Tin plated contacts: Problems due to Fretting corrosion and whisker growth

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Part 1 – Fretting corrosion

Fretting - Implications in electrical contacts

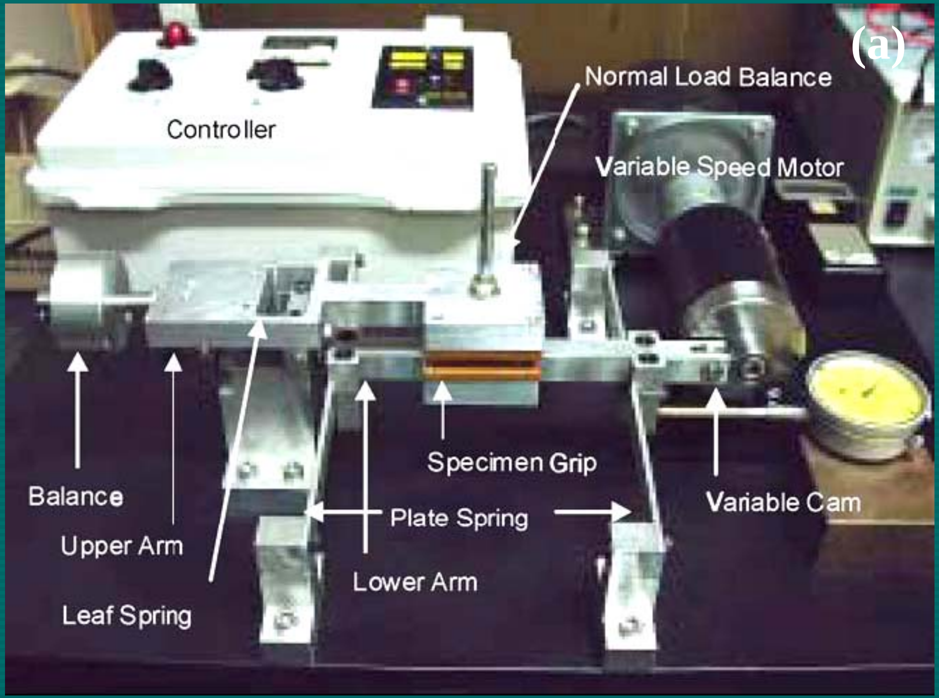
- Fretting - An accelerated surface damage that occurs at the interface of contacting materials subjected to small oscillatory movement
- Fretting in electrical connections - influences the reliability and system performance
- Gold or precious metal plated contacts offers high reliability
- Tin plated contacts – low cost alternative to gold – in automobile connectors and in many consumer applications
- High susceptibility of tin plated contacts for fretting corrosion is the major limitation for their use in electrical connectors

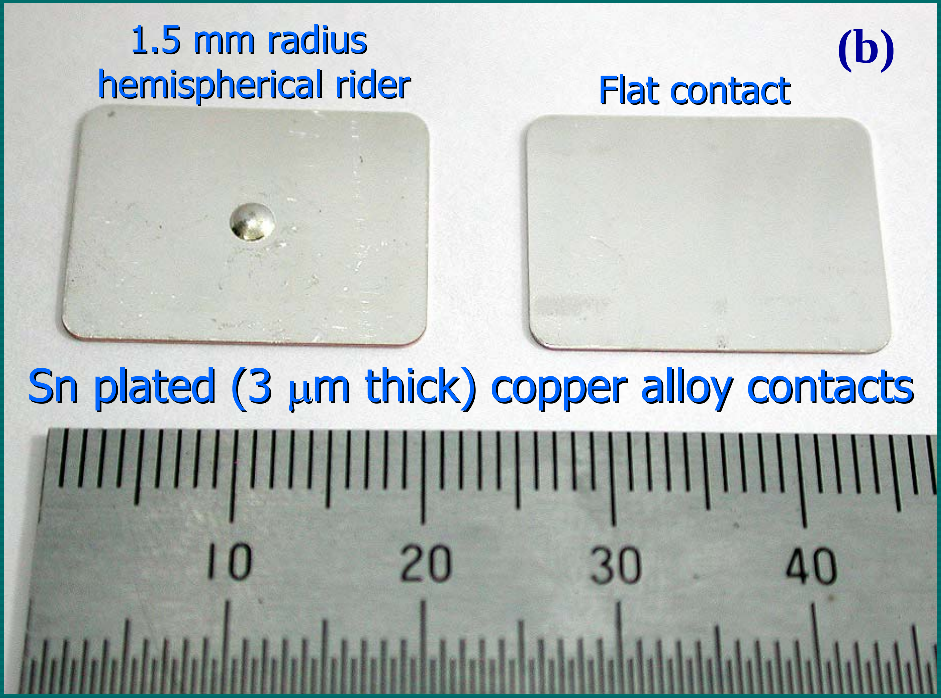
Fretting – Implications in electrical contacts

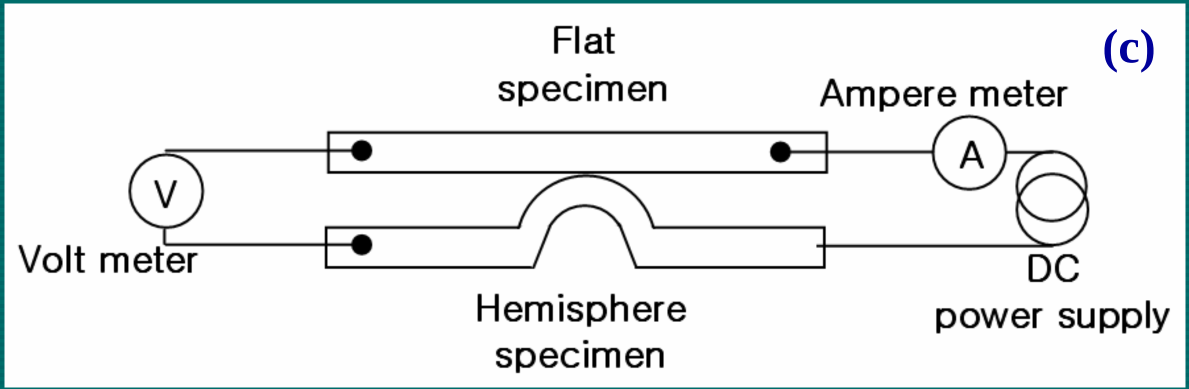
- Fretting itself may not result in failure of an electrical connection
- The deleterious effect of fretting is a great deal of concern
  - Fretting leads to the accumulation of the wear debris and oxidation products in the contact zone in the form of a thick highly localized insulting layer
  - rapid increase in contact resistance that leads to virtually an open circuit
  - Though such a phenomenon evolves with time, it is influenced by many factors and it is not easy to detect

Factors influencing fretting corrosion of Sn plated contacts

- A variety of factors influence the performance of Sn plated contacts
  - Fretting amplitude (track length)
  - Frequency
  - Temperature
  - Humidity
  - Normal load
  - Current load







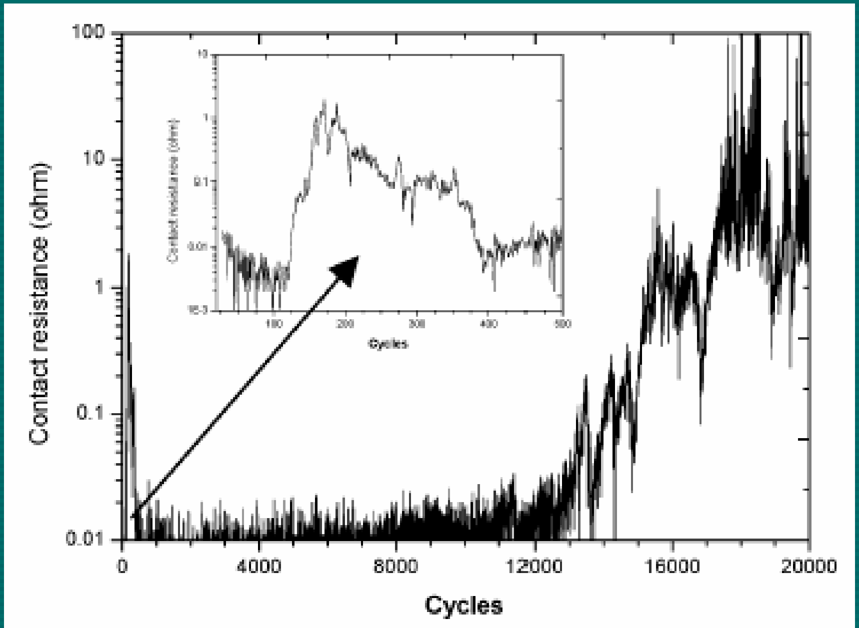
(a) Fretting corrosion test assembly; (b) tin coated rider and flat contacts; and (c) geometry of the rider and flat samples and the circuit used to measure the contact resistance

Test conditions used to study the fretting corrosion behaviour of tin plated contacts

- The fretting tests - Gross slip conditions
- Contact resistance - Continuously measured as a function of fretting cycles - 100 mΩ is chosen as a threshold value for failure
- LSM – To assess the surface profile, surface roughness and wear depth
- SEM, EDX and X-ray elemental mapping - To assess the extent of fretting damage, chemical nature and elemental distribution across the contact zone

Variable	**Range**
Frequency	3, 5, 7, 10, 15 and 20 Hz
Amplitude	± 5 µm, ±25 µm, ±50 µm and ± 90 µm
Load	0.1, 0.5, 1 and 2 N
Temperature	27, 55, 65, 75, 85, 105, 125, 155 and 185°C
Humidity	20-45, 45-75, >85% RH
Current load	0.1, 0.5, 1.0, 1.5, 2.0, 3.0 A

Contact resistance of tin plated contacts measured as a function of fretting cycles



A hump – between 100 and 400 cycles - presence of thin film of tin oxide on the surface which is removed in a short span of time

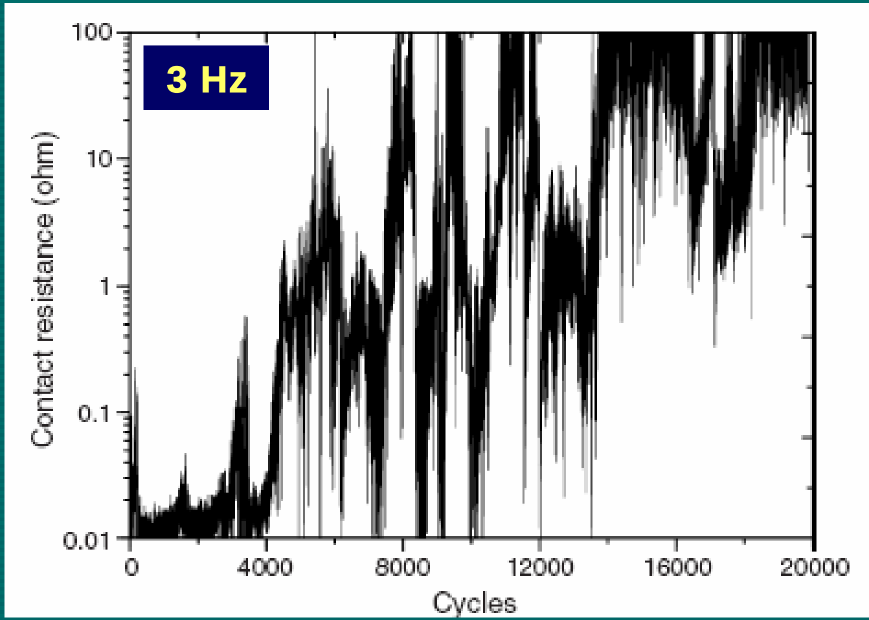
400 to 8000 cycles – low CR - conducting nature of the soft tin plating

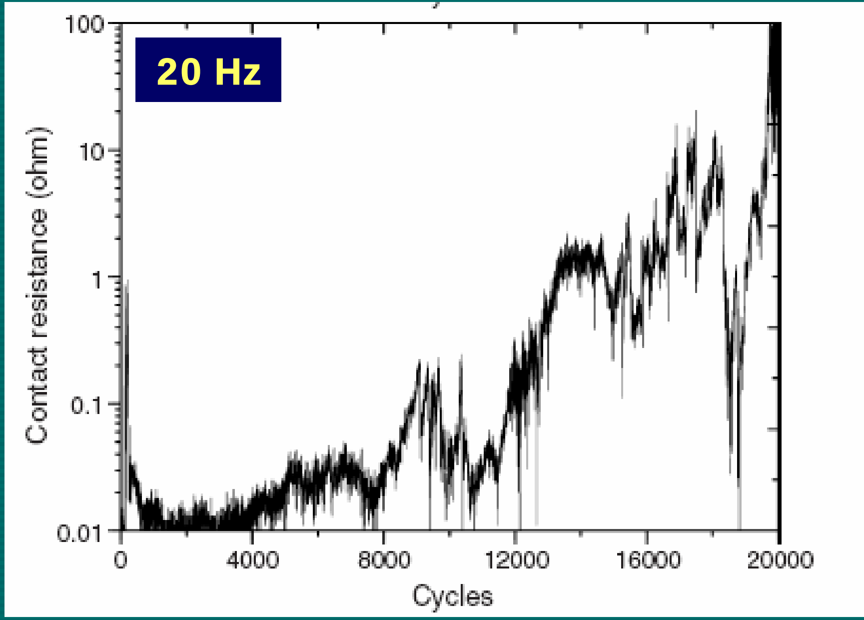
8,000 to 12,000 cycles - slight increase in CR - initial stages of oxidation

12,000 to 15,000 cycles - gradual increase in CR – oxidation of contact zone

Beyond 15000 cycles – Rapid increase in CR - accumulation of wear debris and oxidation products, which reduces the electrical conducting area

Experimental Conditions:
Frequency: 10 Hz
Amplitude: ± 90 μm
Temperature: 27°C
Humidity: 45% RH
Normal load: 0.5 N
Current load: 0.1 A





Amplitude: ± 25 μm; Temperature: 22°C; Humidity: 55 % RH; Normal load: 0.5 N; Current load: 0.1 A

Influence of frequency

At 20 Hz - the rate of wear of tin coating is high

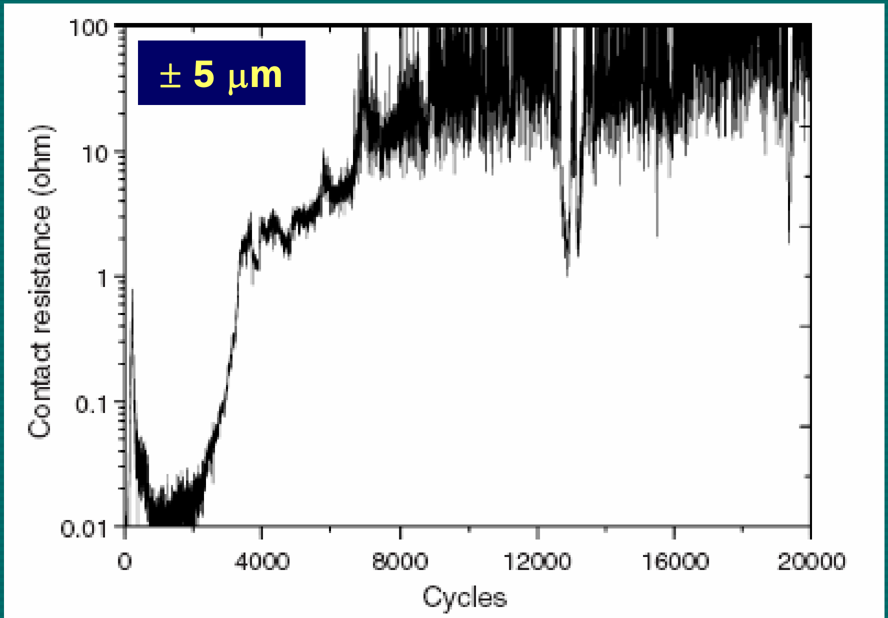
At 3 Hz - the contact zone gets more time for oxidation

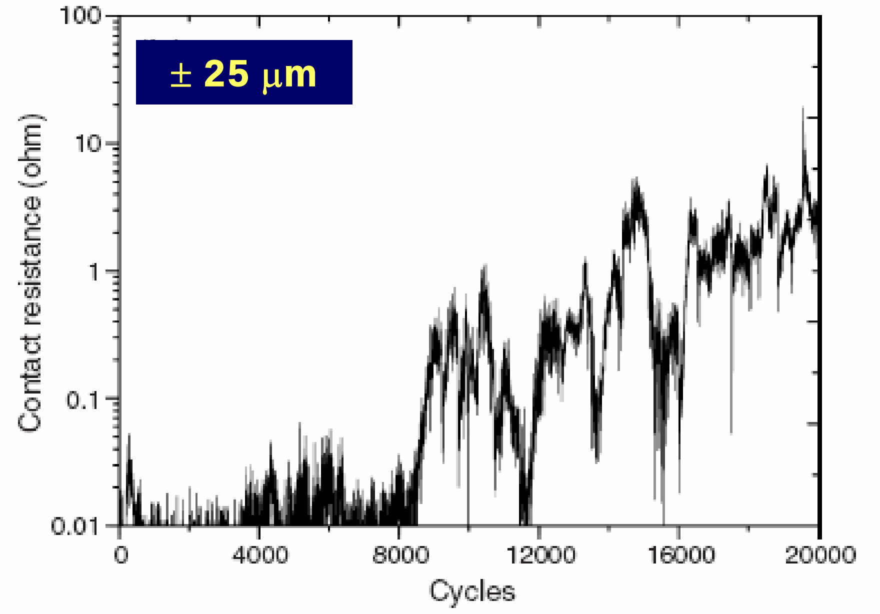
The threshold value of CR (100 mΩ) is reached early at 20 Hz – due to the faster removal of tin coating that results in the formation of higher quantities of wear debris and oxidation products

At 20 Hz – the contact zone gets relatively lesser time for oxidation

Increase in wear rate leads to an increase in the extent of accumulation of wear debris and oxidation products at the contact zone, which causes a rapid increase in contact resistance

Influence of fretting amplitude





Frequency: 10 Hz; Temperature: 22°C; Humidity: 32% RH; Normal load: 0.5 N; Current load: 0.1 A

