Tin Whiskers: The Unexplained Phenomenon

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November 5, 2003 10:00 am – 11:00 am (CST)





Tin & Lead Elimination

- Solderability and corrosion protection are main reasons why tin and tin/lead coatings are specified.
- Tin-lead is the only universally accepted "cure" for protection against whiskering.
- Pure tin and lead-free tin alloys are gaining market share as a way to eliminate lead. Tin has a propensity to whiskering.
 - "Tin whiskers" have the potential to cause electrical shorts as component miniaturization and pitch reduction continue.

Tin & Other Whiskering Phenomena

- Recent Studies have indicated that compressive stresses due to substrate stress and/or copper-tin intermetallic compound formation may provide the main driving forces for tin whisker growth.
- Whisker growth reported to occur in tin, cadmium, zinc, silver and many alloys.
- Whiskers have been found to grow from within the bulk of electro deposits and at the base metal interface.



Factors Reported to Influence Whisker Growth Intermetallic Compounds



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Examples of Tin Whiskers



















Examples of Tin Whiskers (cont'd)





Tin Whiskers

- Tin whiskers are single crystals, commonly 1-3 microns in diameter and several millimeters in length.
- Usually straight but can change direction.
- Can be solid, perforated or hollow.
- External surfaces often have striations.
 - Deep striations believed to be the boundaries of two whiskers growing together



Tin Whiskers (cont'd)

- Growth rates are highly variable. Grows more quickly at first, slows over time, and eventually stops completely.
- **Electrical resistance of 3 mm long whisker ~ 50 ohms.**
- **Current carrying capacity ~ 10 50 mA.**
- Yield strength approx.. 100 times that of wrought tin.





A Discussion of the Significance of Metal Whisker Formation to the High Reliability Community



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Outline

- What are Metal Whiskers (Tin and Zinc)?
- Why Are Metal Whiskers A Concern?
 - Failure Modes
 - Limited Fundamental Understanding
- Metal Whisker Problems-PRACTICAL Examples
 - Tin Whiskers!
 - TIN-LEAD WHISKERS!!
 - ZINC WHISKERS!!! Beware Your Raised Floor Systems
- Whisker Mitigation Strategies for USERS?
- Conclusions & Recommendations

Cover Photo: Zinc Whiskers on Zinc-Plated Steel Raised Floor Structures N-

13

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What are Tin (and Zinc) Whiskers?

- "Hair-Like" Single Crystal Structures that May Grow from mostly pure Tin (or Zinc) Finished Surfaces
- LENGTH: Up to 10 mm
 (Typically < 1mm)
- DIAMETER: from 0.006 to 10 mm (Typical ~ 1 mm)
- Grow from the Base Not the Tip
- Growth Mechanism(s): UNKNOWN! Diffusion Processes within Finish or on Surface are likely involved, but what drives diffusion into specific grains and then launches them OUT from surface?

Fundamental Research is INCOMPLETE

Whiskers are <u>NOT</u> Dendrites



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Metal Whisker Shapes & Features



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Sneaky Metal Whiskers!!!

Incubation Period

Initiation of growths may occur after <u>MANY YEARS</u> of Dormancy

Growth Rate

Variable ! Sometimes Fast... Sometimes VERY SLOW





Inspection is DIFFICULT

Often INVISIBLE under Low Mag Device Handling Can Hide Evidence Sometimes Forests of Growths, Sometimes"Needle in a Hay Stack"



Challenges This Poses for Many Hi-Rel Applications

- Long Application Life (5, 10, 20 or 30 YEARS)
- Application May Not Be Field Serviceable (e.g., Space)
- Only One Chance for Success (e.g., Military, Space)





Factors that "May" Influence Metal Whisker Growth

	Plating Chemistry Pure Sn Most Prone Some Alloys (Sn-Cu, Sn-Bi Use of "Brighteners" Incorporated Hydrogen Codeposited Carbon pH	, rarely Sn-Pb) In Genera Eactors th	Materia Substra Interme Substra	Substrate al (Brass, Cu, Alloy 42, Steel, etc.) ate Stress (Stamped, Etched, Annealed) etallic Compound Formation ate Element Diffusivity into Sn		
		Increase STRE Promote DIFF Within the De GREATE WHISKE PROPENS	ESS or USION eposit R R ITY	Environment Temperature Temperature Cycling (CTE Mismatch) Humidity (Oxidation, Corrosion) Applied External Stress (Fasteners, bending, scratches) Current Flow or Electric Potential???		
HOWEVER						

Many Experiments Show Contradictory Results For These Factors



Converging Issues Fuel Hi-Rel User Concerns

The PAST:

