Effects of Tin Mitigation Processes on Whisker Growth and Solder Joint Reliability for Chip and Small-Outline Package Components

Tom Lesniewski

Northrop Grumman Network Communications Division
San Diego, CA 92128
Topics

• Study Overview
  – Objectives and Test Plan
  – Variables and Components Covered
  – Pass/Fail Criteria

• Results & Discussion

• Conclusions & Recommendations
Objectives—to answer these questions

• What is the risk for tin whisker growth?
• Do tin mitigation processes introduce mechanical damage or degradation to the parts?
• Are tin mitigation processes effective in reducing or preventing tin whisker growth?
• Are the quality and reliability of the solder joints affected by tin mitigation processes?
What is “Tin Mitigation”?

• Process or action that results in decreased risk for failure caused by tin whiskers
• Examples: find substitute parts, replace tin material, encapsulate
• In this paper, tin mitigation refers to the act of replacing pure tin layer with tin-lead
  – 2 processes: solder dip to component body or Pb addition
Test Plan

Baseline – visual inspection, SEM/EDX to verify pure tin

Tin mitigation process

Post-process evaluation – visual inspection, SEM/EDX, cross section

Install on PWB

Temp cycle & constant temp/humidity (JESD) tests

Post-test evaluation – visual inspection, SEM/EDX, Xray, electrical test (module)
Variables tested

- 19 different component PNs in 8 part “families”
- Component finish: lead-free (pure tin, SnBi, NiPdAu, flash gold) vs. tin mitigated (SnPb)
- 3 tin mitigation process suppliers
- PWB materials: epoxy/glass and teflon based
- PWB pad finishes: immersion silver vs. electroless nickel-immersion gold (ENIG)
- Solder reflow environment: air vs. nitrogen environment
- Conformal coating (urethane) vs. no conformal coat
### Types of Components tested

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Description</th>
<th>Termination Materials/ Finish</th>
<th>Mitigation Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSSOP</td>
<td>48-leads, plastic gullwing flatpack</td>
<td>Copper leads, matte tin plating</td>
<td></td>
</tr>
<tr>
<td>PLCC</td>
<td>32 J-leads, plastic surface mount QFP</td>
<td>Copper or Kovar/Alloy 42 leads, matte tin plating</td>
<td>Sn63 solder dip</td>
</tr>
<tr>
<td>SOT23</td>
<td>3 leads plastic surface mount package</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DFN8</td>
<td>8 lead, plastic sfc mount pkg</td>
<td>Copper leads, matte tin plating</td>
<td></td>
</tr>
<tr>
<td>QFN64</td>
<td>64 lead frame chip scale pkg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0402 chip</td>
<td>Ceramic capacitor</td>
<td>Nickel barrier, pure tin</td>
<td></td>
</tr>
<tr>
<td>1206 chip</td>
<td>Ceramic capacitor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0402 chip</td>
<td>Ceramic resistor</td>
<td>Silver thick film metallization, nickel barrier, pure tin</td>
<td>Sn63 solder dip</td>
</tr>
<tr>
<td>1206 chip</td>
<td>Ceramic resistor</td>
<td>Phosphor bronze leads, pure tin with light gold on contact areas</td>
<td>Sn63 solder dip</td>
</tr>
<tr>
<td>Connector</td>
<td>125 pin plastic surface mount</td>
<td>Pure tin &amp; AgPd finish</td>
<td></td>
</tr>
<tr>
<td>1206 chip</td>
<td>Ceramic filter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOIC</td>
<td>6 pin plastic GaAs MMIC switch</td>
<td>Plastic minimold, SnBi finish</td>
<td>None</td>
</tr>
<tr>
<td>SOIC</td>
<td>48 pin plastic surface mount</td>
<td>NiPdAu</td>
<td>None</td>
</tr>
<tr>
<td>QFN</td>
<td>12 pin plastic GaAs MMIC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT23 &amp;343</td>
<td>3 or 4 leads, plastic package</td>
<td>Pure tin finish</td>
<td>None--pure tin control</td>
</tr>
<tr>
<td>LPCC</td>
<td>8 lead plastic package</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large module</td>
<td>Encapsulated surface mount DC-DC converter module</td>
<td>External pins SnPb, internal components pure tin plated</td>
<td>None</td>
</tr>
<tr>
<td>BGA</td>
<td>256 ball plastic encapsulated</td>
<td>SnAgCu balls, underlayers: Ni = 5-10µm, Au = 0.5µm min Cu = 35µm</td>
<td>Reballed with SnPb</td>
</tr>
</tbody>
</table>
Test article

- CCA with up to 32 leadless surface mount chip components, 9 multi-leaded surface mount components and one surface mount connector.
- No through-hole components
- PWB was 3”x4” in size and 0.032” thick with 2 layers
- Pad patterns and materials were representative of JSF PWBs
- Pure tin and other lead-free parts tested without mitigation
- CCAs built at 2 locations (air and nitrogen purged ovens); 30 submitted for testing
Evaluation of Parts before & after solder dip
Why dip all the way to the component body?