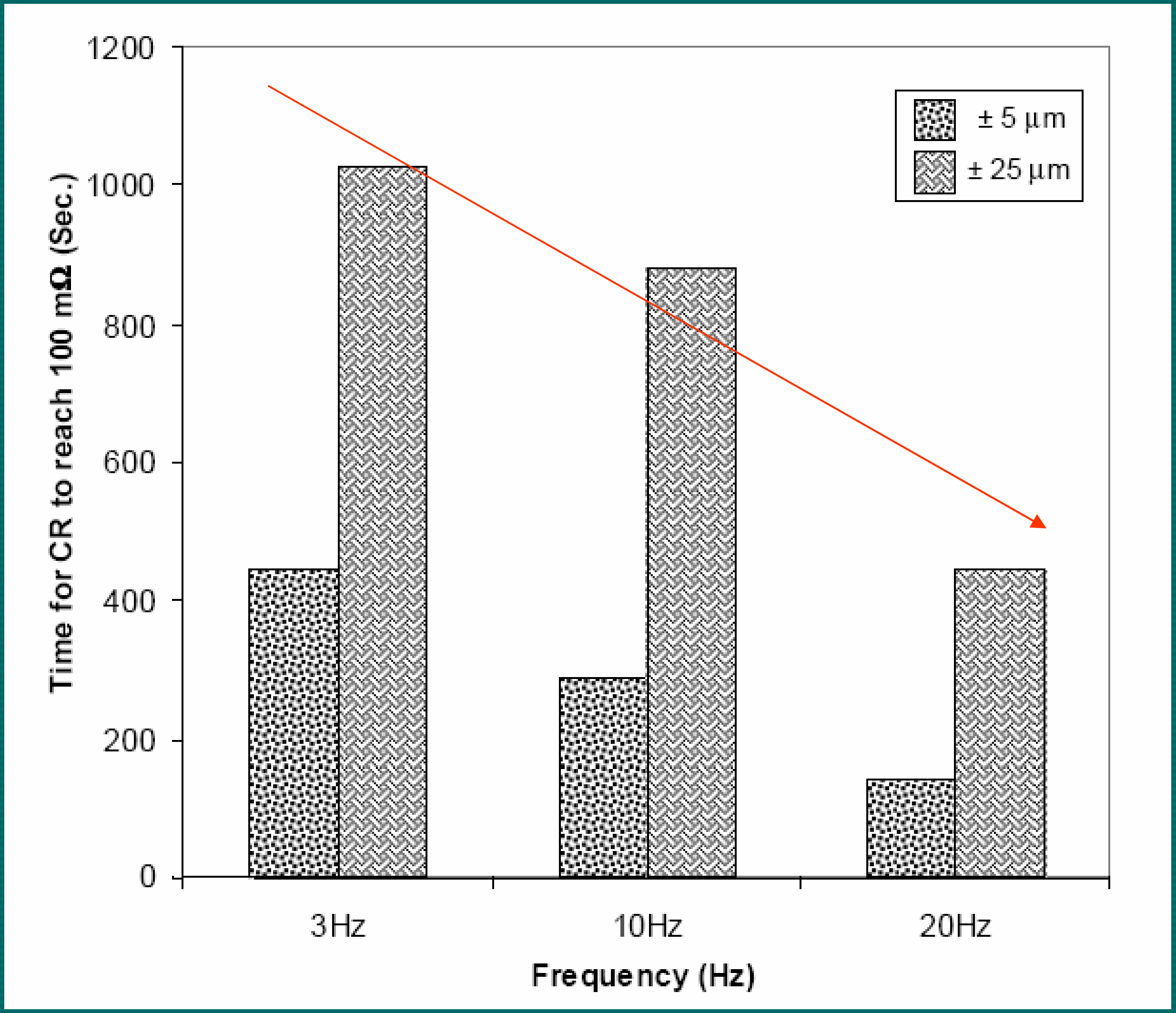
Higher amplitude – Provides more fresh metal for oxidation and generates more oxide debris

The threshold value of 100 mΩ is reached very rapidly at lower amplitude of ± 5 µm

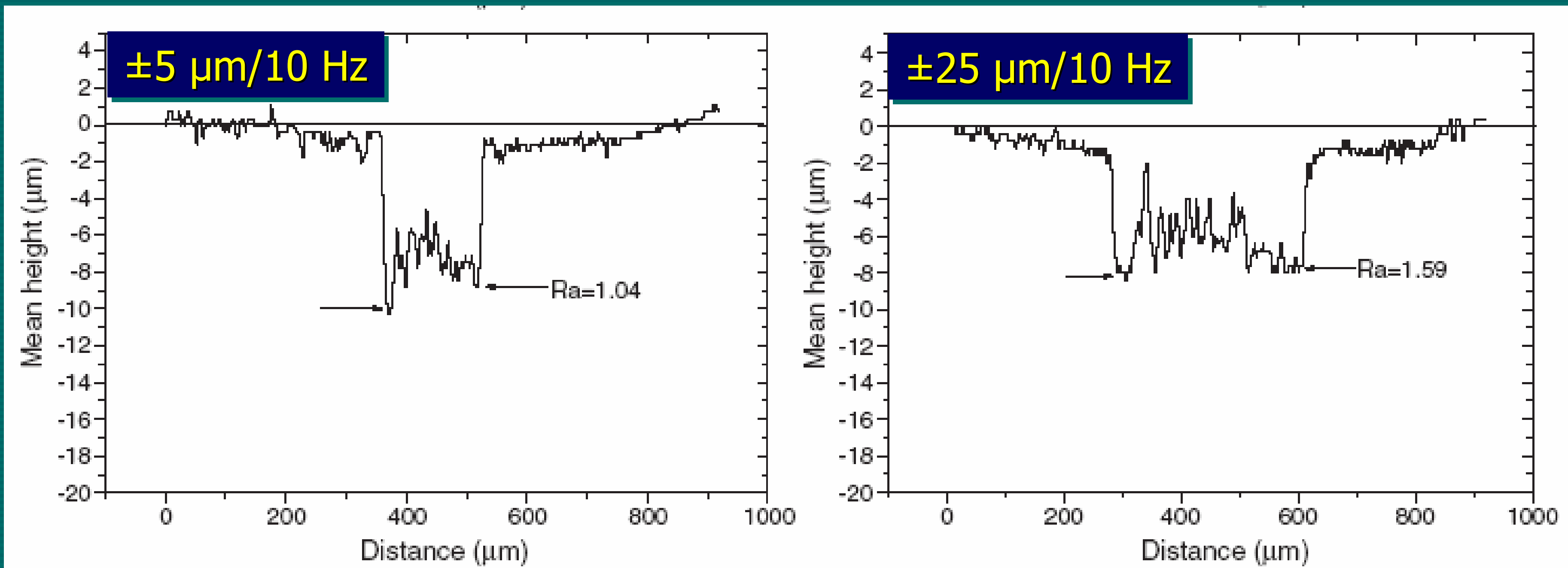
Asperity contact model – increase in CR – reduction in real area of contact

Granular interface model – granular interface consists of wear debris – accumulation of the wear debris that leads to the failure of the contact

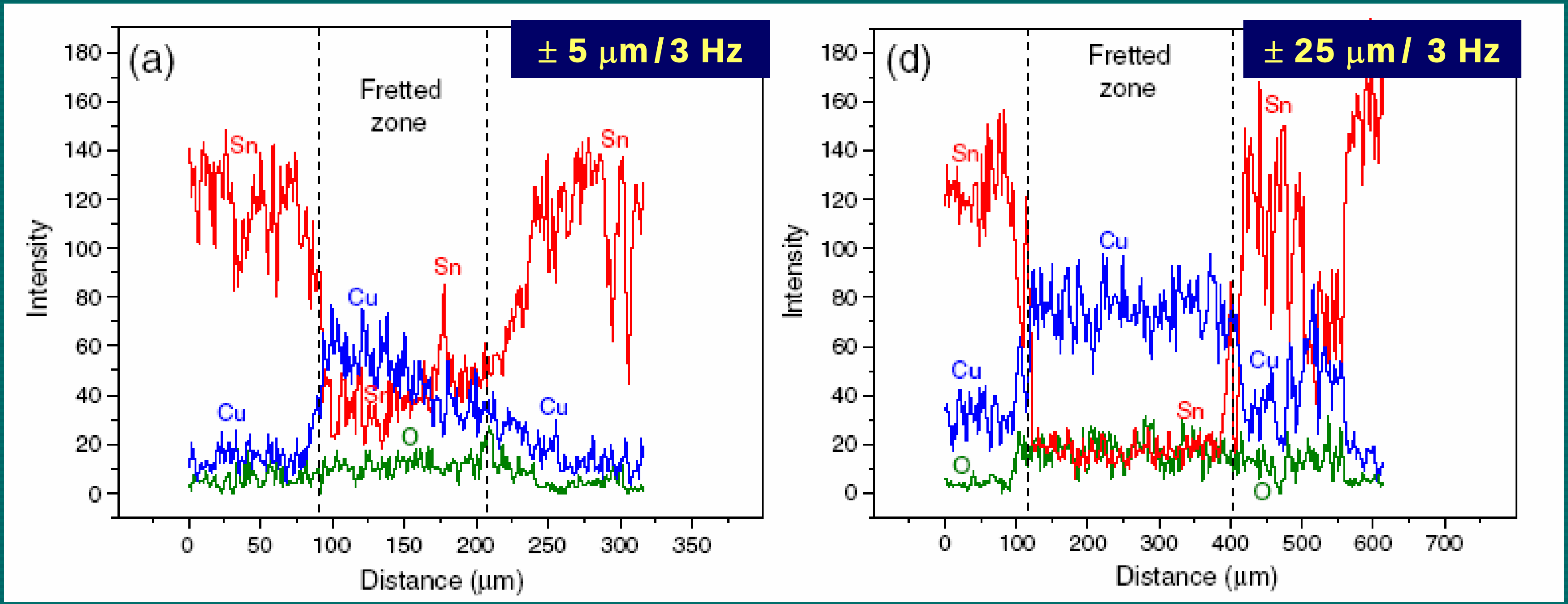
At low amplitudes of ± 5 µm accumulation of wear debris and oxidation products within a confined area causes the percolation limit for electrical conduction to reach at a shorter time



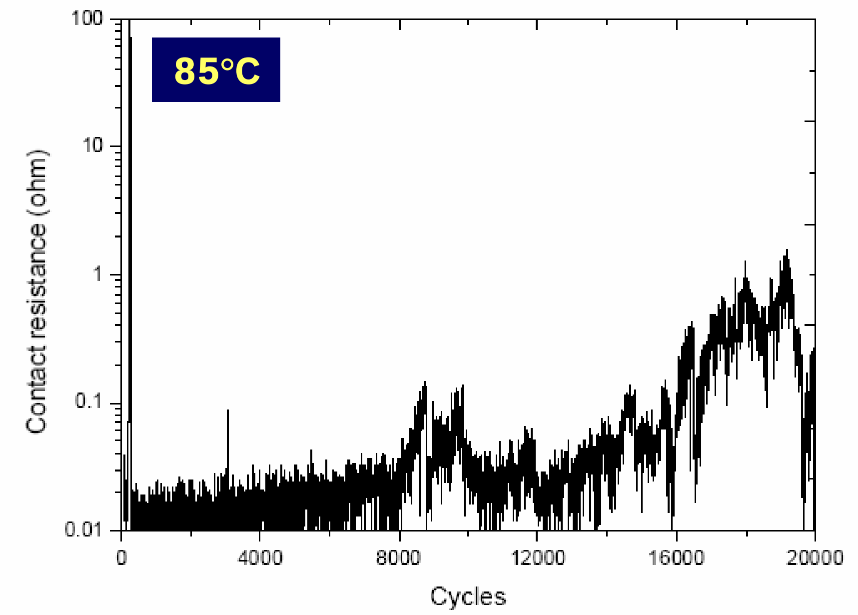
Plot of the time required for the contact resistance to reach a threshold value of 100 mΩ for the track lengths of ±5 μm and ±25 μm at three different fretting frequencies of 3, 10 and 20 Hz

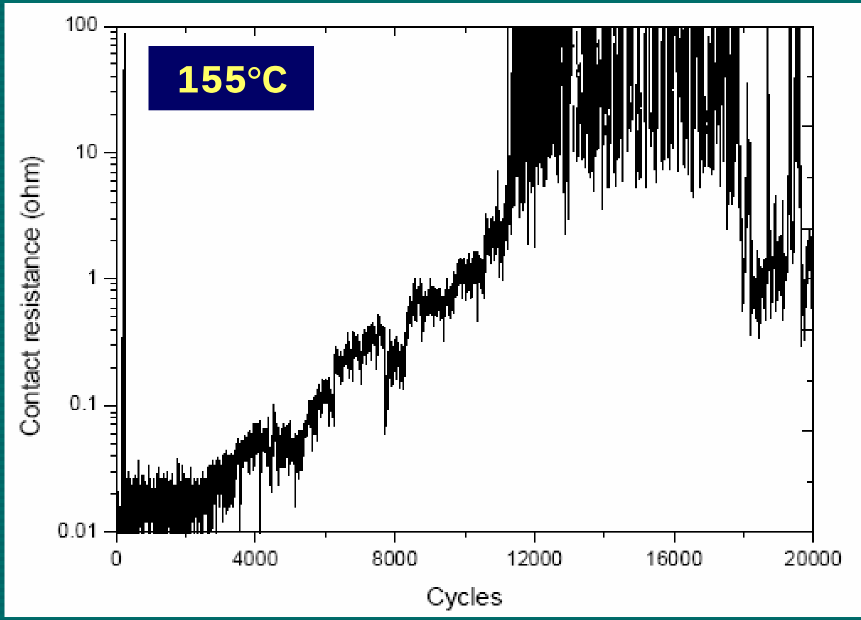


Surface profile across the fretted zone of the tin plated contacts after 20,000 cycles



EDX line scan performed across the fretted zone after 20,000 fretting cycles





Amplitude: ± 90 μm; Frequency: 10 Hz; Humidity: 55% RH; Normal load: 0.5 N; Current load: 0.5 A

Influence of temperature

Temperature has a greater influence on the extent of fretting corrosion of tin plated contacts

At elevated temperatures

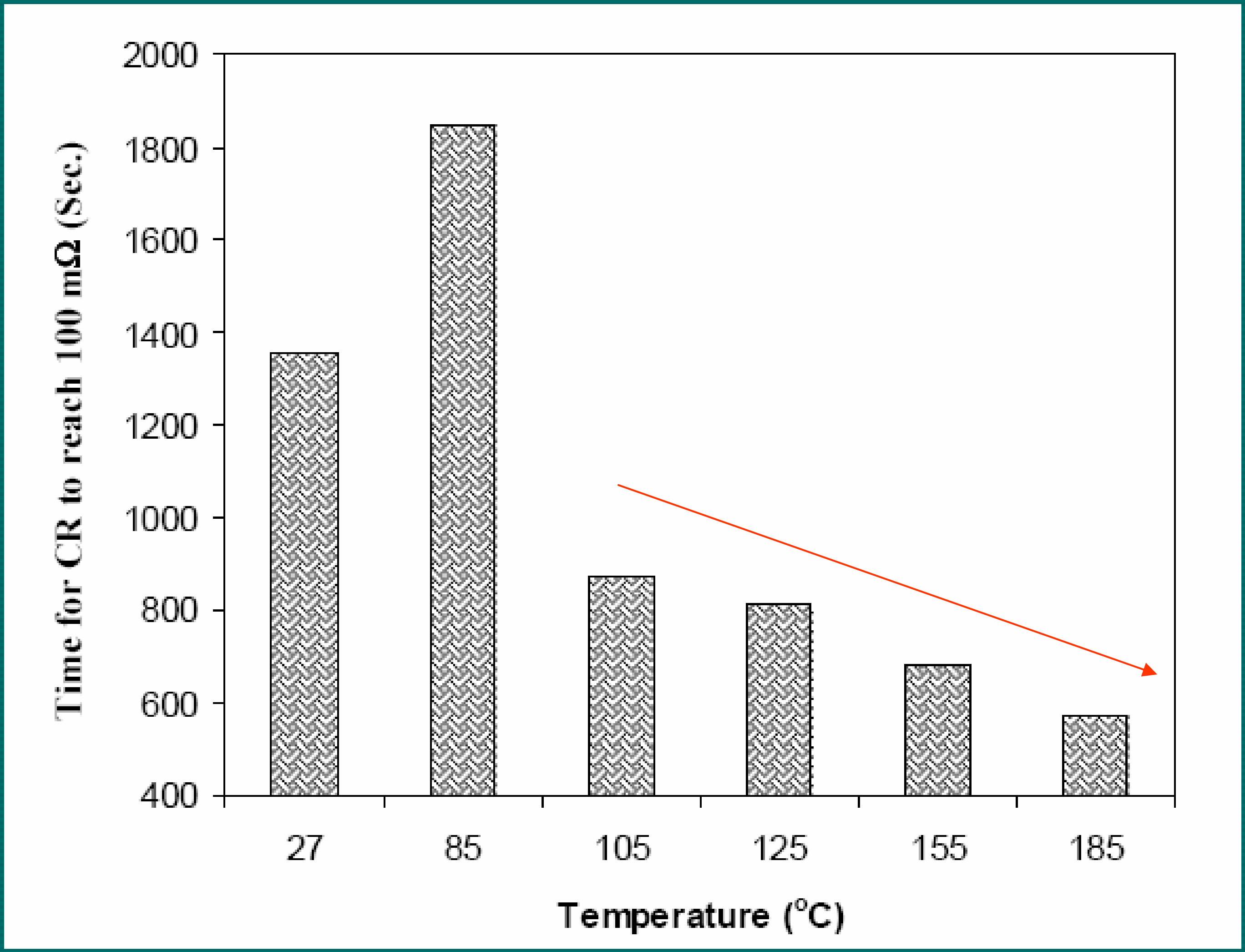
- Rate of oxidation of tin increases
- Hardness of tin decreases
- Diffusion and formation of IMC's

The extent of oxidation increases with increase in temperature

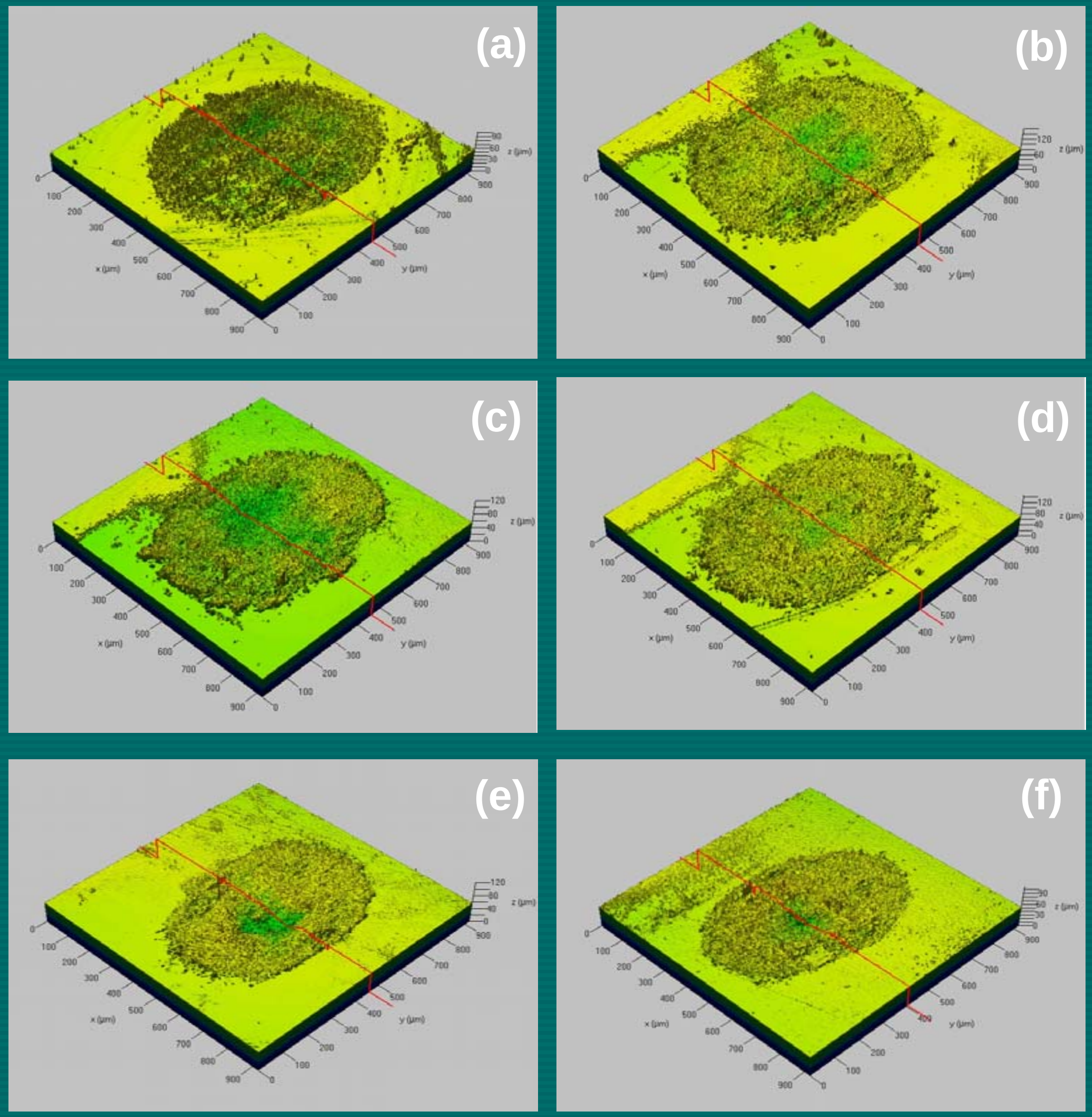
The softening of tin around 85°C enables a low CR for longer cycles