- Metal (Sn, Zn, Cd, other) Whiskers Known for ~60 Years
- HUNDREDS of Independent Studies of TIN Whiskers Alone
- Numerous "Disparities" Exist in Published Literature
- The PRESENT: Combination of CONCERNING Factors

Electronics Industry Conversion to Pure Tin Finishes Due to Pending Pb-Free Legislation

Lower Application Voltages

SMALLER Circuit Geometries

No Consensus Understanding of Whisker Growth Mechanism(s)

> No "Accepted" Accelerated Whisker Tests

"CONTINUING" Discoveries of Whisker-Prone Items



Whisker Failure Modes

Electrical Short Circuits

- Permanent (if current < 10's of mA)
- Intermittent (if current > 10's of mA) Whisker Melts

Debris/Contamination

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- Interfere with Sensitive Optics or MEMS
- Shorts in Areas REMOTE From Whisker Origins (Zinc Whiskers on raised flooring are a PRIME Example)

METAL VAPOR ARC

- Under Some Electrical/Atmospheric Conditions, Whisker Shorts May Vaporize into Conductive PLASMA of Metal Ions
- Plasma Forms Arc Capable of Carrying <u>HUNDREDS OF AMPS!</u> <u>With Resulting CATASTROPHIC DAMAGE</u>









A "Few" Reported Metal Whisker Problems (Only the Last 15-20 Years Considered)

		Year**	Application	Industry	Failure Cause	Whiskers on?
ernth	1	19 <mark>86</mark>	Heart Pacemakers	Medical (RECALL)	Tin Whiskers	Crystal Can
6	2	1986	MIL Aircraft Radar	Military	Tin Whiskers	Hybrid Package Lid
1 m	3	1987	MIL/Aerospace PWB	MIL/Aerospace	Tin Whiskers	PWB traces
	4	1988	Missile Program "A"	Military	Tin Whiskers	Relays
	5	1989	Missile Program "B"	Military	Tin Whiskers	Electronics Enclosure
1	6	1990	Apnea Monitors	Medical (RECALL)	ZINC Whiskers	Rotary Switch
	7	1992	Missile Program "C"	Military	Tin Whiskers	Xsistor Package +Standoff
1	8	1993	Govt. Electronics	Govt. Systems	Tin Whiskers	Transistor, Diode, Lug
	9	1995	Telecom Equipment	Telecom	ZINC Whiskers	Framework
	10	1996	Computer Routers	Computers	ZINC Whiskers	Chassis
	11	1996	MIL Aerospace	MIL Aerospace	Tin Whiskers	Relays
	12	1998	Aerospace Electronics	Space	Tin Whiskers	Hybrid Package Lid
7	13	1998	Commercial Satellite #1	Space (Complete Loss)	Tin Whiskers	Relays
A	14	1998	Commercial Satellite #2	Space	Tin Whiskers	Relays
	15	1998	Commercial Satellite #3	Space	Tin Whiskers	Relays
	16	1998	Computer Hardware	Computers	ZINC Whiskers	Chassis
	17	1998	Military Aerospace	Military Aerospace	Tin Whiskers	Plastic Film Capacitor
	18	1999	Eng Computer Center	Architectural	ZINC Whiskers	Floor Tiles
	19	199X	Telecom Equipment	Telecom	ZINC Whiskers	PSU Housing
1	20	2000	Missile Program "D"	Military	Tin Whiskers	Terminals
	21	2000	Commercial Satellite #4	Space (Complete Loss)	Tin Whiskers	Relays

Many of these Incidents Involve "Multiple" Failures

17

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A "Few" MORE Reported Metal Whisker Issues

(Only the Last 15-20 Years Considered)

	100,500,500 200	Year**	Application	Industry	Failure Cause	Whiskers on?
2	2	2000	Commercial Satellite #5	Space (Complete Loss)	Tin Whiskers	Relays
2	3	2000	Power Mgmt Modules	Industrial	Tin Whiskers	Connectors
2	4	2001	Commercial Satellite #6	Space	Tin Whiskers	Relays
2	5	2001	Space Ground Test Eqpt	Ground Support	ZINC Whiskers	Bus Rail
2	6	2001	Nuclear Power Plant	Power	Tin Whiskers	Relays
2	7	2001	Hi-Rel	Hi-Rel	Tin Whiskers	Ceramic Chip Caps
2	8	2002	Commercial Satellite #7	Space	Tin Whiskers	Relays
2 2	9	2002	Military Aircraft	Military	Tin Whiskers	Relays
3	0	2002	Electric Power Plant	Power	Tin Whiskers	Microcircuit Leads
3	1	2002	Hospital Computer Center	Medical	ZINC Whiskers	Tiles More Abo
/ 3	2	2002	Govt Computer Center	Commercial	ZINC Whisker: Floor	Tiles This Cond
3	3	2002	E-Comm. Comp Center	Commercial	ZINC Whiskers Floor	Tiles
3	4	2002	Library Computer Center	Public Service	ZINC Whiskers Floor	Tiles
3	5	2002	GPS Receiver	Aeronautical	Tin Whiskers	sure
3	6	2002	MIL Aerospace	MIL Aerospace	Tin Whiskers	Mountil lardware (nuts)
3	7	2002	Commercial Electronics	Power Supply	ZINC Whiskers	Mounting dware
3	8	2003	Commercial Electronics	Telecom	Tin Whiskers	RF Enclosu
3	9	2003	Telecom Equipment	Telecom	Tin Whiskers	Ckt Breaker
4	0	2003	NASA Data Center	Ground Support	ZINC Whiskers	Floor Tiles
4	1	2003	Missile Program "E"	Military	Tin Whiskers	Connectors
4	2	2003	Missile Program "F"	Military	Tin Whiskers	Relays



