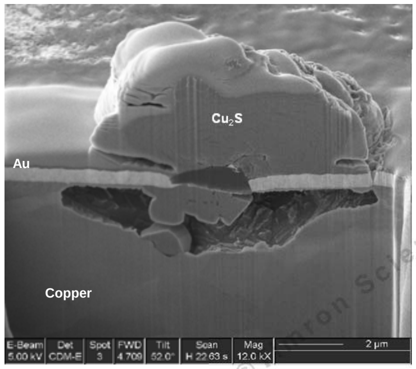
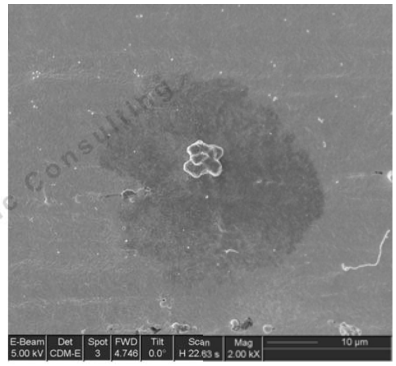
Pore Corrosion





Example of copper sulfidation through a pore in a gold layer [*from Sun, Moffat, Enos and Glauner, Sandia National Labs, IEEE Holm Conf. Electrical Contacts, September 2005*].

Connector Testing: Mixed Flow Gas (MFG) Composition

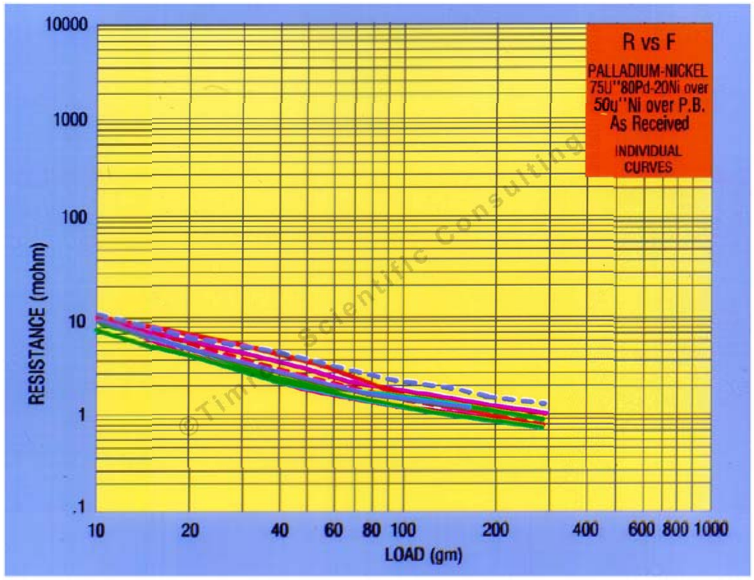
MFG TEST CONDITIONS FOR ACCELERATING THE EFFECTS OF ENVIRONMENTAL CLASSES II, III AND IV

	Severity Class		
	II	III	IV
Temperature (°C)	30 ± 2	30 ± 2	40 ± 2
Relative Humidity (%)	70 ± 2	75 ± 2	75 ± 2
Chlorine (Cl_2), ppb	10 ± 3	20 ± 5	30 ± 5
Nitrogen Dioxide (NO_2), ppb	200 ± 50	200 ± 50	200 ± 50
Hydrogen Sulfide (H_2S), ppb	10 ± 5	100 ± 20	200 ± 20

ppb=parts per billion of each gas in air.

Class IIa includes 100 ± 20 ppb SO_2 (for Ag)
Class IIIa includes 200 ± 50 ppb SO_2 (for Ag)