Beyond 125°C, the contact resistance increases rapidly

The formation of Cu-Sn based IMC's at elevated temperatures also has a major influence on the performance of tin plated contacts



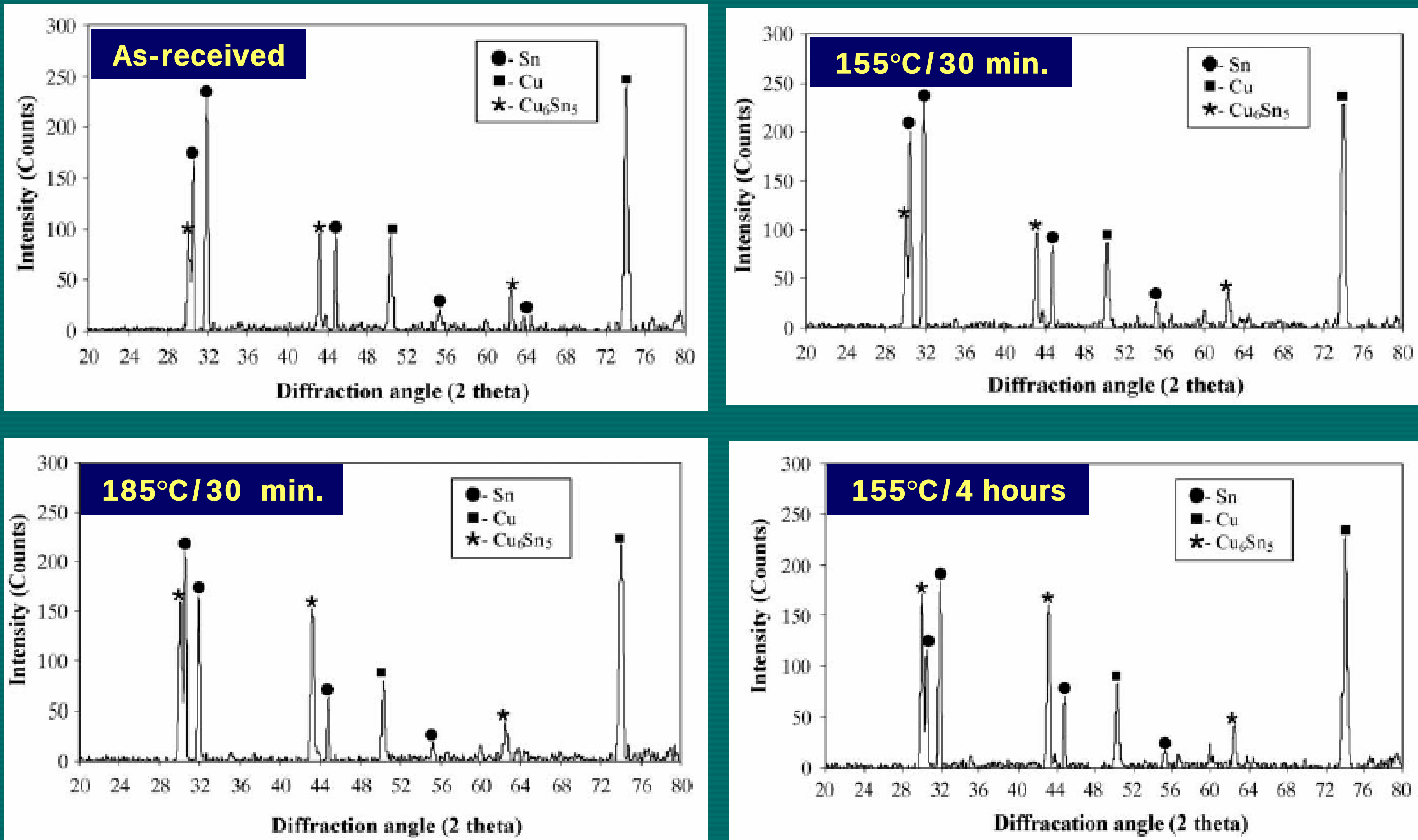
Plot of time required for the contact resistance to reach a threshold value of 100 mΩ at various temperatures (Amplitude: ± 90 μm; Frequency: 10 Hz; humidity: 55% RH; normal load: 0.5 N; and current load: 0.5 A)



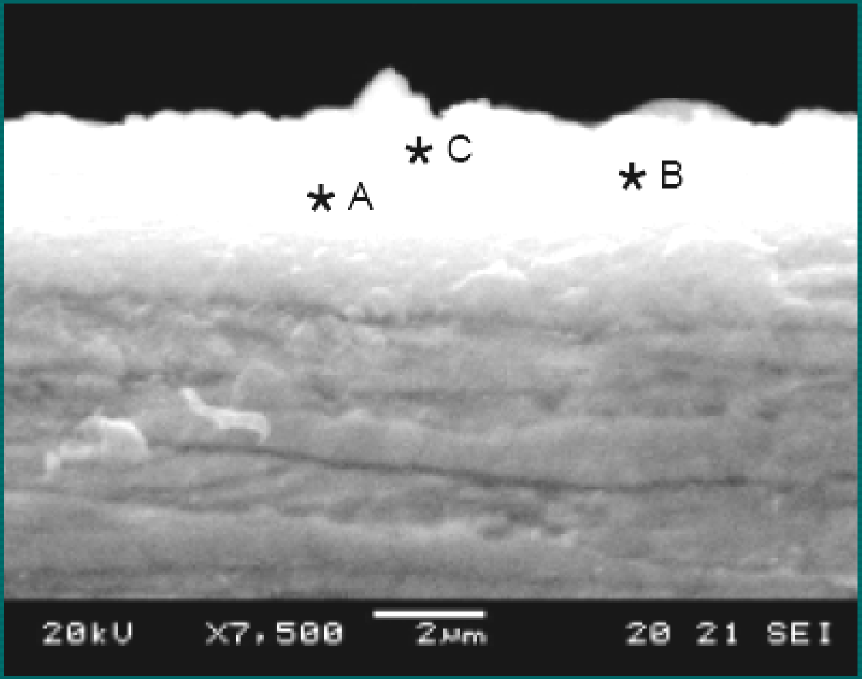
3-Dimensional view of the surface profile of the fretted zone of tin plated contacts subjected to fretting at various temperatures for 20000 cycles (a) 25°C; (b) 85°C; (c) 105°C (d) 125°C (e) 155°C; and (f) 185°C

Roughness parameters calculated using the surface profiles of the fretted zone of tin plated contacts subjected to fretting for 20000 cycles at various temperatures

Roughness parameter (μm)	27°C	85°C	105°C	125°C	155°C	185°C
Arithmetic mean deviation, Ra	1.71	2.77	2.46	2.16	1.96	1.81
Highest peak, Rp	28.69	48.91	64.50	31.87	31.34	33.64
Lowest valley, Rv	23.68	40.00	37.00	38.45	35.93	29.74
Absolute peak to valley, Rt	52.37	88.90	101.50	70.32	67.27	63.38
Average peak to valley, Rz	24.56	31.98	22.61	27.47	21.96	19.22
Maximum peak to valley, Rmax	52.37	88.90	90.54	57.70	59.73	63.32



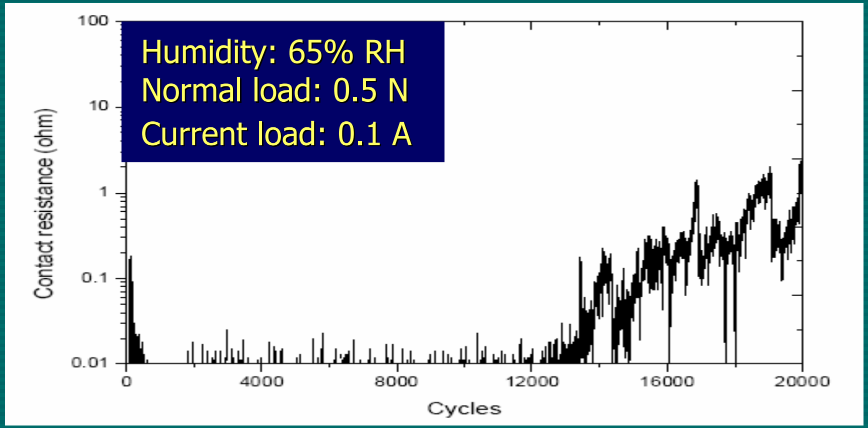
XRD pattern of tin plated copper alloy contacts in as-received and annealed conditions

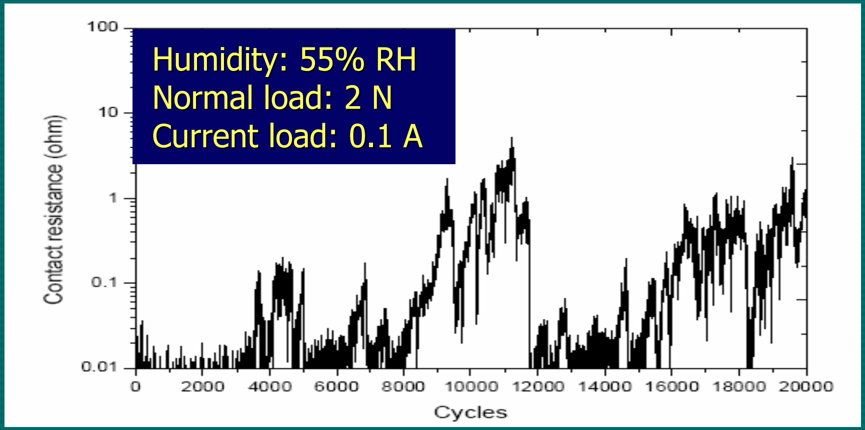


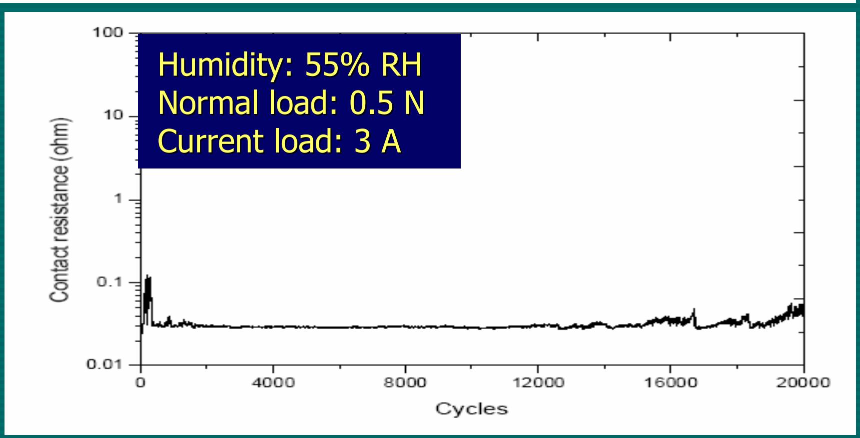
Cross sectional SEM of tin plated contact annealed at 155°C/30 min.

Results of the EDX measurement performed across the copper alloy-tin coating interface on samples subjected to thermal treatment at various temperatures

Point A			Point B			Point C		
Cu (wt.%)	Sn (Wt.%)	Assign-ment of phase	Cu (wt.%)	Sn (Wt.%)	Assign-ment of phase	Cu (wt.%)	Sn (Wt.%)	Assign-ment of phase
79.63	20.37	Cu_3Sn	61.80	38.20	Cu_6Sn_5	47.85	52.15	Cu_6Sn_5







Frequency: 10 Hz; Amplitude: ± 90 µm; Temperature: 27°C; Current load: 0.1 A

Influence of humidity, normal load and current load

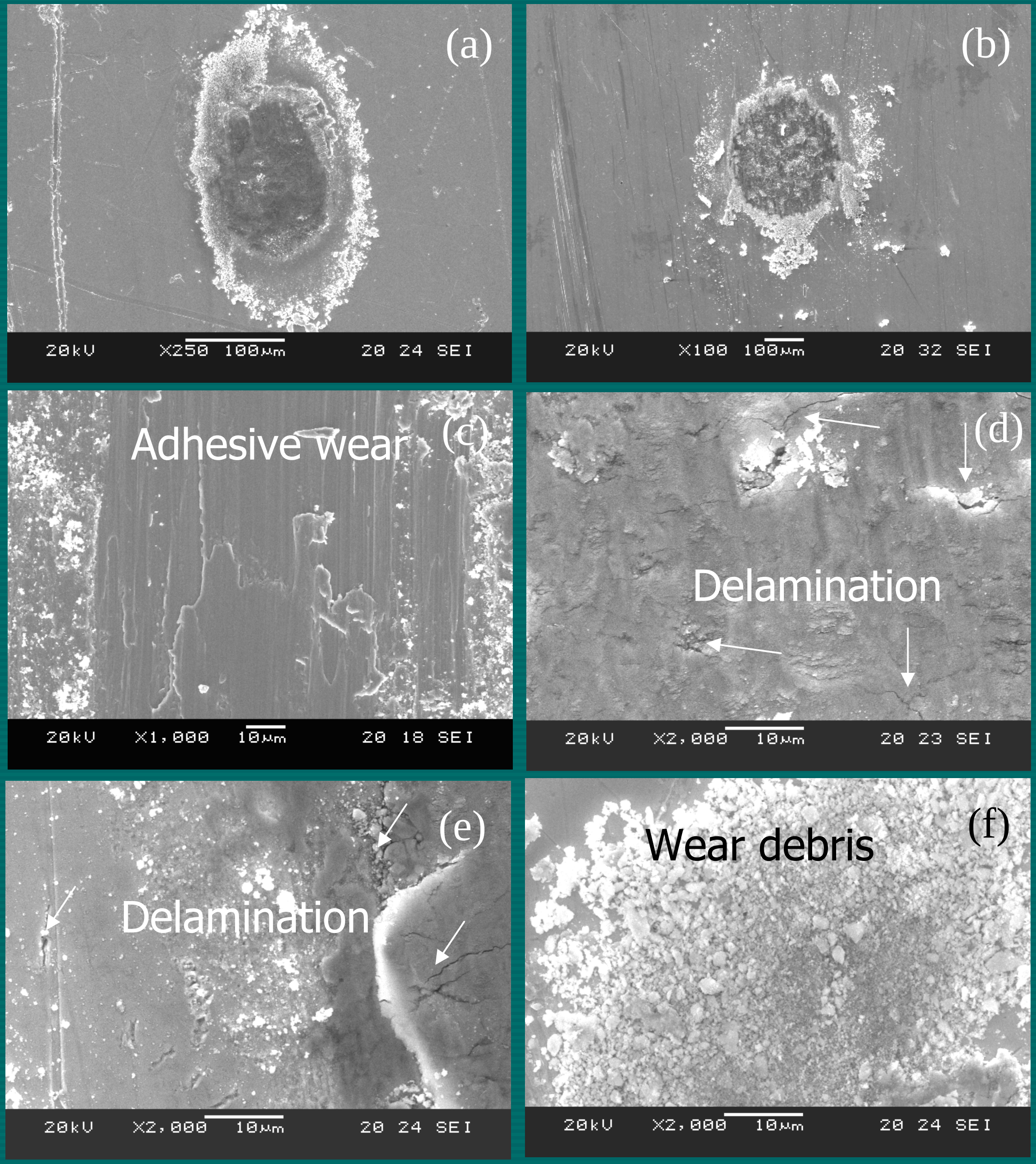
At >85% RH – better performance - condensation of water vapour provides lubrication at the contact interface and enables a low and stable CR for longer fretting cycles

High loads -2 N - rate of wear of tin coating is higher

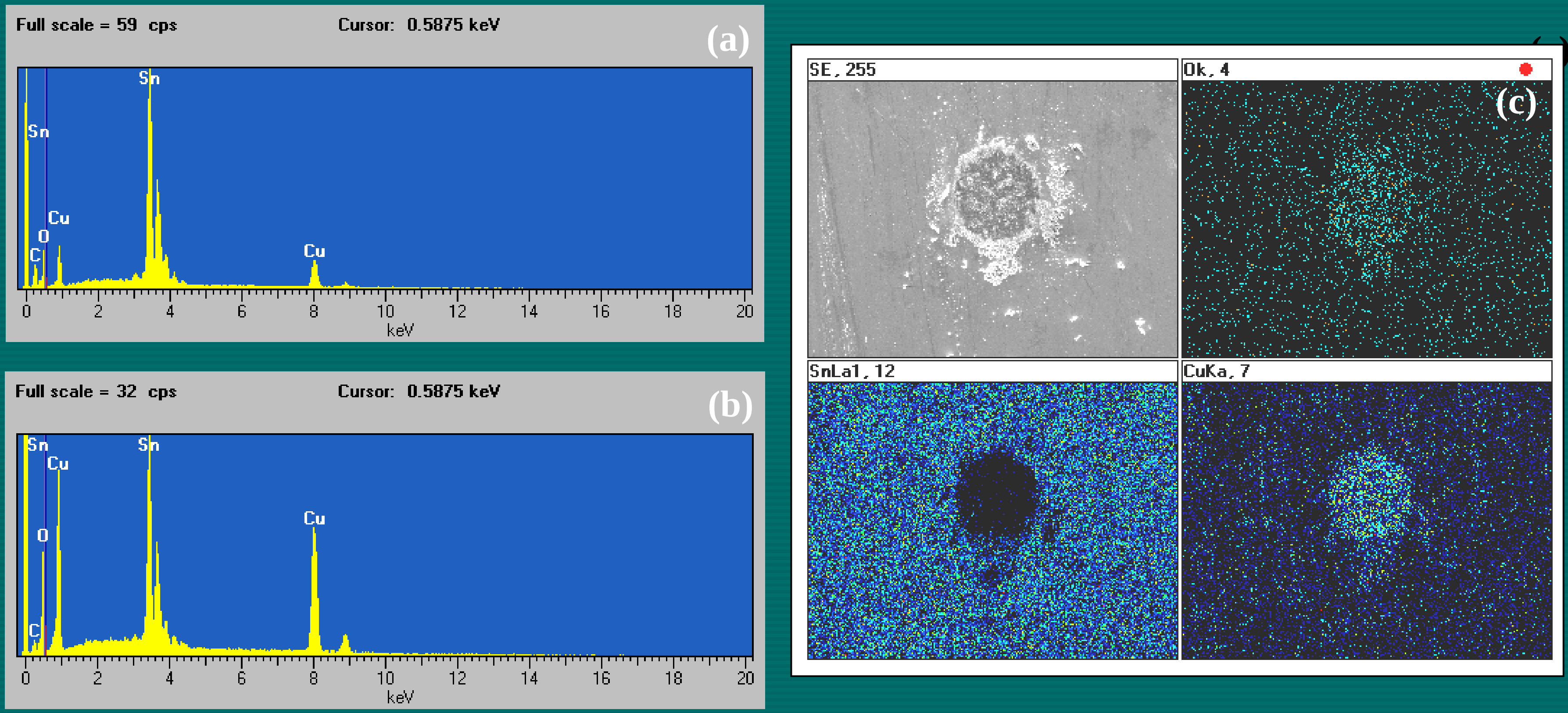
Higher load of 1 or 2 N helps to establish a better electrical contact and provides a stable contact resistance for longer cycles