NOT Just a Problem of "The Past"

About

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Microcircuit Leads

("Matte" Tin-Plated)

Observed in 2002

Pin #7

Pin #6

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ASSO ELECT Whiskers from this Component Caused a FAILURE in the Electric Power Utility Industry > 20 YEARS!!! After Fielding the System

Hybrid Microcircuit Package Lid (Pure Tin-Plated) Observed in 1998

Whiskers up to 2 mm Long Found Growing INSIDE Package

> Whiskers Like these Reportedly Have Broken Loose Inside Hybrids Creating Intermittent Shorts/Field Failures

> > INSIDE

1 mm

40.0×

Exterior Surfaces of Electromagnetic Relays (Tin-Plated Terminals, Case, Header)

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Whisker Shorts Between Terminal to Terminal, Terminal to Header, Case to Other Component, Whisker to Whisker!!!

<u>INTERIOR</u> Surfaces of <u>Electromagnetic Relays</u> (*Tin-Plated Steel Armature*) ~14 Years Old Observed in 2002



Beware What May be <u>INSIDE</u> your Devices (Up to 3 mm Long Found in This Part)

и од о <u>риат</u>0= 22 10/08/02 CRP Examples of Components with Tin Whiskers



L= SE1

Ceramic Chip Capacitor (Pure Tin-Plate Over Nickel Terminations) **Observed in 2001**

> **Conductive Epoxy Mounted** Inside Hermetically Sealed Hybrid

Whiskers appeared AFTER Thermal Cycle -40°C / +90°C (~200 Cycles Shown Here)



Terminal Lugs Pure Tin-Plated ("AS-RECEIVED"/ Observed in 2001)



Whiskers up to 0.25 mm Long Inside Crimp Barrel And in the Exterior Seam

EHT- 20.0 KV WD= 26 mm MAG= X 1.50 K PHOTO= 1 20 Examples of Components with Tin Whiskers





L- SE1

Do Whisker "Free" Tin (or Zinc) Coatings Exist?

Answer

Most Likely "YES"!

Caveats

How Can One Judge Propensity?

Without Validated Fundamental Models of Growth Mechanism,

- For How Long Will it be Whisker-Free?
- Under What Use Conditions? Environment? Mechanical Stress?
- Will "Subtle" Day to Day Process Variations in My Supplier's Recipe Affect Whisker Propensity?



A Few Words About Tin-Lead (Sn/Pb) Whiskers

Sn/Pb Whiskers on

Reflowed Sn63/Pb37

- Sn-Pb Finishes CAN Grow Whiskers, BUT...
 - Typical Lengths 5 15 microns which TODAY are Generally Benign
- Why might Pb "Inhibit" Whisker Formation?
 - Pb has low solubility in Sn (<1%)
 - Almost all Pb collects in Sn grain boundaries
 - Pb in grain boundaries may Limit Sn Diffusion

But Sometimes Even SMALL Sn/Pb Whiskers

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Results

Pb peak

Sn peak

Sn peak

Sn peak

Sn peak

Pb⁻peak

A Bonafide Sn-Pb Whisker Induced Short

Whiskers from <u>REFLOWED Sn-Pb Eutectic Solder</u> (Sn63Pb37) Min. Shorting Distance = <u>3 microns Heat Sink to Semiconductor</u>

Is THIS the Melted Tip of what was once a Longer Sn-Pb Whisker?

Heat Sink

10 microns

Sn/Pb Solder Die Attach



"Splatter" Remants from a Melted Sn-Pb Whisker?

Semiconductor

Insulator

A Word or Two About One of Our Most Recent Whisker Concerns ZINC Whiskers on Raised Floor Structures

Zinc-Plated Steel Underside of Floor Tile

Typical "Raised" Floor Computer Room

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Zinc Whisker or Tin Whisker?