Tin whiskers on incompletely dipped IC components
Pre-test evaluation

Tin whisker on PLCC component prior to solder dip
Post solder dip, pre-test evaluation

Cross section of SOT23 component after solder dip—excessive solder
Post solder dip, pre-test evaluation

Cross section of TSSOP lead after solder dip—no residual tin
Cross section of SOT23 lead after solder dip—no perceptible residual tin

Tin-lead solder

SOT23 lead--Kovar
Post solder dip, pre-test evaluation

Cross section of PLCC/J leads shows no damage or delamination but some cases of excessive solder
Post solder dip, pre-test evaluation

SEM examination of TSSOP showed no damage at lead egress. EDX was consistent with Sn63.
Post solder dip, pre-test evaluation

Cross section of ceramic chip part shows no cracks or damage to ceramic. Minimal solder coverage at corners—possible solderability issue
Post solder dip, Pre-test evaluation

Area where connector leads are housed in plastic—very difficult to replace tin coating with SnPb after connector has been built.

Pure tin surfaces on connector leads were not fully mitigated due to lead/body configuration.

Another concern: solder may wick up onto contact surfaces.
Post solder dip, Pre-test evaluation

Tantalum capacitor with “wrap-around lead configuration”

EDX analysis of pulled back leads revealed that solder dipped part had incomplete solder coverage

Tin surfaces on wrap-around leads of “low profile” capacitors were not fully mitigated due to tight of space between lead & body

“Pb addition” process yielded Pb across all surfaces of leads
Post solder dip, pre-test evaluation

Lighter areas = Sn

Darker areas = Pb

SEM image of chip part after Pb addition—segregated tin/lead
Evaluation of tin whisker growth after CCA installation and environmental test
Pre-test evaluation

- All baselined PLCC, TSSOP, SOT23, chip parts were pure tin.
- Tin whiskers observed on PLCC and TSSOP baseline parts.
- Largest whisker on baseline parts was about 40 µm long.
- Damaged, poor plating/coating quality was observed on connectors, 0402, 1206, PLCC & SOT23 components.
- On PLCC, TSSOP, SOT23 and chip parts mitigated by solder dipping, pure tin material was completely removed and replaced with SnPb.
- No mechanical damage such as internal cracks, discoloration or delamination, was observed on the tin-mitigated parts.
- Solder dipping does not completely remove pure tin from “low profile” leaded components or connectors.
- Some parts showed excessive solder on the leads after the solder dipping process.
JESD201 defines 4 classes of hardware:

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Guidelines on Pure Tin Usage</th>
<th>Max. Tin Whisker</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Mission/Life Critical applications such as military, aerospace and medical.</td>
<td>Pure tin and high tin alloys are typically not allowed or acceptable</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Business Critical applications such as telecom infrastructure, high-end servers, automotive</td>
<td>Tin whisker mitigation practice is expected. Long product lifetimes and minimal down time required.</td>
<td>40 to 45 µm</td>
</tr>
<tr>
<td>1</td>
<td>Industrial/consumer products with medium lifetimes.</td>
<td>Medium product lifetime, no major concern with tin whiskers breaking off</td>
<td>50 to 100 µm</td>
</tr>
<tr>
<td>1A</td>
<td>Consumer products with short lifetimes</td>
<td>Short product lifetimes, minimal concern with tin whiskers breaking off</td>
<td>50 to 75 µm</td>
</tr>
</tbody>
</table>
## Test & Inspection Conditions