The time to reach a CR of 100 mΩ is very low at 0.1 N - performance of the tin plated contacts is very poor at low load

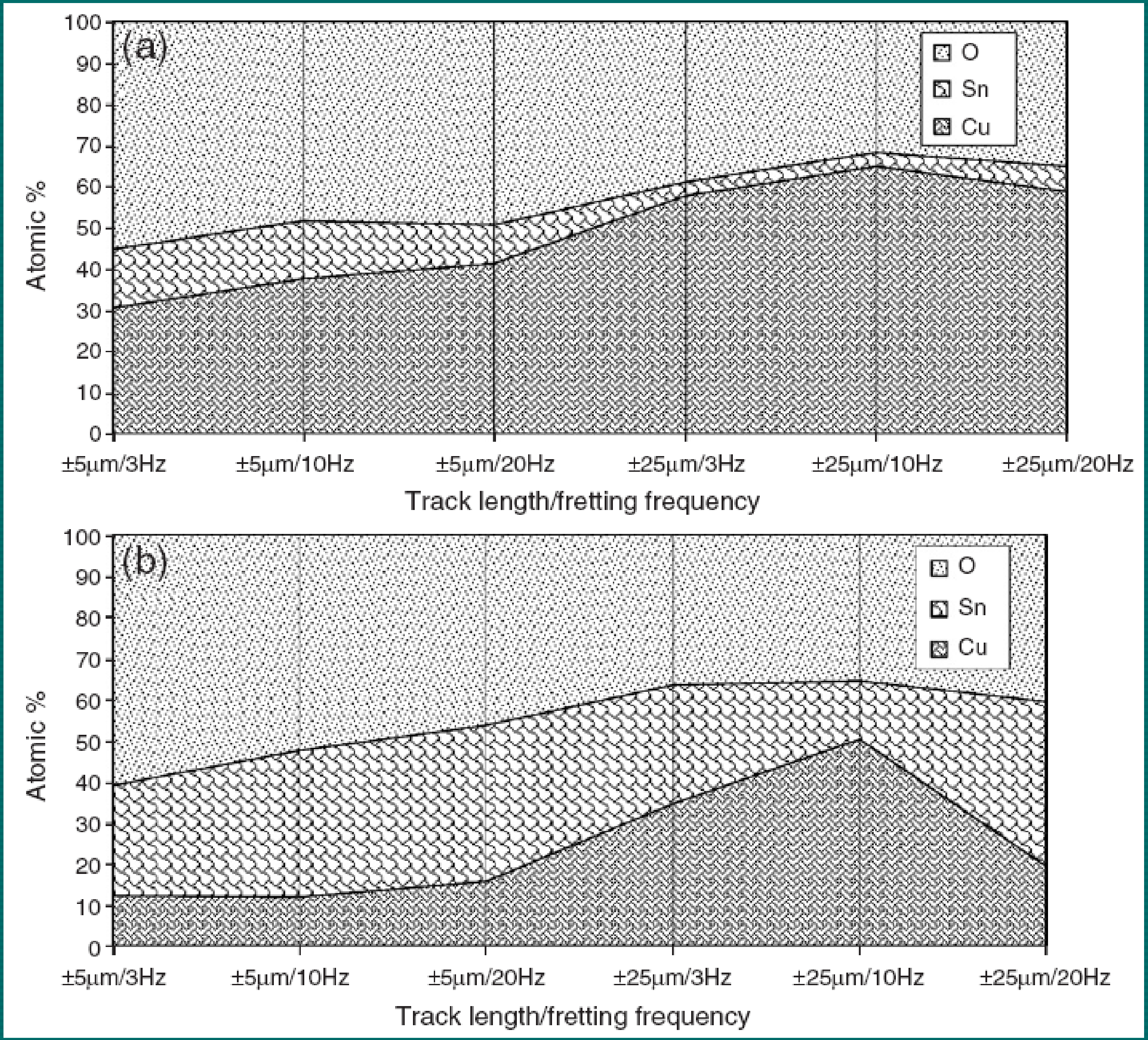
At current load of > 1 A – better performance as this current load enables to break the oxide film and provides a stable and low CR



Scanning electron micrographs of the fretted zone of the tin plated contacts



EDX pattern taken at the centre (a) and edge (b) of the fretted zone
(c) X-ray elemental mapping of oxygen, tin and copper of
the fretted zone taken after 20000 fretting cycles



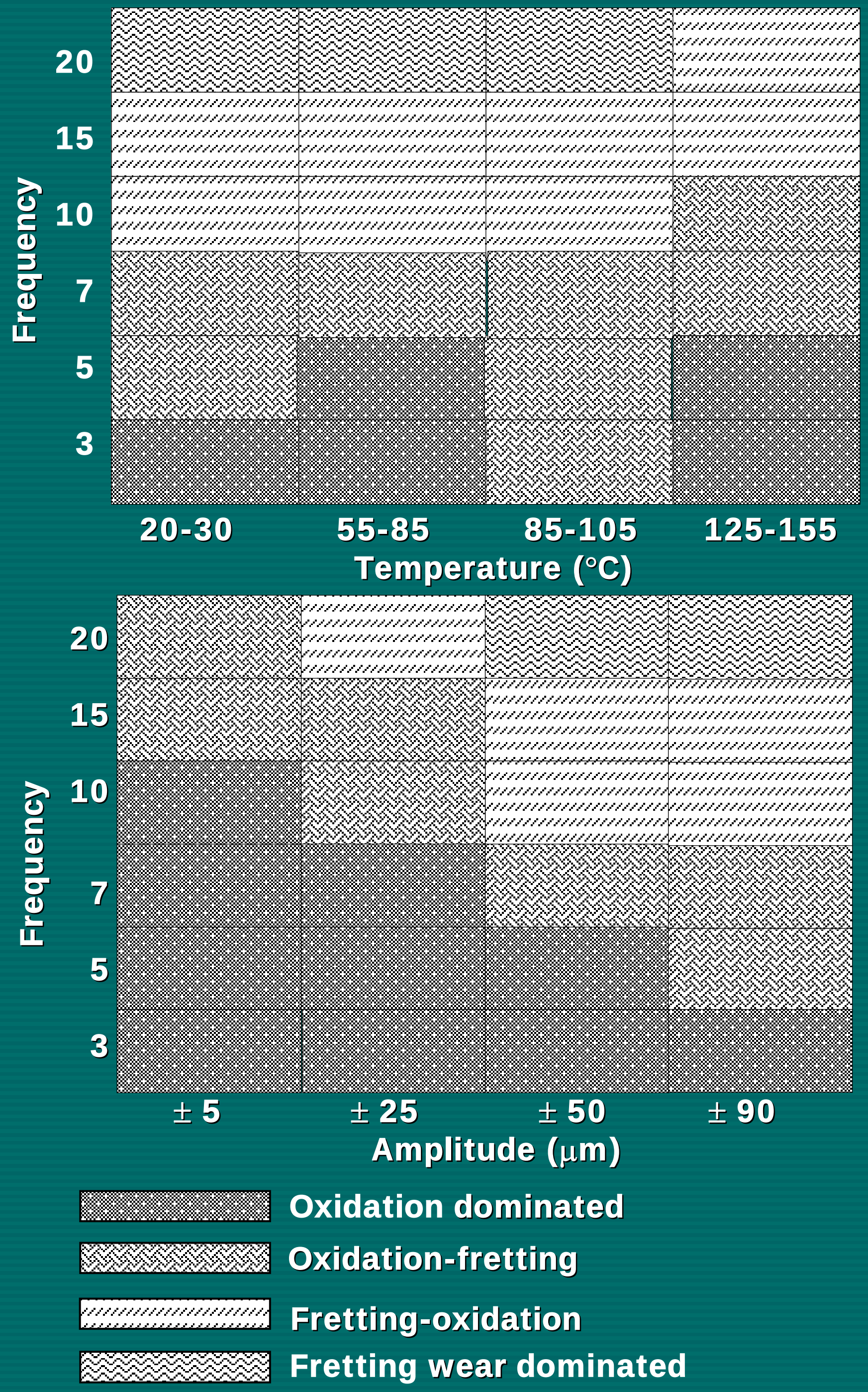
Area plot depicting the variation in atomic concentration of tin, copper and oxygen of the oxide debris as a function of the experimental conditions (a) at the centre of the fretted zone; and (b) edge of the fretted zone

Mechanism of fretting corrosion of tin plated contacts

- The sequence of changes that the tin plated contact will encounter with increase in fretting cycles is as follows:
  - Removal of tin oxide layer;
  - Partial removal of the tin coating - adhesive wear
  - Removal of tin coating in many areas, displacement of wear debris outside the fretted zone and exposure of the copper alloy (base metal) where the coating is removed
  - Initial stages of oxidation of the contact zone and continuous formation and rupture of oxide films;
  - Attainment of a critical level where the number of contact points starts to decrease;
  - Accumulation of wear debris and oxidation products at the contact zone and thickening of the oxide film; and
  - Virtual open circuit

Mechanism of fretting corrosion of tin plated contacts

- The number of fretting cycles at which the above stages occur will vary significantly depending on the conditions used
- rate of fretting wear of the tin coating and the rate of oxidation of the contact zone is dependent on many factors
- The interdependence of extent of wear and oxidation increases the complexity of the fretting corrosion behaviour of tin plated contacts

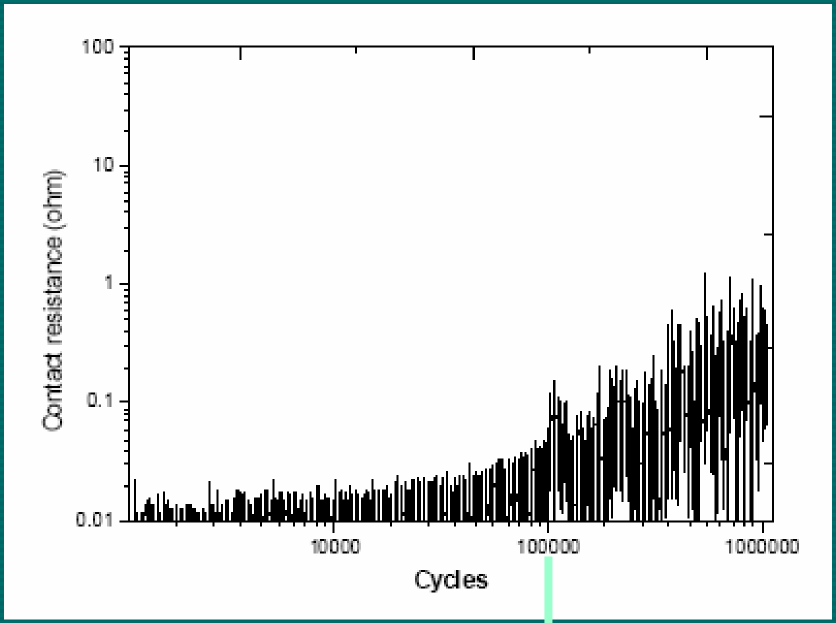


Fretting-corrosion maps

Though oxidation of the contact zone is responsible for the failure of the contact, the fretting wear of the tin coating is initiating the process

Fretting corrosion map is segmented into various zones as oxidation-dominant, oxidation-fretting, fretting-oxidation and fretting wear-dominant, depending on the nature of the predominant process

The conditions which represent the oxidation dominant zone, such as low frequency (3 Hz), low amplitude (± 5 μm), high temperature (125-155°C), low normal load (0.5 N) and low current load (0.1 A), could cause a high-risk of failure of the tin plated contacts



Influence of lubrication

Lubrication - A 50-50 mixture of petroleum oil and zinc diamyldithiocarbamate with a surface coverage of 6.76 ± 1 mg/cm^2

Easily establishes metallic asperity contact between the mated tin plated contacts

CR of lubricated tin plated contacts remains stable for several thousand fretting cycles

100 mΩ threshold – around 100000 cycles

Extent of mechanical wear of the tin coating is significantly reduced

The contact zone experiences a lesser wear damage and exhibit a smoother profile.

The formation of tin oxide is not appreciable

No oxide accumulation at the contact zone

Lubrication is very effective in delaying the fretting wear during the initial stages and in preventing the oxidation and, accumulation of wear debris and oxidation products at the contact zone in the later stages

Concluding remarks

- Tin plated contacts could experience an early failure even at shorter track lengths if there is enough accumulation of wear debris at the contact zone
- The increase in rate of oxidation with increase in temperature and, the high hardness and poor electrical resistance of the Cu-Sn based IMC formed at elevated temperatures, suggests that the tin plated contacts are unsuitable for high temperature applications
- The fretting corrosion of tin plated contacts involves at least seven stages with a periodic increase in the extent of wear of tin coating and the extent of oxidation of the contact zone
- The interdependence of extent of wear and oxidation increases the complexity of the fretting corrosion behaviour of tin plated contacts

Concluding remarks

- A combination of adhesive, abrasive, delamination and oxidative wear is responsible for the failure of the tin plated contact
- Fretting corrosion maps are useful in identifying the dominant zones to assess the risk of failure under a given set of conditions
- Though not quantitative to predict the exact life-time of tin plated contacts these maps will be useful to draw some guidelines on the performance of tin plated contacts under various conditions
- Lubrication of tin plated contacts is a viable preventive strategy to improve the life-time of tin plated contacts

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  - Korea Federation of Science and Technology Societies – Award of a visiting fellowship to TSNSN under the Brain Pool Program
- Technical support
  - Korea Electric Terminal Company for providing the tin plated copper alloy samples
- I express my sincere thanks to Director, National Metallurgical Laboratory, Jamshedpur, for granting me sabbatical leave for one year to carry out this research work at Korea

Part 2 – Whisker growth

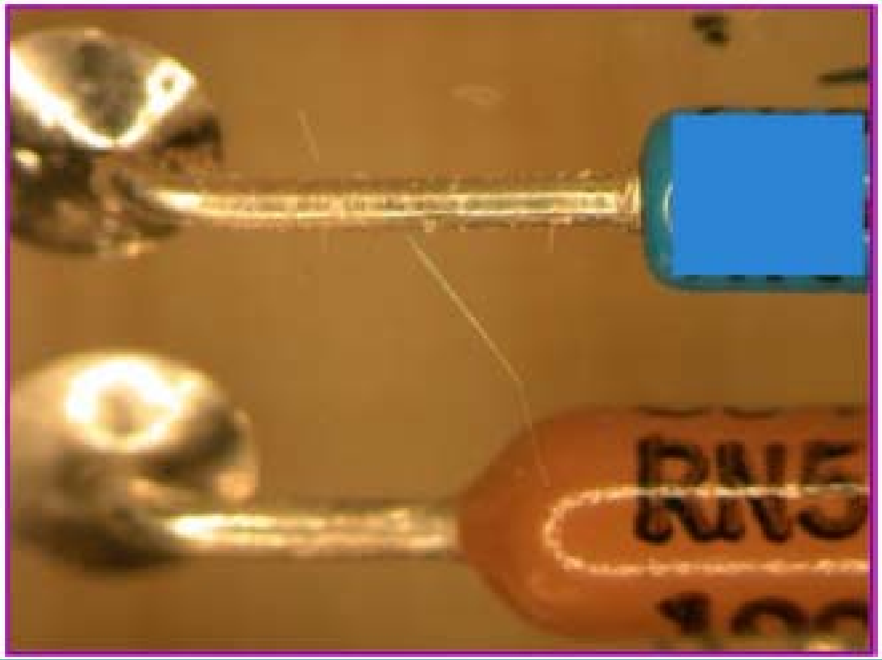
No! Not these whiskers!!

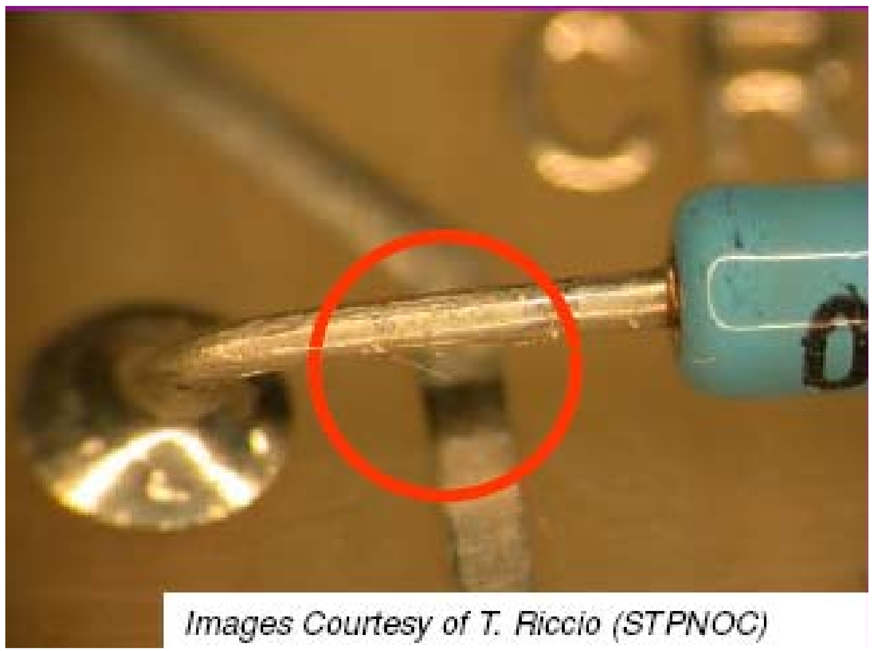
Tin whiskers – A preamble

- Whisker formation in electroplated tin coatings was first observed by Hunsicker and Kenspf in 1947
- Tin whisker - Single crystals of tin
- Spontaneously grow from the surface of tin/tin alloy plating
- Whiskers can grow without electrical field both in vacuum and in atmosphere conditions
- Grows best at room temp to 75 °C (50 °C seems optimum)
- Growth occurs from the base of the whisker
- *Diameters:* 0.3 ~ 10 μm, typically ~ 1 μm (0.04 mils)
- *Lengths:* >1.5 mm (60 mils); up to 10 mm (0.4 inch)
- *Shape:* Perfectly straight, bent, kinked or forked; even hollow

Tin whisker growth in electrical and electronic components

Tin Whiskers on Tin-Plated Axial Leaded Diodes





Images Courtesy of T. Riccio (STPNOC)