Striking Similarities



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Zinc Whisker or Tin Whisker?

Striking Similarities



Steel Substrate

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Conclusions

Failures Due to Metal Whiskers are <u>STILL</u> a Significant Problem

PROBLEMS WILL INCREASE with Increased Use of Mostly Pure Tin and Zinc Coatings Until Significant Discoveries are Made Regarding Effective Mitigation Practices

Factors Affecting Tin Whisker Formation are NOT Completely Understood



Influence of Individual Variables (Multi-Variable Interactions) Not Well-Understood Control of Variables for Experimentation is Very Complex Risk Assessment Based on <u>SUBSET</u> of Published Literature Can Be <u>DANGEROUS</u>



Recommendations

Develop CONSENSUS Model(s) of Whisker Growth Mechanism(s)

- **Comprehensive Model(s) for Tin, Zinc <u>AND</u> Cadmium Whiskers**
 - Models that Hinge upon Unique Attributes of One vs. the Others May be Off the Mark
 - Models should also explain why many finishes appear to "not" be whisker prone
- Accepted Model Needed to have "Confidence" in Any Proposed Accelerated Test

Develop PROVEN "Whisker Propensity" Test(s)

- Fundamental Theory FIRST, then test/validate Theory... THEN develop Whisker Propensity Tests! -- <u>This is COUNTER to Pb-Free NOW Movement!</u>
- Environmental Testing vs. Finish Attributes? (grain size, orientation, etc.)
- Acceleration Factors MUST be Determined for Reliability Prediction
- Tailorable to Assess Varied Constructions, Materials AND Applications



Recommendations

Share Whisker Experiences and Knowledge More OPENLY

- Education vs. MIS-Information
- **Cooperative Collaboration** Amongst Developers, Makers, Users

Develop Whisker Risk Assessment & Mitigation Strategies

- Plating Chemistry/Process Suppliers
- Component Mfrs
- Electronics System Assemblers
 - End Users





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Acknowledgments: NASA Goddard Metal Whisker Investigation Team

Mike Sampson Dr. Henning Leidecker Jong Kadesch

NASA Goddard NASA Goddard Orbital Sciences Corporation

NASA Goddard Tin (and Other Metal) Whisker WWW Site

http://nepp.nasa.gov/whisker



Time for Questions??



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L- SE1 EHT-2.00 KV HD-37 mm 50.0µm SN 5Cu 8/30/99 MAG= X 800. PHOTO= 6 .00of robe Rate Scans/L htness rast lecto

38

Backup Material



User Whisker Mitigation

Research on User-Mitigation Strategies is Limited

- Most Approaches Come with Benefits & <u>Limitations</u>
- Long-Term Effectiveness NOT Quantified

Strategies to Consider (Apparently Beneficial but Not Qualified)

- REDUCE STRESS in the Metal Plating
 - Hot Oil Reflow / Hot Solder Dip (Preferably with Sn/Pb Solder)
 - High Temp Anneal Substrate and Finish
 - Underplate with Diffusion Resistant Barrier May Delay Onset
- USE PHYSICAL BARRIERS to Insulate Against Potential Shorts
 - Conformal Coat or other Insulating Barriers
 - Increase Spacing of Surfaces of Opposite Polarity to > 0.5 inches
- MINIMIZE REINTRODUCING STRESS thru Handling, Assembly & Application

Combine MULTIPLE Mitigation Strategies to Increase Effectiveness

AVOID PURE TIN or ZINC, if Possible

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Whisker Mitigation

Conformal Coat (Urelane 5750 Polyurethane)

NASA Goddard Experiments (>3 Years Observation at 50°C & Room Ambient)

- NO Whiskers THRU 50 mm Thick Uralane 5750
- Conformal Coat REDUCES (but does NOT Eliminate)
 Rate of Whisker Growth Compared to Uncoated Specimen
- Whiskers Have Grown thru ~2 to 6 mm THIN Uralane 5750 After 2.5 Years of Ambient Storage

Whisker Nodule BENEATH 50 μm thick Conformal Coat

Bright" Tin-Plated Brass Substrate

Whisker Escapes thru <u>THIN</u> (~2 to 6 μm thick) Conformal Coat

Some LIMITATIONS of Mitigation Strategies--Hot Solder Dip



Some LIMITATIONS of Mitigation Strategies--Conformal Coat



- Air Bubbles Enable Path For Whisker Shorts??
- Can You Cover Underside of Flush Mount Devices??
- Can You Control Uniformity of Coverage/Thickness??





Plating Processes Subcommittee (4-14) Immersion Tin Specification, IPC-4554 (in progress)

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44