<table>
<thead>
<tr>
<th>Category Description</th>
<th>Details</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test Conditions &amp; Duration:</strong>&lt;br&gt;1. Temperature cycling&lt;br&gt;2. Ambient temperature/humidity storage&lt;br&gt;3. High temperature/humidity storage</td>
<td>-40°C to 85°C, 1000 cycles&lt;br&gt;30°C, 60% RH, 3000 hours&lt;br&gt;60°C, 87% RH, 3000 hours</td>
<td>JESD 22A121</td>
</tr>
<tr>
<td><strong>Sample Size</strong></td>
<td>• Multi-leaded components: minimum of 96 terminations/6 components&lt;br&gt;• Leadless components: minimum of 18 terminations/9 components</td>
<td>JESD201</td>
</tr>
<tr>
<td><strong>Inspection magnification</strong></td>
<td>Minimum 50X for optical inspection, 250X for SEM.</td>
<td>JESD 22A121</td>
</tr>
<tr>
<td><strong>Whisker density classification</strong></td>
<td><strong>Whisker Density</strong></td>
<td># Whiskers per lead</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>&lt; 10</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>10-45</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>&gt; 45</td>
</tr>
</tbody>
</table>

**Reference:** JESD 22A121
Results—tin whisker growth

Tin whiskers on connector lead prior to solder dip
Results—tin whisker growth

25 µm whisker on pure tin PLCC piece part during 60°C, 87% RH test.
Results—tin whisker growth

Whiskers and nodules on tin plated control part--
1206 capacitor--after 1000 temp cycles.
Results—tin whisker growth

Pure tin control part: 0402 resistor after 3000 hours 60°C, 87% RH. High densities of nodules and whiskers were observed, up to 100 µm.
Results—tin whisker growth

36 µm whisker piercing conformal coat on 0402 resistor after 3000 hours 60°C, 87% RH

Presence or absence of urethane conformal coating did not significantly affect whisker length or density
Results—tin whisker growth

“Hillocks” on tin mitigated 1206 part after 1000 temp cycles
Results—tin whisker growth

Whiskers and nodules on pure tin PLCC after 3000 hours 30C, 60% RH
Results—tin whisker growth

39 µm tin whisker growing from PLCC piece part after 3000 hours 30C, 60% RH
Results—tin whisker growth

36 µm tin whisker on pure tin PLCC part after 3000 hours 30°C, 60% RH
Results—whisker growth

4 µm Pb whisker on tin mitigated 0402 chip after 1000 temp cycles
Results—whisker growth

≈10 µm whisker growing from tin mitigated TSSOP part after 1000 temp cycles
Area 1 = Pb
Area 2 = Sn
Area 3 = SnPb
Results—Xray evaluation

- Encapsulated modules and reballed BGAs could not be visually or SEM inspected
- X-ray analysis was attempted to discern whisker growth, with resolution down to approximately 10 µm.
- No whiskers were detected; BGA solder balls looked OK
- Encapsulated modules passed electrical test.
- Ceramic-filled coating and encapsulation may inhibit proliferation of whiskers
### Summary of Whisker Density Data

<table>
<thead>
<tr>
<th>Part type ↓</th>
<th>Finish</th>
<th>Baseline</th>
<th>Post-Temp cycle test</th>
<th>Post-30°C, 60% RH test</th>
<th>Post-60°C, 87% RH test</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSSOP</td>
<td>Pure tin</td>
<td>Medium</td>
<td>High</td>
<td>High/Med</td>
<td>High/Med</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>None</td>
<td>Low/Med</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>PLCC</td>
<td>Pure tin</td>
<td>High</td>
<td>NA</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>None</td>
<td>Low/Med</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>SOT23</td>
<td>Pure tin</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>None</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>DFN8</td>
<td>Pure tin</td>
<td>NA</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>NA</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>QFN64</td>
<td>Pure tin</td>
<td>NA</td>
<td>NA</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>NA</td>
<td>Low</td>
<td>Low</td>
<td>None</td>
</tr>
<tr>
<td>0402 chip</td>
<td>Pure tin</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>None</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>1206 chip</td>
<td>Pure tin</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>None</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>connector</td>
<td>Pure tin</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>SnPb</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>

Tin mitigation greatly reduces but does not eliminate whiskers.
Tin mitigation reduces length of whiskers by 3X to 15X
Fig. 4 Decrease in Whisker Size Due to Tin Mitigation & Span of Largest Whisker

- % Decrease in maximum whisker length due to tin mitigation
- % Lead Separation spanned by largest whisker on pure tin part
- % Lead Separation spanned by largest whisker on SnPb part

Largest whiskers spanned only 30% of span between conductors.
Test results: tin whisker growth

- Temp cycling and temperature/humidity storage induced whisker growth.
- Whiskers grew on all pure tin parts and most tin mitigated parts
- No whiskers were observed to “short” between leads; the largest percentage of lead separation spanned by a tin whisker was about 30%.
- Whiskers pierced and grew along surfaces beneath urethane conformal coating.
- Among 7 part types tested in significant numbers, the decrease in maximum whisker length effected by tin mitigation was 30 to 70% relative to the pure tin components.
- No significant differences in whisker density or size were noted among parts mitigated by tin mitigation suppliers/processes.
- No significant differences in whisker density or size were noted on parts installed on PWBs with different materials, pad finish or with air or nitrogen reflow atmosphere.