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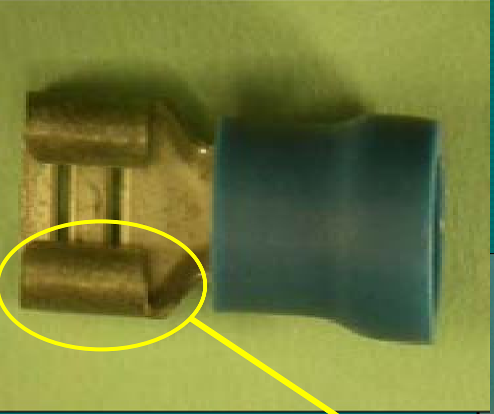
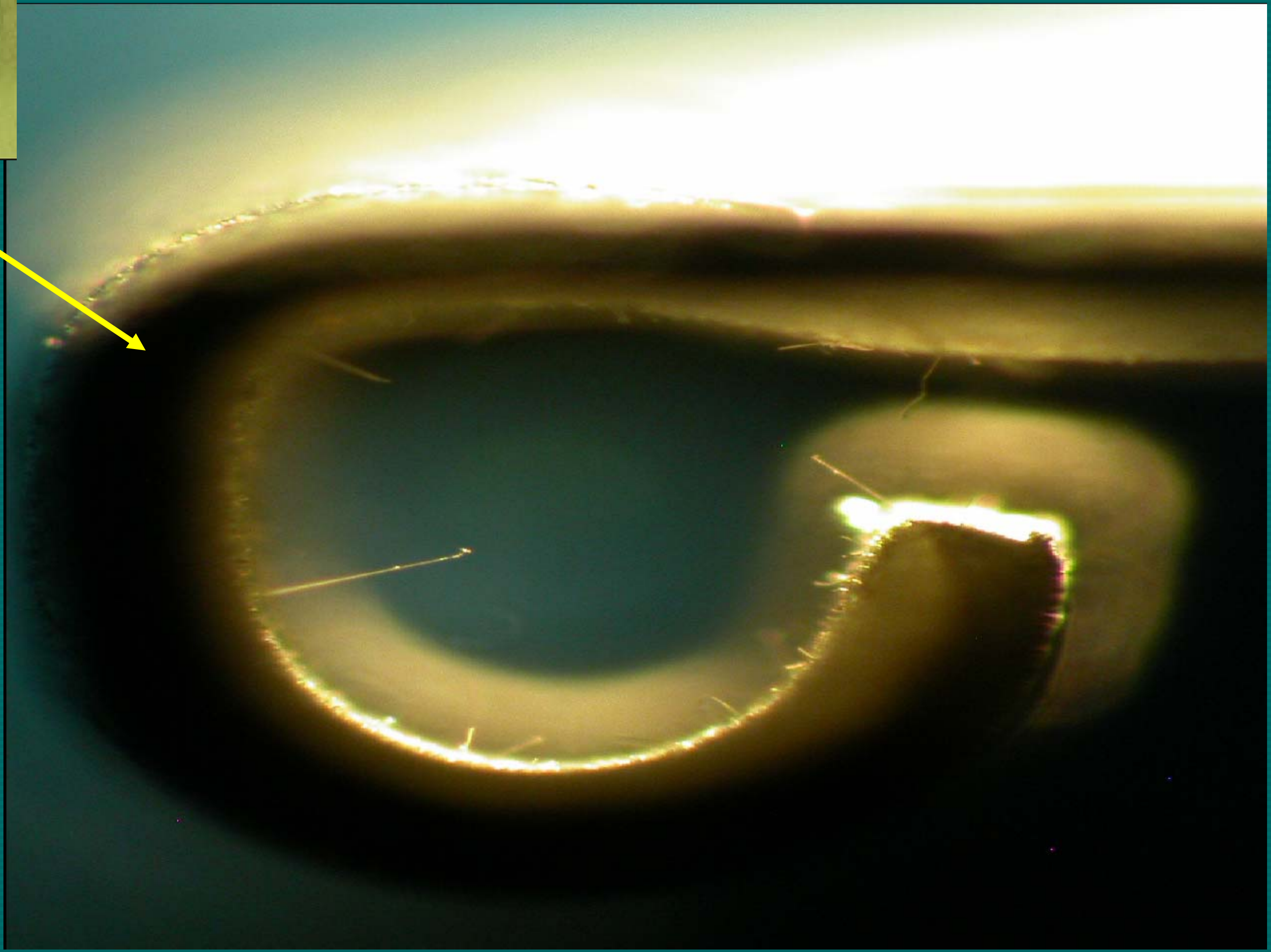
Tin-Plated Terminal Lugs





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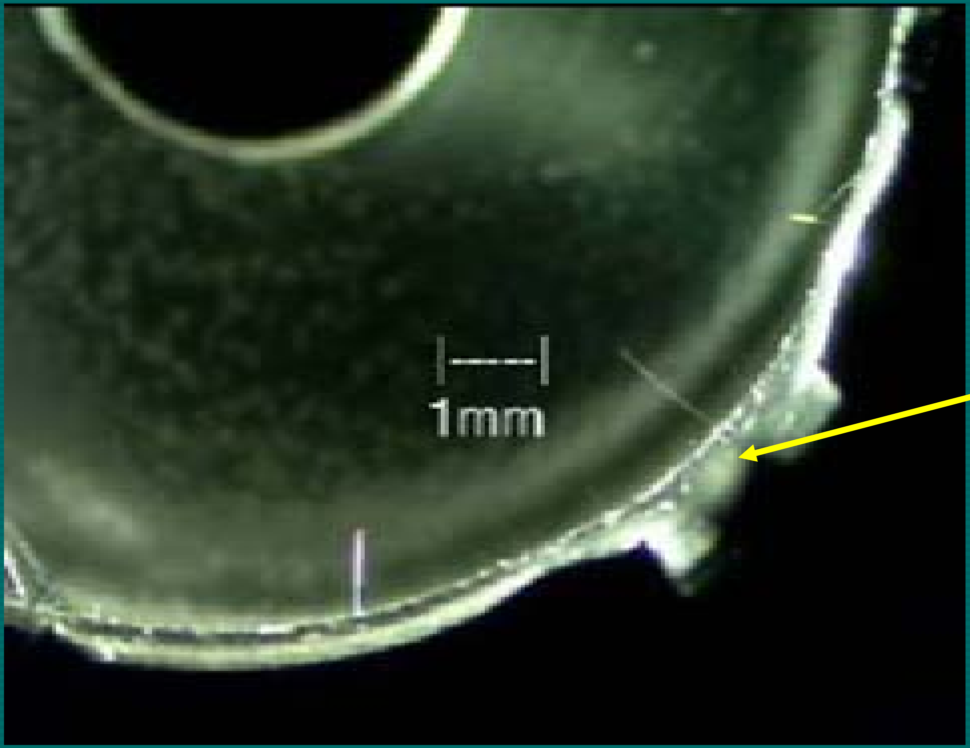
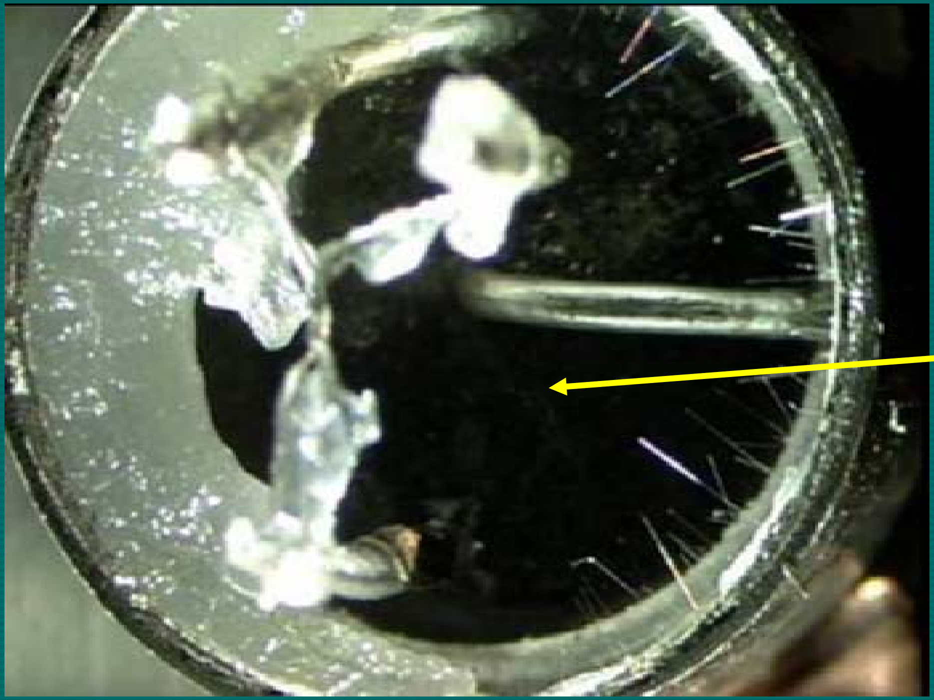
Tin-Plated Transformer Can



Tin whiskers observed in as-received cans Coincidental with Mfr Switch from Tin-Lead to Pure Tin Finish

Source:

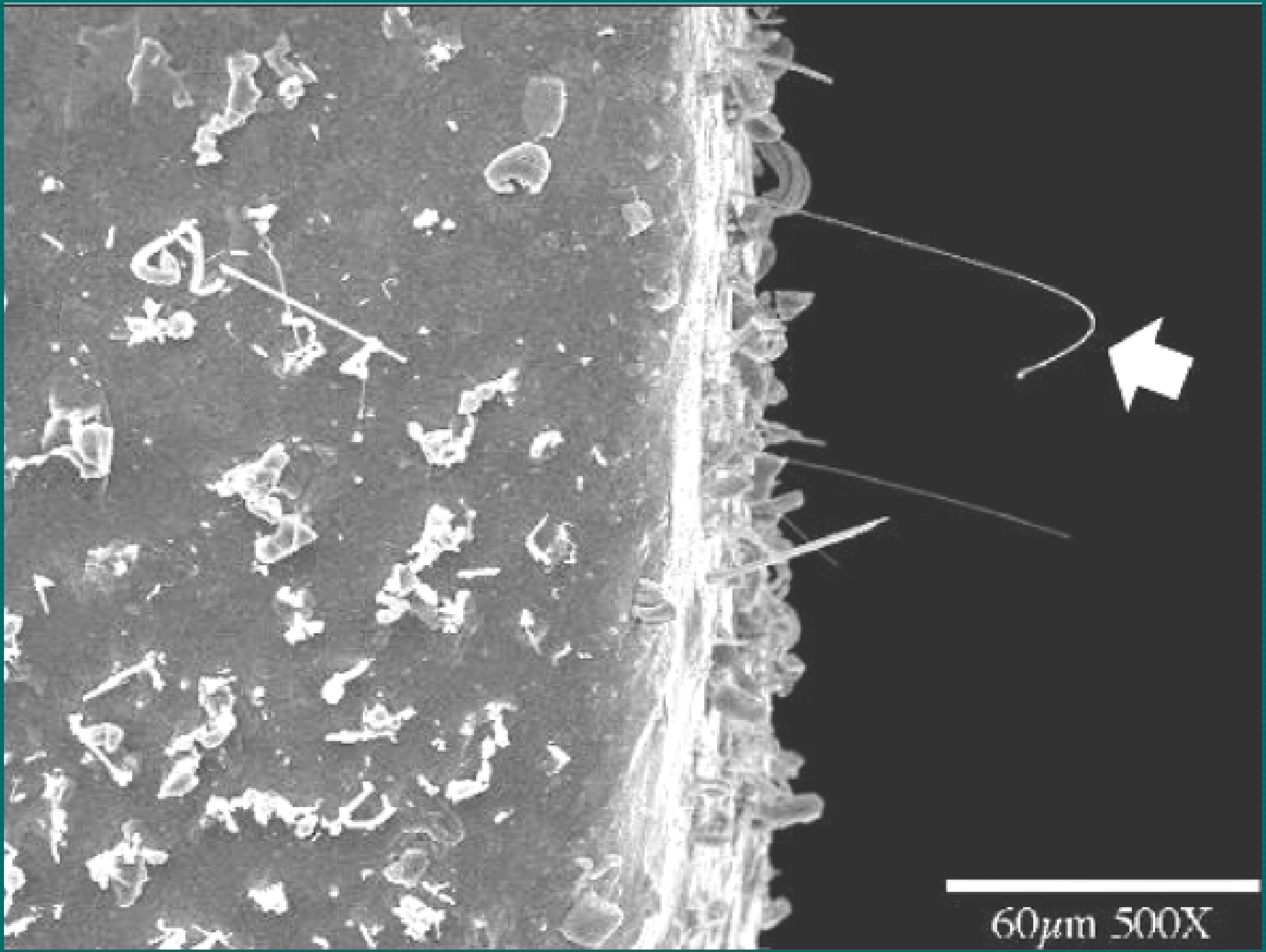
Tin plated transistor

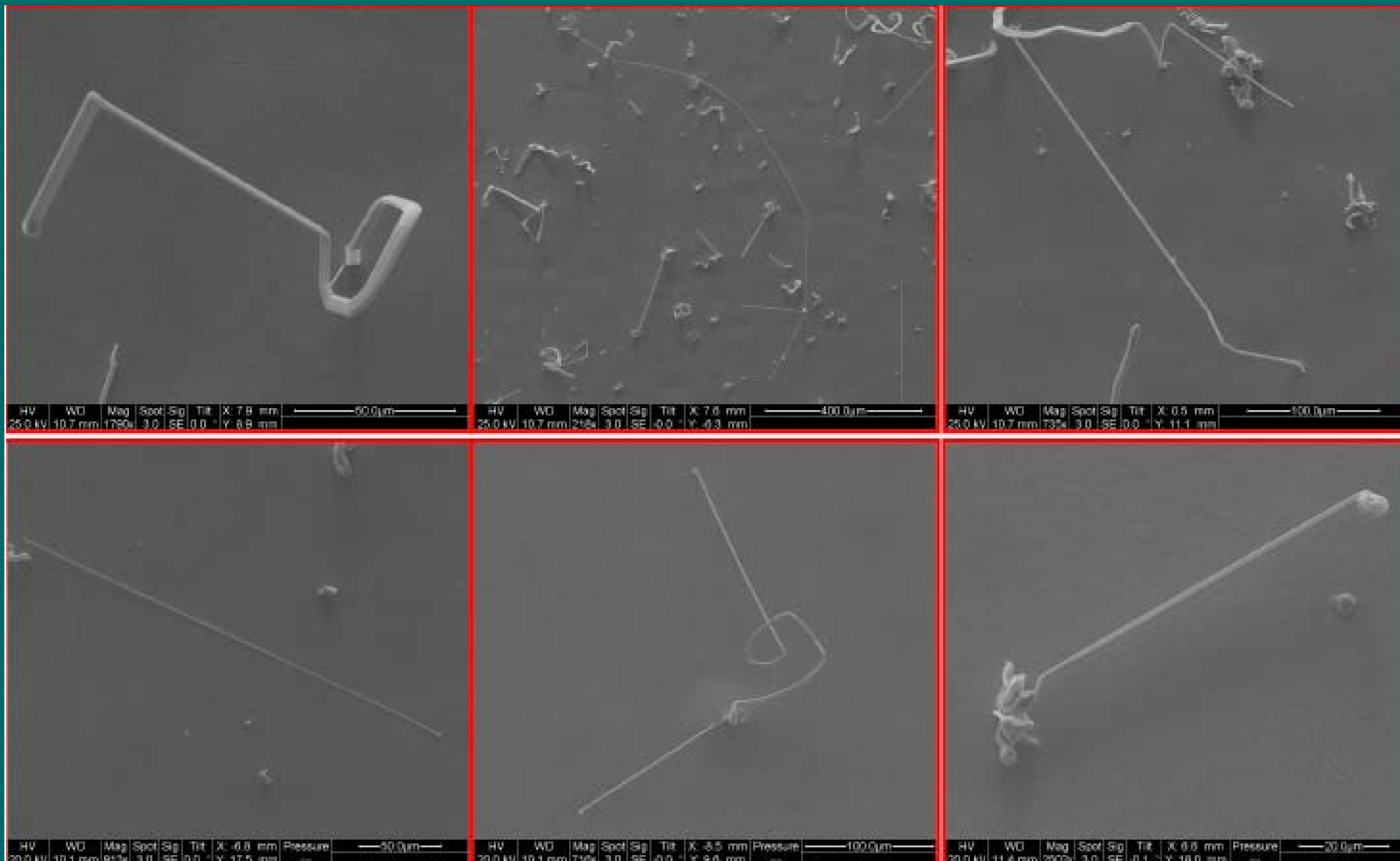


Tin plated transistor - Many radio malfunctions have been attributed to whiskers shorting case to terminals

Source:

Tin whiskers – At a closer look how do they appear?