Film Formation in a Corrosive Environment



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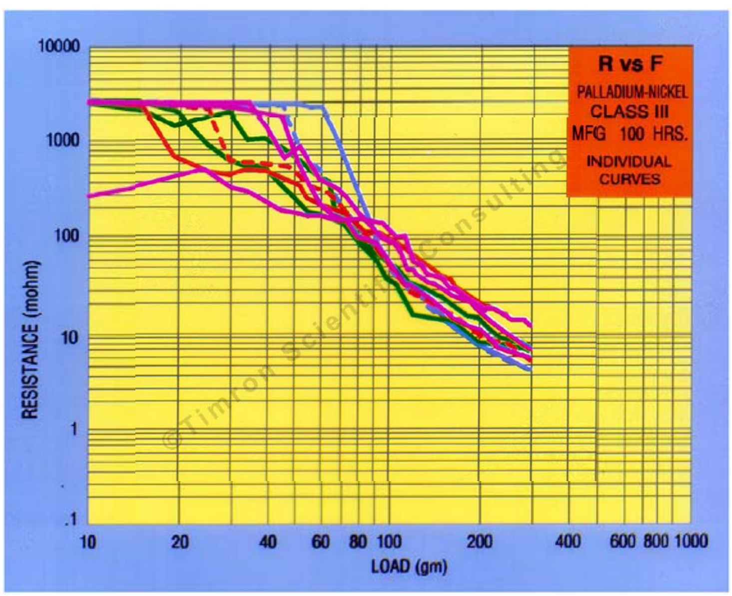
Film Formation in a Corrosive Environment



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SIGNIFICANCE OF BURN-IN IN ELECTRICAL CONTACTS

Selected Burn-In Methods

- *Pass a large current through contacts*

  possible beneficial effects:

  - *slight overheating of contact spots, causing negligible metallurgical effect, may soften contact spots and increase the true contact area to reduce contact resistance*
  - *slight differential expansion in contact region may cause local abrasion of surface contaminant films and reduce contact resistance*

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SIGNIFICANCE OF BURN-IN IN ELECTRICAL CONTACTS

Selected Burn-In Methods

- *Pass a large current through contacts*

  possible deleterious effects:

  - *overheating of contact spots with possible metallurgical changes in the contact region*
  - *increased oxidation*
  - *overheating of contact springs or connector components with possible decrease in contact force due to stress relaxation or metal-creep*

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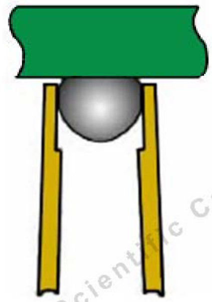
solder ball contact



- *passing a large burn-in current through some types of contacts, such as those using low melting-point materials, may be particularly deleterious to contact reliability*

SIGNIFICANCE OF BURN-IN IN ELECTRICAL CONTACTS

Selected Burn-In Methods

- *Reciprocating motion of pin in socket while passing current, but without contact disconnect*
  major beneficial effect:
  - *disperse surface contaminant films and reduce contact resistance*

SIGNIFICANCE OF BURN-IN IN ELECTRICAL CONTACTS

Selected Burn-In Methods

- *Reciprocating motion of pin in socket while passing current, but without contact disruption*
  possible deleterious effects:
  - *generate unwanted mechanical wear on contact surfaces and removal of thin protective electroplates*
  - *increase a permanent set in receptacle springs*
  - *possible arcing*
  - *other effects*

SUMMARY

Major Parameters and Mechanisms
Affecting Contact Resistance

1. *SurfaceRoughness:* **Asperity density and shape can optimize connector function**
2. *Surface Hardness*: **Hardness determines real contact area**
3. *Interdiffusion:* **Usually deleterious to contact performance**
4. *Electroplates:* **To modify surface hardness and provide protection against mechanical wear and corrosion; underplates reduce interdiffusion between electroplates and substrate**

SUMMARY

Major Parameters and Mechanisms Affecting Contact Resistance

5. ***Surface Insulating Films:*** **Usually deleterious to contact performance since they add to contact resistance; these films may increase susceptibility to fretting corrosion**
6. ***A-spot Temperature:*** **Controls interdiffusion processes and other mechanisms such as oxidation and corrosion rates; elevated temperatures are usually deleterious to contact performance. Temperature can be evaluated from the V-T relation**

SUMMARY

Major Parameters and Mechanisms Affecting Contact Resistance

7. ***Signal Frequency:*** **The "skin effect" begins to have a noticeable effect on connection resistance at a frequency of a few MHz**
8. ***Small Contacts:*** **Classical contact theory breaks down for *a*-spot radii smaller than a few hundred nanometers**
9. ***Contact Degeneration Mechanisms:*** **Oxidation, corrosion, fretting corrosion, intermetallic growth, differential thermal expansion etc.. eventually limit connector life.**