Tin mitigation severely limits whisker growth but does not completely eliminate tin whisker formation.
Evaluation of solder joint reliability after temperature cycling
Results--Solder joint evaluation

Cracked solder joint on 1206 chip resistor after 1000 temp cycles
Results--Solder joint evaluation

Cracked solder joint on 1206 chip resistor after 1000 temp cycles
Results--Solder joint evaluation

Cracked solder joint on PLCC solder joint after 1000 temp cycles
Results—solder joint reliability after 1000 cycles -40 to 85° C

- All part types except the DFN8 showed some cracks in the solder joints
- Small qty of cracked solder joints appeared severe enough to impact CCA reliability. No parts showed cracks on 100% of the leads.
- No cracks or other anomalies were observed on the component bodies.
- Damage was more widespread on larger components than smaller ones.
- Solder joints on PLCCs installed on epoxy PWBs with silver finish reflowed in air showed more cracks than on the other types of boards.
- Among all part types, there were no consistent trends between solder joint quality and PWB material, PWB pad finish or reflow condition.
- No anomalies were noted on parts with non pure tin lead-free finishes (SnBi, NiPDAu and AgPd). In very small sample sizes, parts with these finishes showed similar solder joint quality as tin mitigated components.

Robust solder joints can be made with components that have been through tin mitigation processes.
Discussion—Component Reliability

• Most likely degradation mechanisms:
  – Degraded solderability
  – Damaged interfaces, materials, and interconnects.
  – Degraded electrical performance, i.e. die-level

• Solder dip usually helps with solderability since there is a fresh coat of SnPb

• No component damage noted in SEM, Xray or cross section
  – Navy ManTech study also showed no degradation

• Automated solder dip process recommended
  – Much better controls than manual dipping

Well-controlled tin mitigation processes will not adversely affect the types of parts studied in this report.
Findings & Conclusions

- Automated solder dip/Pb addition effectively replaced Sn with SnPb on exposed Sn leads.
- Tin mitigation processes did not induce damage on parts.
- Cracked solder joints were observed on about ½ of the parts.
- No catastrophic solder joint failures on tin mitigated parts or lead-free parts after 1000 temperature cycles.
- Whiskers grew on almost all of the parts, even SnPb surfaces.
- Maximum whisker length on tin mitigated parts was 30 to 70% smaller than on pure tin parts.
- Pb and “mixed” SnPb whiskers were also observed.
- Whiskers grew beneath and through conformal coatings.
- Tin mitigation supplier, PWB material, pad pattern or solder reflow condition had little effect on tin whisker growth or solder joint cracking.

Tin whisker tests failed on all but 2 pure tin component types and passed on all tin-mitigated component types.
Recommendations

- Approve pure tin and SnBi parts for limited use as long as their leads/terminations are mitigated prior to installation.
- Approve NiPdAu parts—no mitigation needed.
- Parts selection team should request/require JESD201 test data from component suppliers for all pure tin parts.
- Low profile components, encapsulated parts and many connectors cannot be completely mitigated
  - Need to be evaluated on a case-by-case basis.
- Mechanical parts, radial leaded parts, parts with glass seals or special sensitivities to heat or ESD (<100 V) were not covered by this study
  - Need to be evaluated separately.
# Recommendations on dealing with Lead-Free Parts

<table>
<thead>
<tr>
<th>Option</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Find alternate equivalent part</td>
<td>May be “drop-in”</td>
<td>May require approval</td>
</tr>
<tr>
<td>“Last time buy” on part before it becomes lead-free</td>
<td>Guaranteed quantities</td>
<td>Up-front cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accurate forecast may not be possible</td>
</tr>
<tr>
<td>Redesign</td>
<td>Can change parts</td>
<td>Cost, schedule</td>
</tr>
<tr>
<td>Mitigation</td>
<td>Avoid redesign &amp; last time buys</td>
<td>Extra handling, processing &amp; cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May not eliminate all risks</td>
</tr>
<tr>
<td>Qualify new parts/finishes</td>
<td>Avoid redesign &amp; last time buys</td>
<td>May not be offered by suppliers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extensive cost &amp; technical obstacles</td>
</tr>
</tbody>
</table>