60μm 500X



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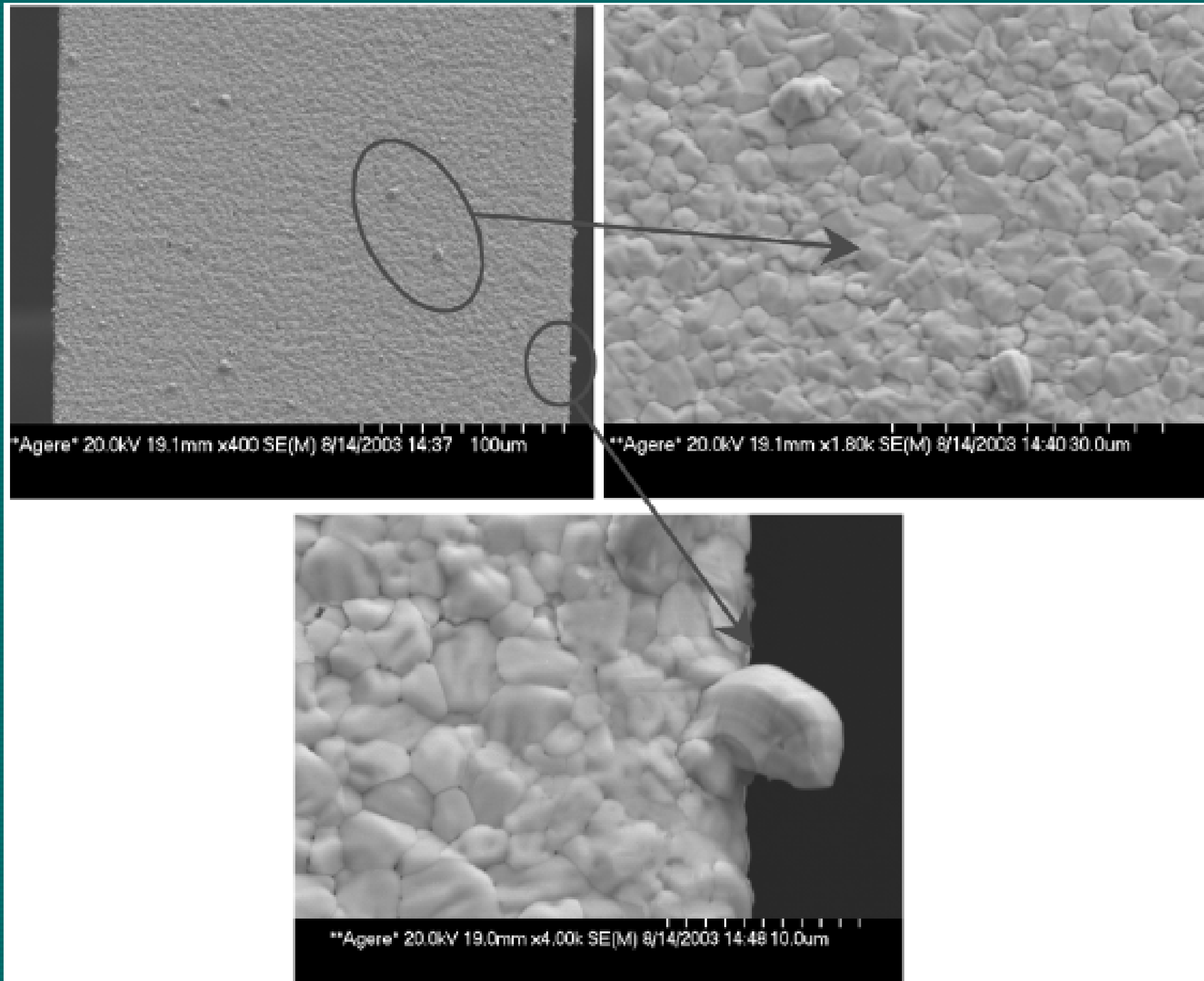
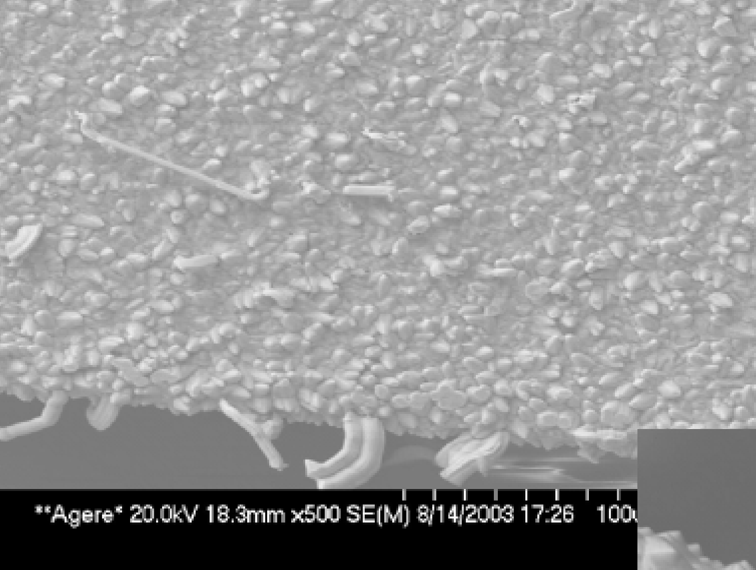
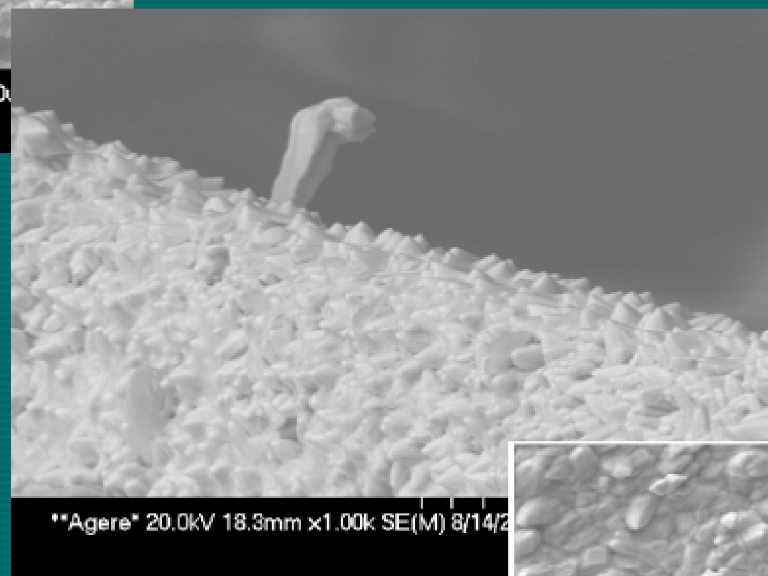
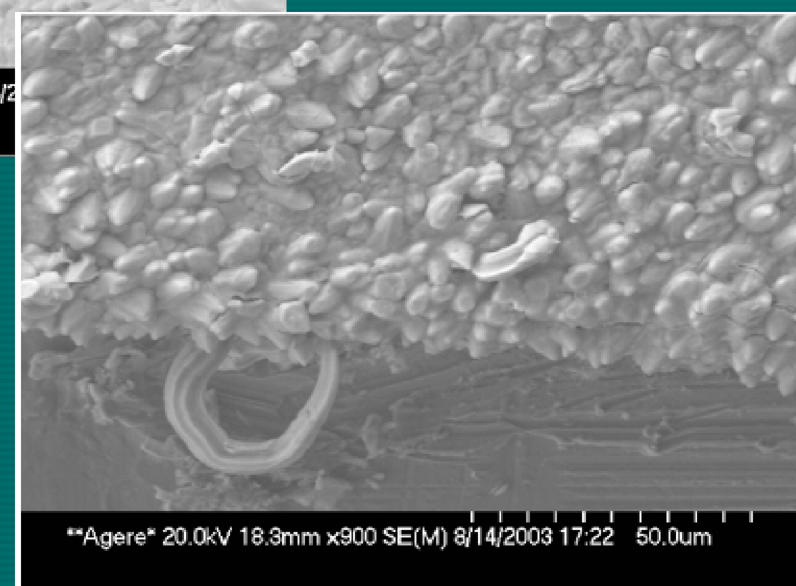
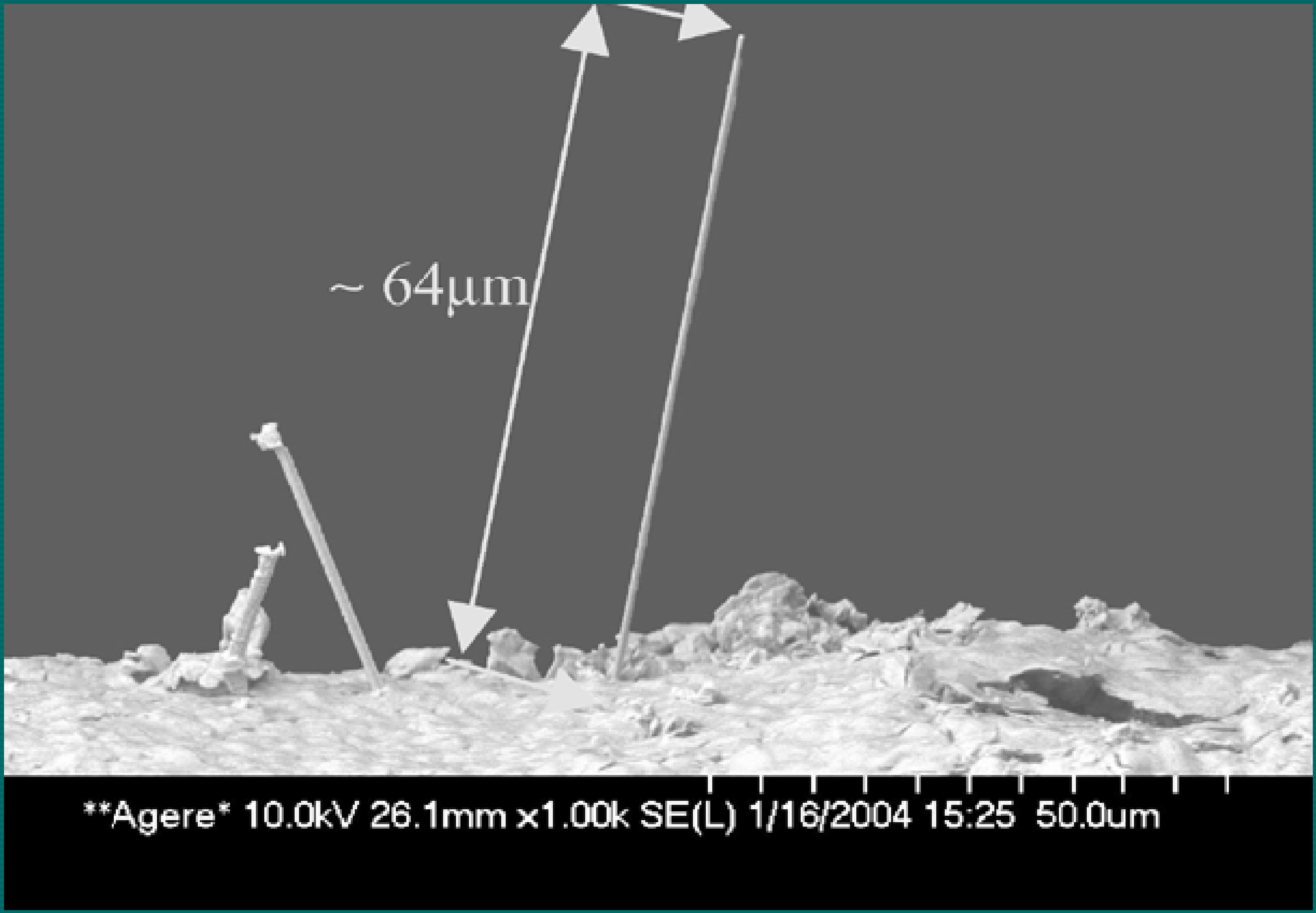
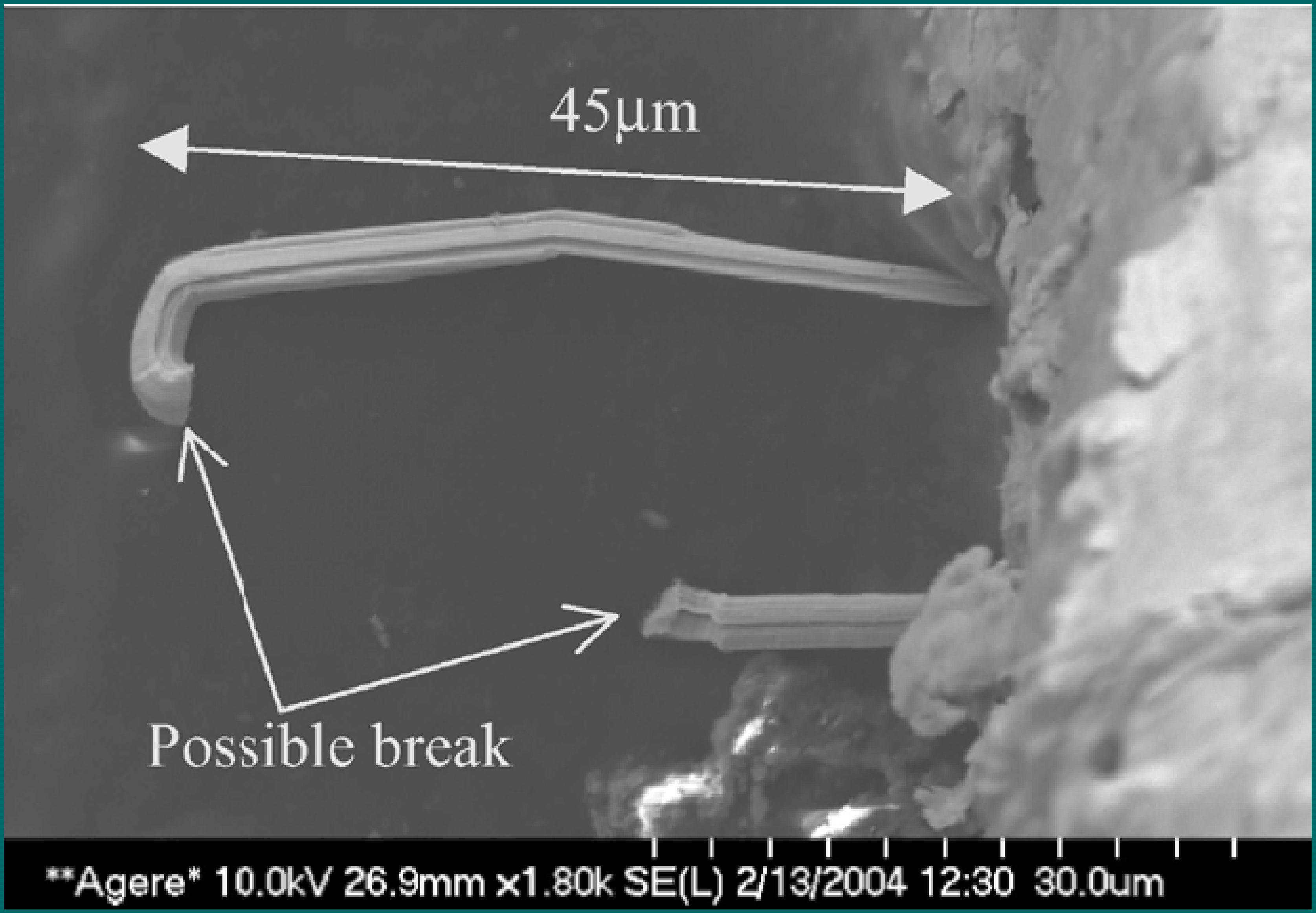

Agere 20.0kV 19.1mm x400 SE(M) 8/14/2003 14:37 100um
**Agere* 20.0kV 19.1mm x1.80k SE(M) 8/14/2003 14:40 30.0um
**Agere* 20.0kV 19.0mm x4.00k SE(M) 8/14/2003 14:48 10.0um

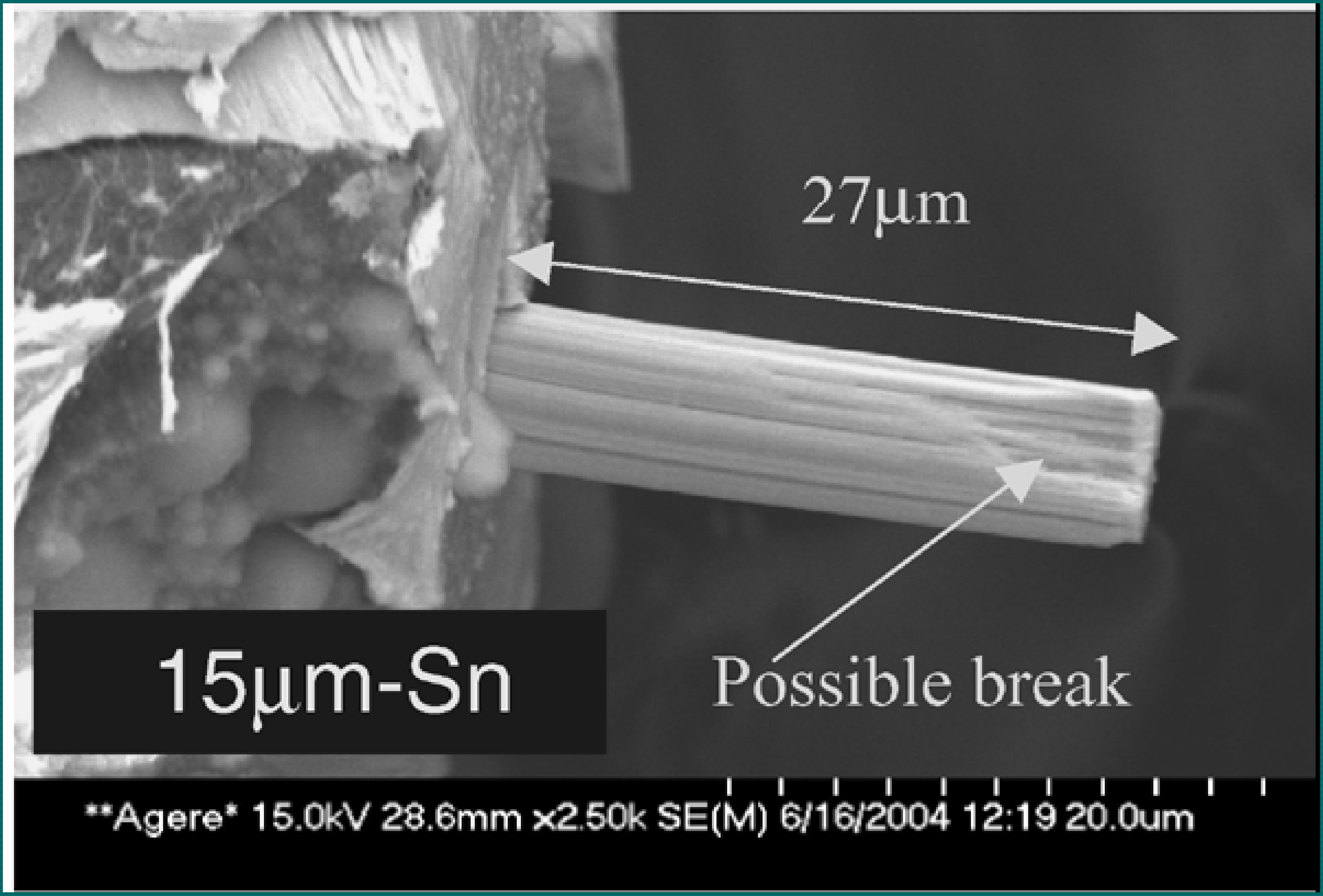

**Agere* 20.0kV 18.3mm x500 SE(M) 8/14/2003 17:26 100

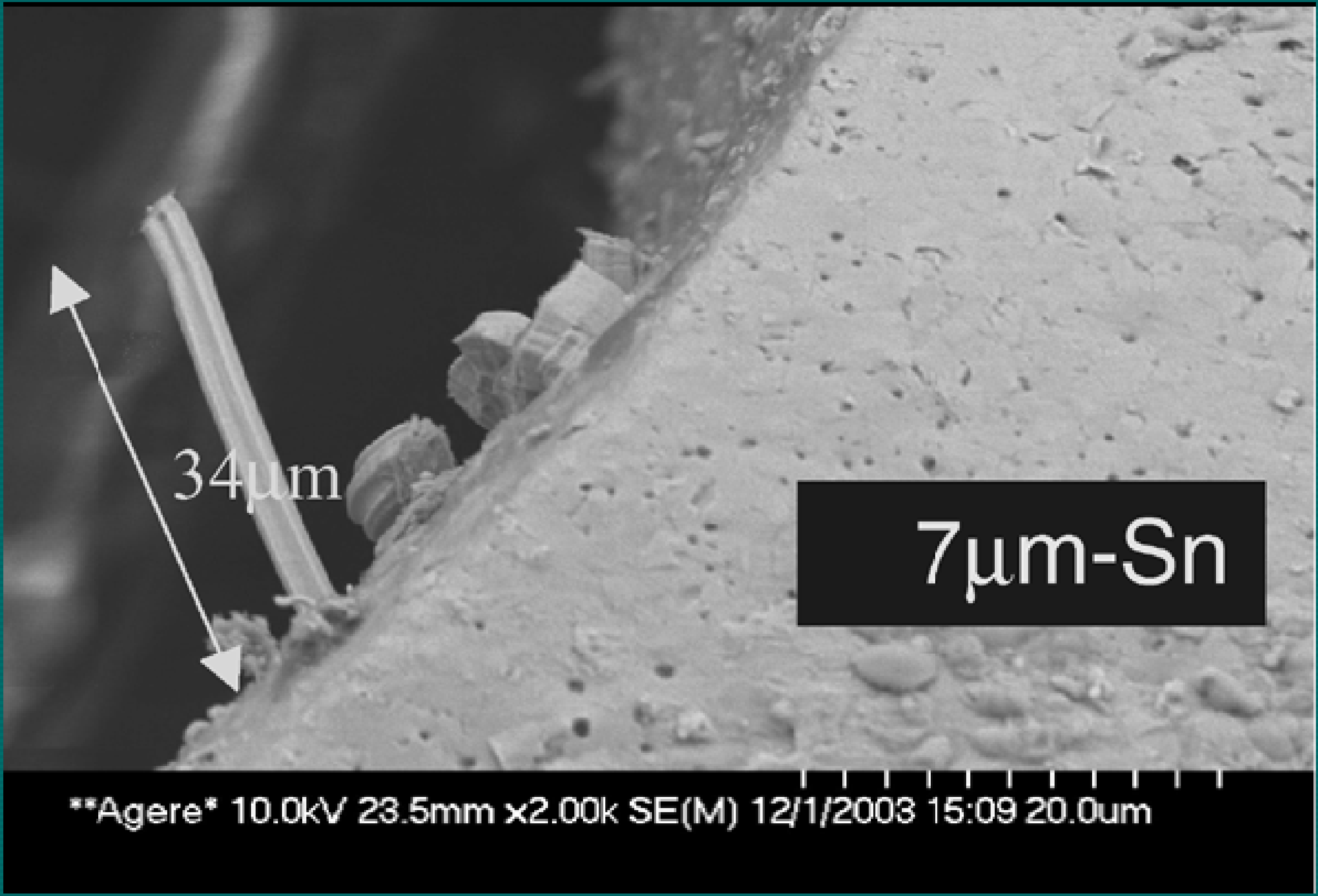

**Agere* 20.0kV 18.3mm x1.00k SE(M) 8/14/2


**Agere* 20.0kV 18.3mm x900 SE(M) 8/14/2003 17:22 50.0um


~ 64µm
**Agere* 10.0kV 26.1mm x1.00k SE(L) 1/16/2004 15:25 50.0um

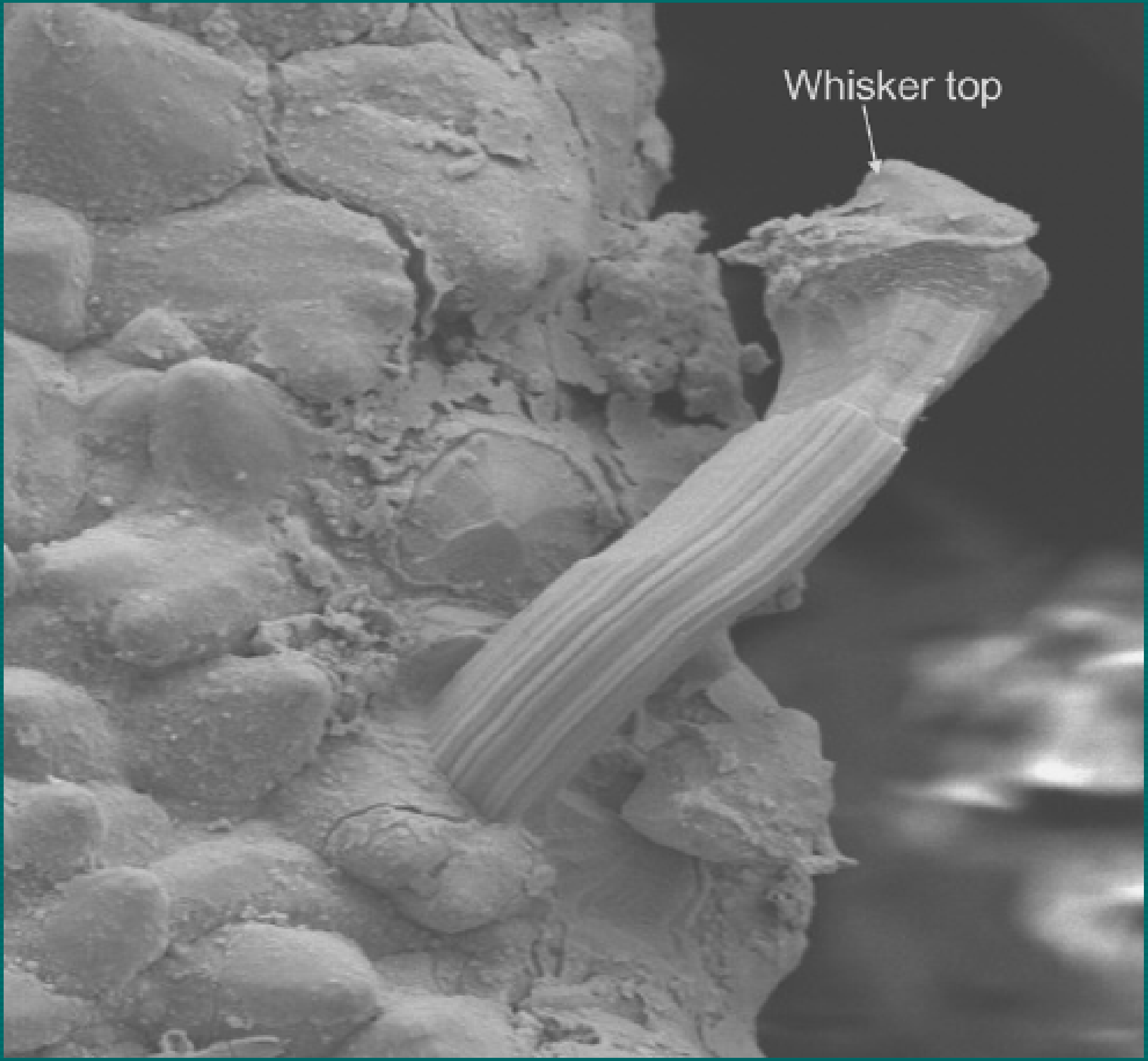

45µm
Possible break
**Agere* 10.0kV 26.9mm x1.80k SE(L) 2/13/2004 12:30 30.0um


27µm
15µm-Sn
Possible break
**Agere* 15.0kV 28.6mm x2.50k SE(M) 6/16/2004 12:19 20.0um


34µm
7µm-Sn
**Agere* 10.0kV 23.5mm x2.00k SE(M) 12/1/2003 15:09 20.0um

The whisker top appears to match almost perfectly the surface depression surrounding the whisker.

There appears to be a tear in the surface layer of the Sn film near the edge of the depression.



Tin whisker found after 26 weeks of aging at 60 °C/93%RH on a 15 μm-thick Sn on Cu plus post-plate 150 °C/1-h anneal

Whisker growth continues even a decade after initiation

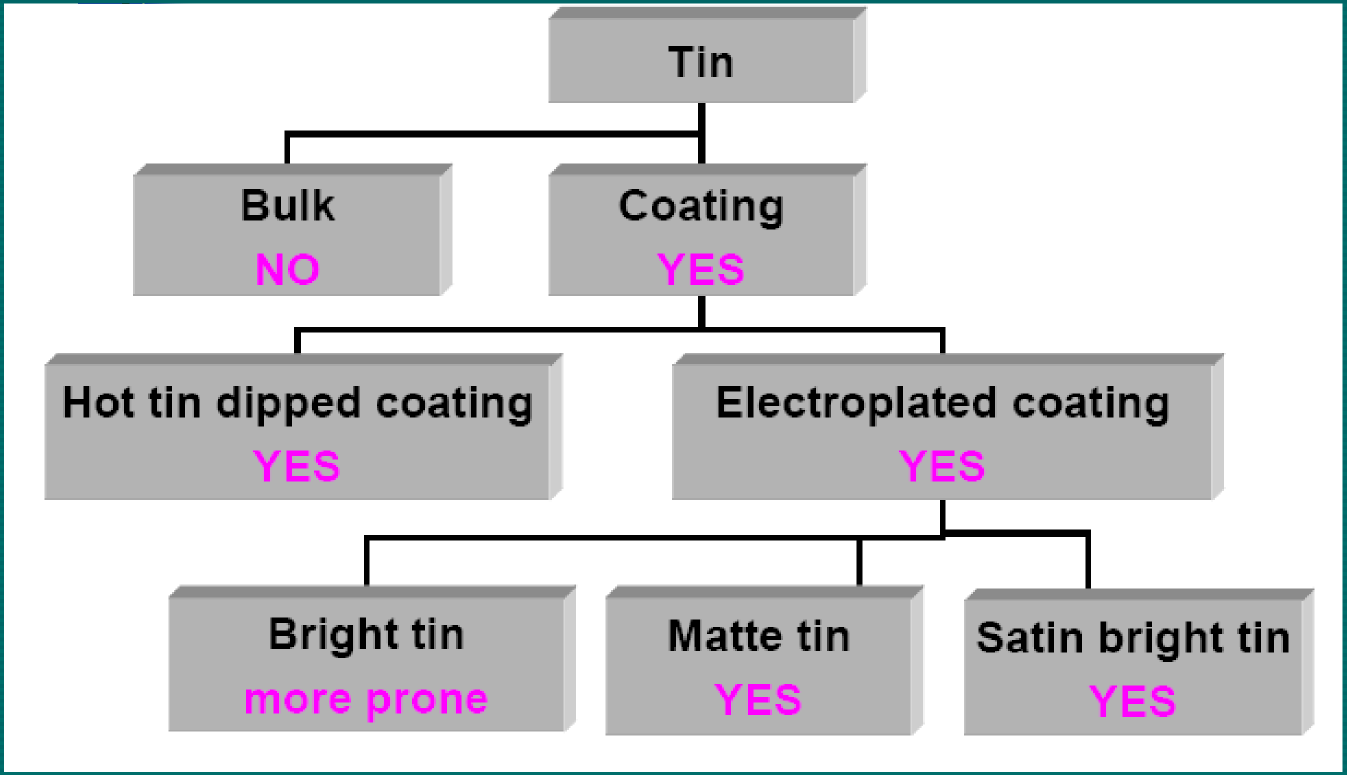
Source:

Whiskers – Is it really a problem?

Failures attributed to tin whiskers

Heart pacemaker	Tin whisker short from tin-plated case of a crystal component caused a complete loss of pacemaker output
F-15 Radar and Phoenix Air to Air Missile	Tin whisker short inside hybrid package
US Missile program	Tin whisker from tin plated relays and TO-3 transistor
Patriot Missile II	Tin whisker from tin plated terminals
Galaxy IV and Galaxy VII	Complete loss of satellite operation. Tin whisker short from tin plated relays
Nuclear utilities	Tin whiskers on contact support arms on relays that causes a resistive shunt path

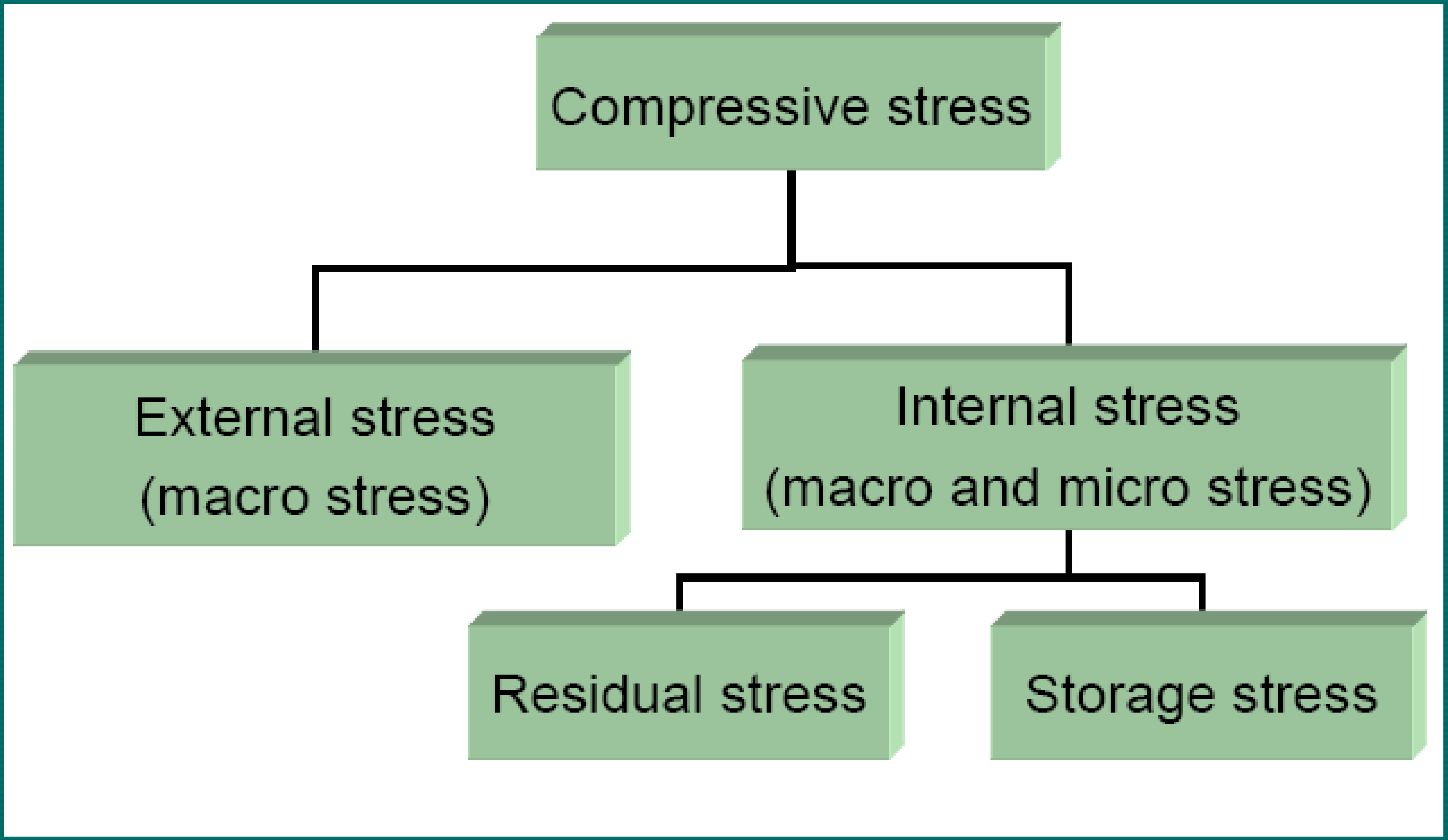
Where tin whiskers occur?



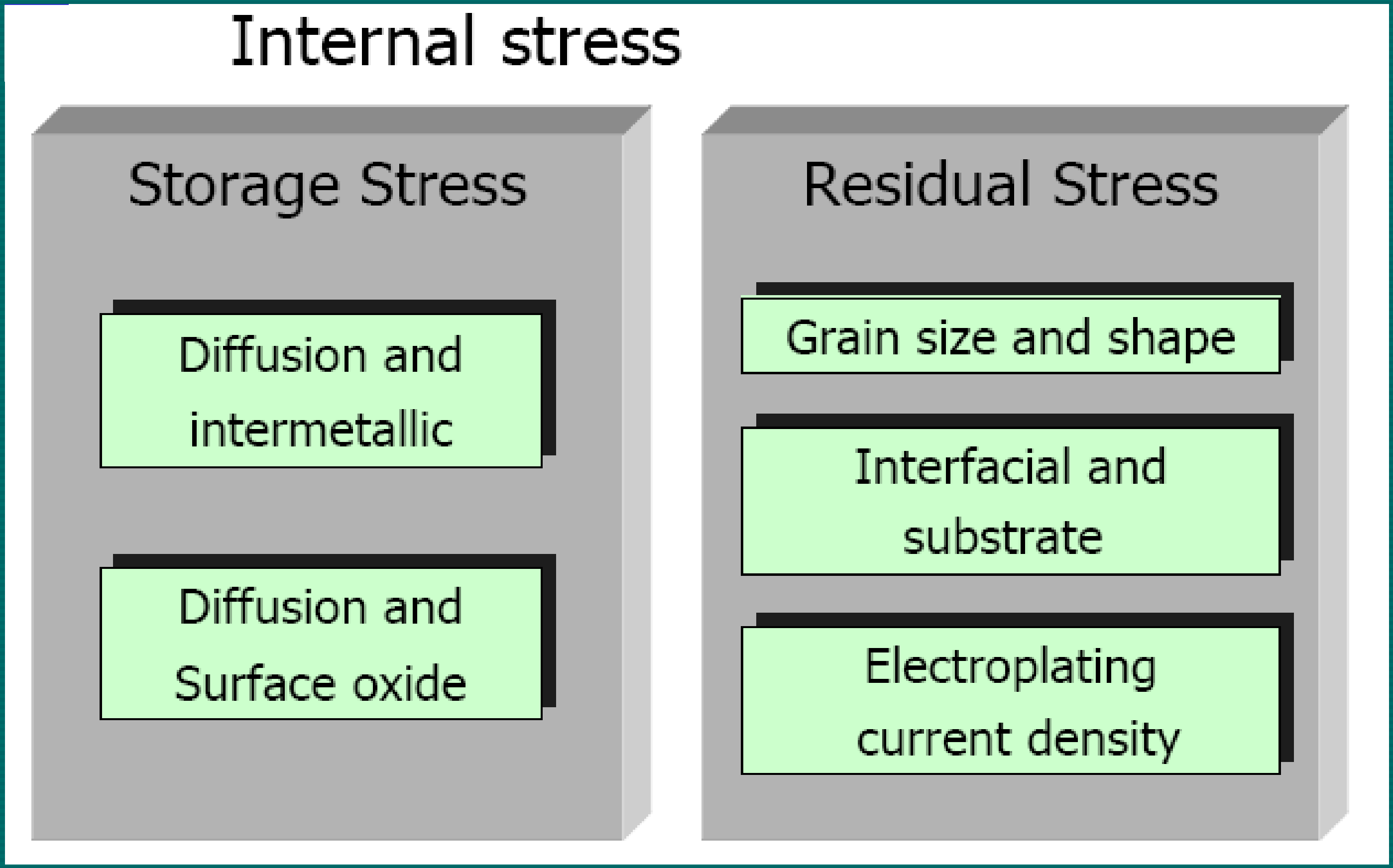
Thermodynamics and kinetics issues of tin whisker growth

- Thermodynamics
  - What is the driving force for tin whisker growth?
  - Why tin whiskers grow spontaneously?
  - ⊙ Compressive stress
- Kinetics
  - Growth rate - How fast do Sn whiskers grow?
  - ⊙ Various factors

Thermodynamic factors affecting Sn whisker growth



Thermodynamic factors affecting Sn whisker growth



Pathways for stress formation in electroplated Sn films

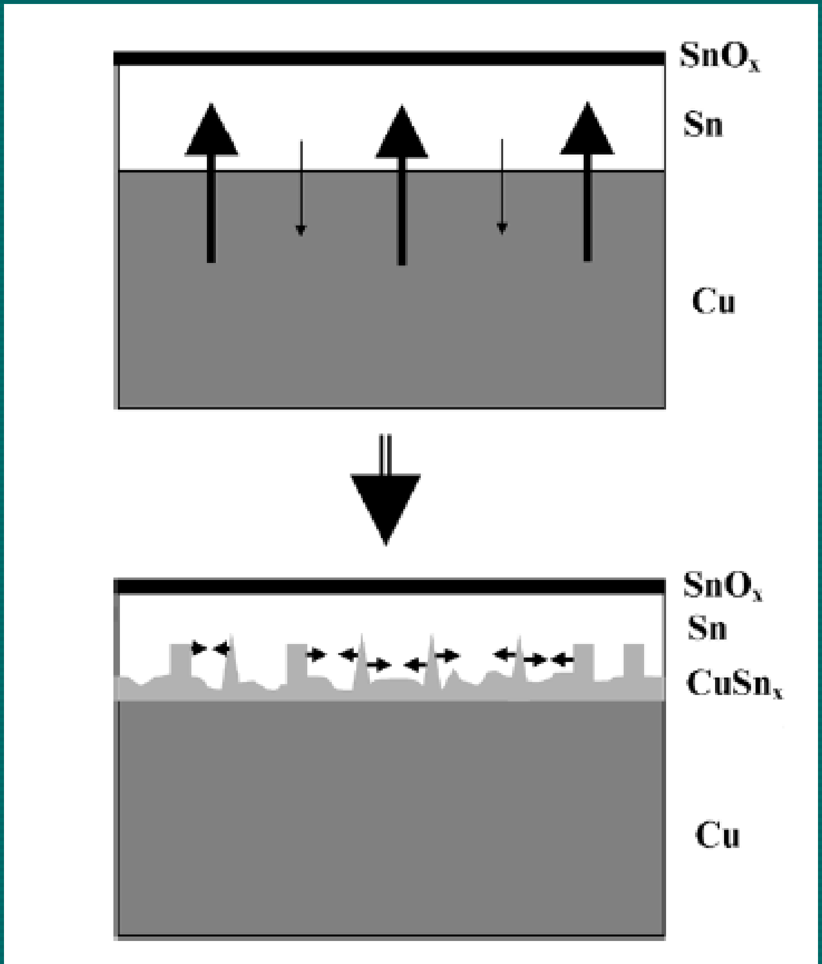
- Residual stress generated during plating
- Applied mechanical stress (e.g., mech. deformation)
- Stress formation due to interfacial reactions between Sn layer and Cu substrate
- Stress due to coefficient of thermal expansion mismatch between Sn layer and substrate during thermal cycling

Residual stress generated during plating

- Stress formation during electrodeposition can either be compressive or tensile in nature
- The nature of stress depends strongly on process chemistry
  - Type of additives used in the plating bath
  - Type of plating bath
  - Plating conditions
    - current density
    - temperature

Interfacial reactions between Sn layer and Cu substrate

- Both inter diffusion and intermetallic compounds (IMC) formation occur at the Cu–Sn interface.
- Inter diffusion occurs through bulk (vacancy and interstitial, slow), grain boundary (fast) and surface diffusion (crack or pores, very fast) pathways.
- Cu preferentially moving into Sn, whereas very little Sn moves into Cu
- IMC formation occurs directly at the Sn–Cu interface as well as in grain boundaries
- Depending on the temperature, both Cu_3Sn and Cu_6Sn_5 can be formed



Schematic illustration of inter diffusion and intermetallic formation at Sn–Cu

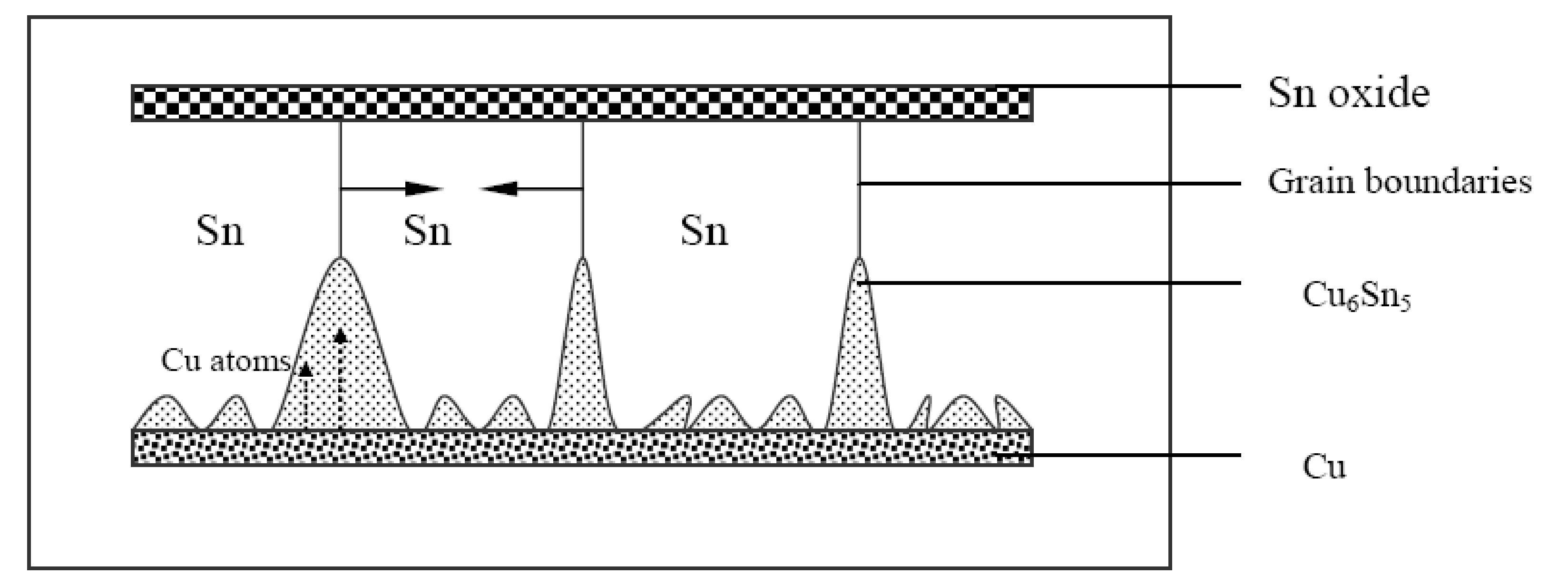
Stress generated due to the difference in coefficient of thermal expansion (CTE)

- Pure Sn – one of the highest linear CTE (22×10^{-6}/K)
- Cu - much lower linear CTE (16.5×10^{-6}/K)
- During thermal cycling of Sn plated Cu:
  - heating stage, Sn will expand more than the Cu substrate, which impose a compressive stress within the Sn film
  - cooling cycle, Sn will contract more than Cu, which will add a tensile stress to the Sn film
- Since the Sn coating expands or contracts differently than Cu, it undergoes alternating cycles compressive-tensile stresses

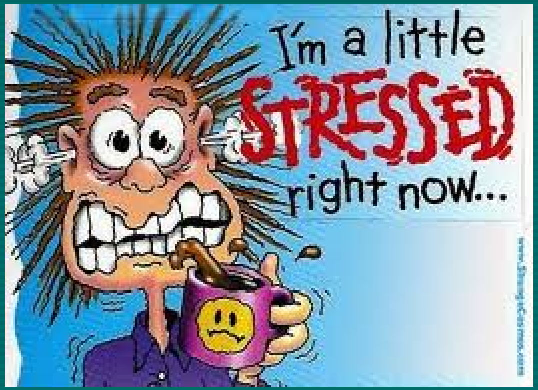
How tin whisker growth occurs?

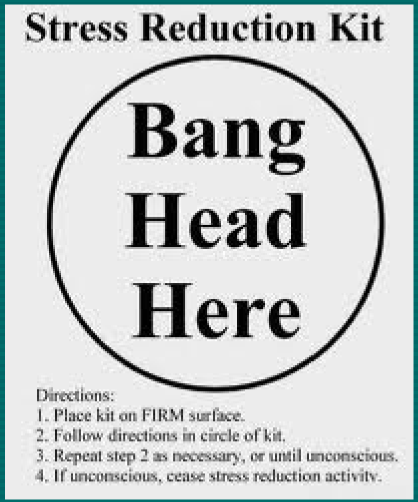
- Cu diffusion into the tin film grain boundaries combined with IMC formation at the Sn–Cu interface creates an excess of material that results in the generation of a compressive stress within the tin film.
- The presence of Sn oxide prevents this stress from being released
- This compressive stress increases with time, and in the presence of surface defects or strain mismatch, creates conditions required to break through the oxide layer
- Whisker growth – it is a way of reducing the stress generated with the system

How tin whisker growth occurs?



Any analogy with the real life situation on the ways we adopt to reduce the stress?





Mitigation strategies

Physical and electrical methods

- Removing a tin whisker by brushing it from the spot does not prevent it from further growth
- High voltage will electrically breakdown the whiskers

Alloying

- Tin whisker growth can be reduced by the addition of Pb (minimum 3%)
- Sn-Pb plating also exhibit whisker growth – length of the whisker – 20 μm
- No alloying replacement to prevent whisker growth

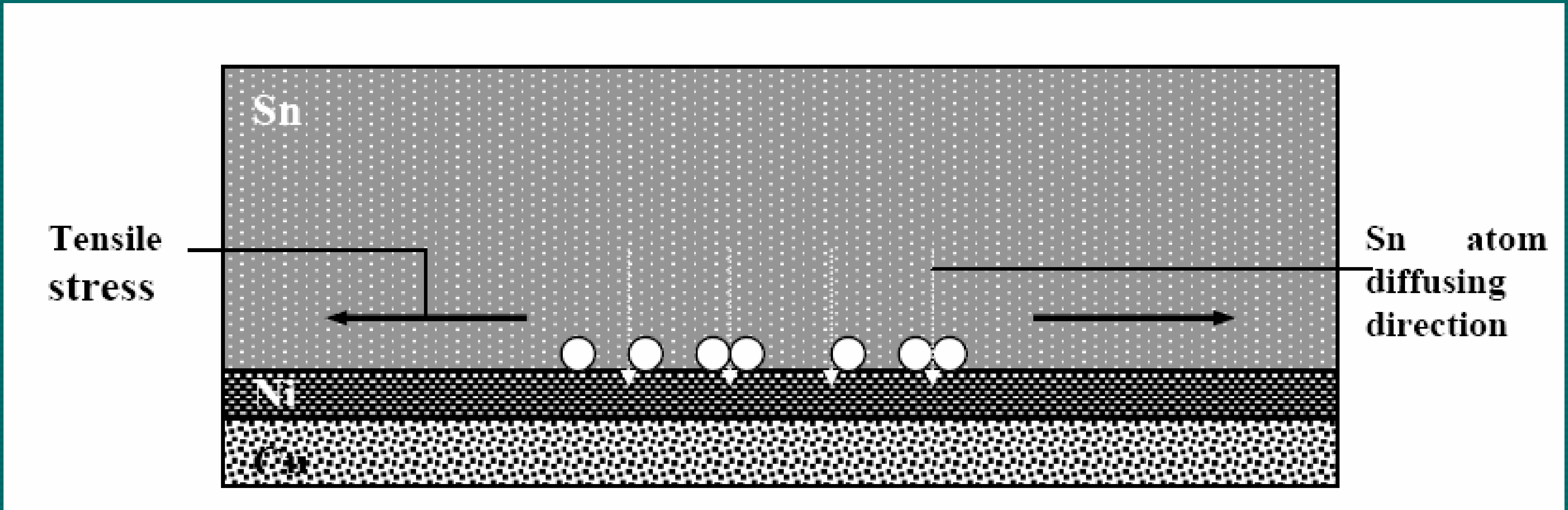
Mitigation strategies

Plating chemistry

- Manipulate plating chemistry to avoid compressive residual stress
  - ✓ Low carbon
  - ✓ Matte finish
  - ✓ Low as-plated stress
  - ✓ Optimized crystallographic orientation

Barrier layer/Reflow/conformal coating

- Use Ni as the barrier layer (min.1.27 μm thick)
- Ni also forms IMC with Sn – these IMCs induce tensile stress in the deposit
- Use reflowed tin – Not possible at all times
- Use thick conformal coatings – Parylene



Tensile Stress Built up in Sn Film by Diffusion of Sn Atoms into Ni Layer

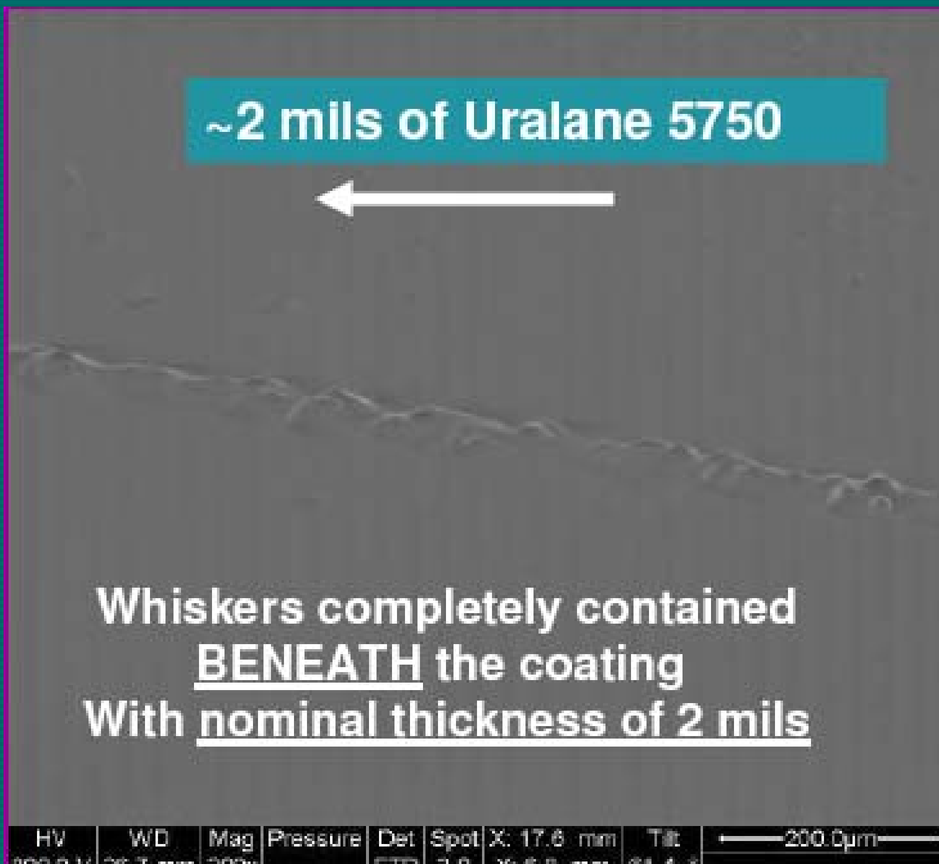
Whisker mitigation – Role of conformal coating

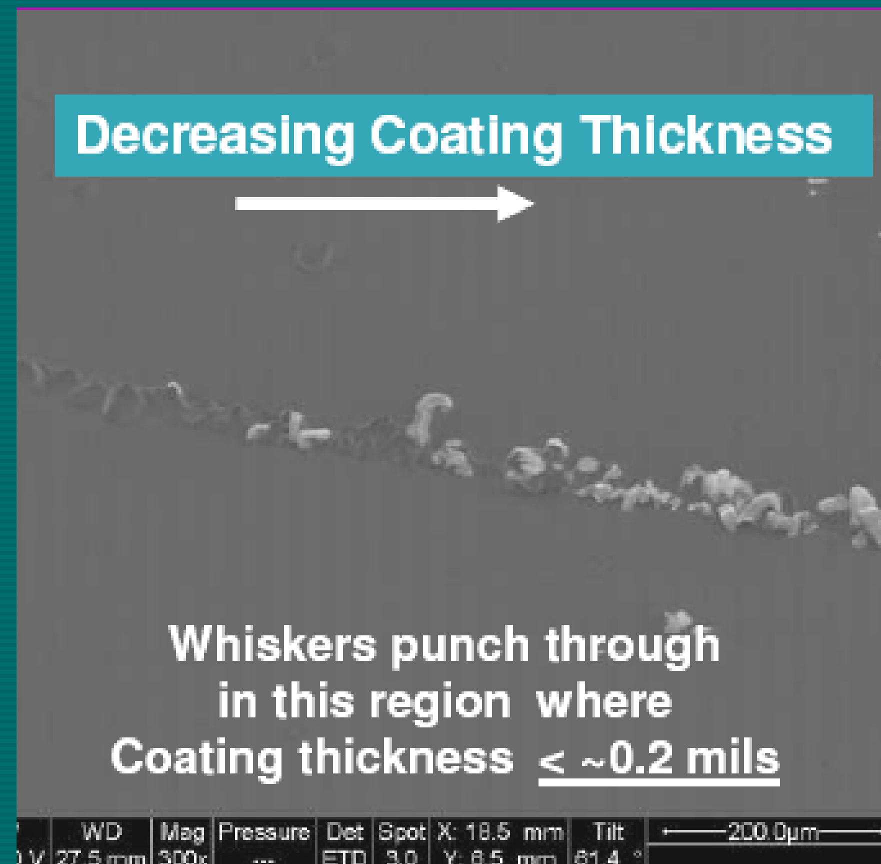
Observations after 9 Years at Ambient Storage conditions

Conformal Coated (Uralane 5750* Polyurethane)

Source:

Whisker Puncture vs. Coating Thickness

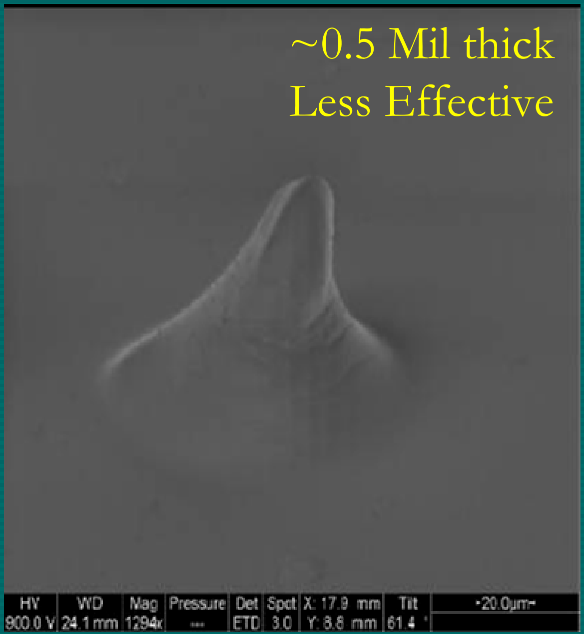




Source:

Performance of the Uralane 5750 Polyurethane Conformal Coating after 9-Years of storage at ambient conditions

Whiskers are breaking Through the "Thin" Coating

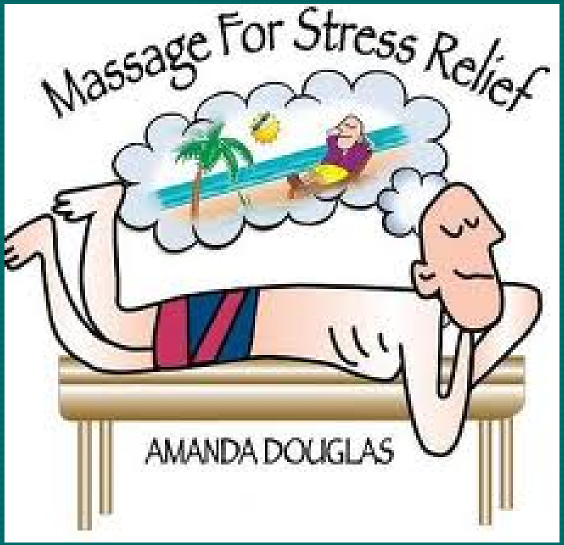


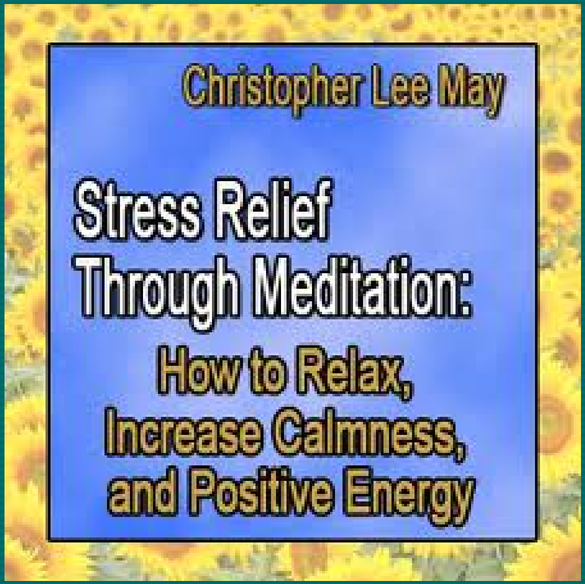
Whisker is Lifting the Coating like a Circus Tent; but Not Yet Penetrating

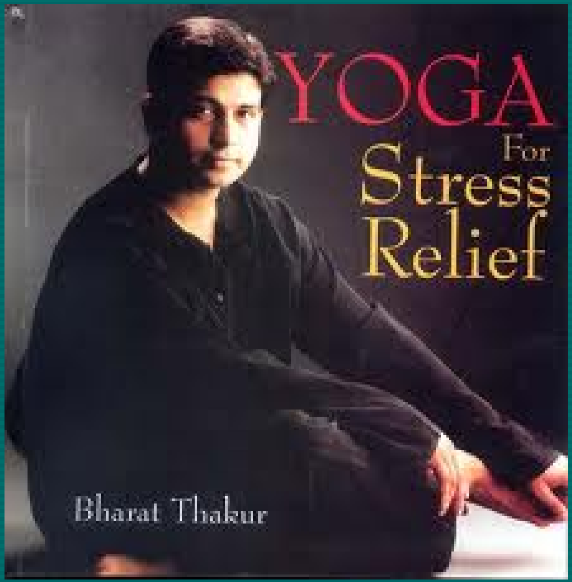
Whiskers are completely entrapped under the coating

Source:

The choices we have to relieve our stress







The choice for tin coating to relieve the compressive residual stress?

Thank you!