Solder Joint Fatigue Study Under Low Temperature Martian Conditions (#1310)

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Acknowledgements

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Introduction

- Previously, electronics on Mars mission rovers have been centrally enclosed in a “warm electronics box” (WEB).

- A distributed, non-heated architecture outside the WEB is being considered for MSL and will have to survive in 120°C to 85°C for 2010 cycles.
  - Typical Mil-Spec rating: -55 °C to 125°C for a few hundred cycles.

- Thermally induced fatigue due to CTE mismatches and materials property transitions, and the low temperature environment are high risk potential failure modes.
Background

• Extreme low temperature, fatigue conditions failure modes:
  - Martensitic phase transformation between the phases within the SnPb solder.
    - SnPb solder has the same unit cell structures as austenite (f.c.c.)-α/ Pb-phase and martensite (b.c.t)-β/ Sn-rich phase [1]
  - Under low temperature conditions below -110ºC, Sn phase becomes brittle [2].

• Intermetallic embrittlement of solder joints
  - Cracks can occur in the intermetallic or at the interfaces
  - Shear stresses due to CTE mismatch and delta T
  - Fatigue cracks were found underneath surface mount leads on Thin Small Outline Packages (TSOPs) under thermal shock conditions [3].
  - Intermetallic compounds in solders are typically more brittle than the bulk material [2,4,5].
Packaging Materials selection

- **Connector:**
  - 37-pin Nanonics Dualobe® connector (nano-connector) with Sn60Pb40 finish
  - Selected as a part with standard finish.

- **Solder:**
  - In80Pb15Ag5 (Indalloy #2)
  - Selected for thermal fatigue resistance and better wetting to Au.

- **Coating:**
  - Dow Q1 4939 1:10 (silicone)
  - Selected for its high compliance and function as a good moisture barrier.

- **Substrate:**
  - Polyimide printed wiring board (PWB)
  - Selected for its space heritage and advantageous material properties as an organic.
Test vehicle design, assembly, testing

• Design:
  ■ 8-layer polyimide PWB had a thickness of 1.60 mm +/- 0.127 mm.
  ■ Au plating (1.016-1.524 μm) at 99.97% purity with a Ni underplate (2.54 – 5.08 μm) per SAE-AMS-QQ-N-290 Class 2, over a top Cu layer (~107 μm).

• Assembly:
  ■ Leads and Au pads were pre-tinned with In80Pb15Ag5 solder and Indalloy Tacflux 012 RMA flux
  ■ PWBs were cleaned with ethyl alcohol and brushed carefully.
  ■ Dow Q1-4939 1:10 silicone coating was applied and cured at 80°C for 4 hours.
  ■ Continuity measurements were taken before and after conformal coating.

• Testing:
  ■ Environmental test chamber, Tenney Model T6C-LN2, was used
  ■ Each cycle, programmed between -130°C to 92°C, averaged a 5°C/minute ramp rate.
  ■ The test vehicles were thermal cycled between -120°C to 85°C and held at each temperature for at least 10 minutes.
  ■ Nano-connectors were continuously and periodically manually verified for functionality every 250-300 cycles.
  ■ High resistance values or infinity indicating electrical opens were defined as failures.
Flow of Test Vehicle Experiment

- Materials Selection and DOE
- Design of Test Vehicles (TVs)
- Assembly of TVs
- QA inspection and photograph TVs
- Continuity at 0 cycles
- Place into Thermal Chamber
- Connect cables on Select test vehicles for continuous monitoring
- Remove TVs At 500 cycles and Verify continuity manually
- Remove TVs and manually verify continuity every ∼250 cycles until 2100+ cycles and every 100 cycles thereafter

Tenney Model T6C-LN2 Environmental test chamber

Thermocouple Cycling Data
Results and Discussion-1

- Between 638-1431 cycles 13 out of 1110 lead contacts on 4 out of 30 nano-connectors failed.
- First failures occurred between 638 – 863 cycles.
- Optical and SEM results have indicated that lead lifting was the cause of the open.
- Root cause of failure was due to micro-cracking.
- Failure Modes:
  - Martensitic phase transformation, brittle nature of Sn phase, and intermetallic embrittlement
Results and Discussion-2

- Crack initiation site at the Sn60Pb40 lead finish and the In80Pb15Ag5 solder interface (at least one case)
- Two failure modes were crack propagation and separation at the interface.
- Martensitic phase transformation which resulted in a Sn-rich phase at low temperatures down to \(-120^\circ C\).
- Local stresses and volume changes within the microstructure due to phase transformation of the Sn in the SnPb phase (f.c.c) to a Sn-rich phase $\beta$ (b.c.t)
- Loss of ductility of the Sn phase.
• Secondary crack propagated at the In80Pb15Ag5 solder and PWB interface.
• Fatigue failure occurred due to fatigue stress and intermetallic embrittlement.
• Repetitive thermal cycling caused cyclic strains in the solder joint
• $\Delta T = 205 \, ^\circ C$
• BeCu lead- 16.7 ppm/$^\circ C$ [6]
• Polyimide PWB- 16.50 ppm/$^\circ C$ (measured in the x, y- dir.) [7]
• In80Pb15Ag5 solder- 28 ppm/$^\circ C$ [8]
Results and Discussion-4

- Spot Scans- 30keV, 10.10 kx, and a working distance of 12mm.
  - 7 EDS Spectra (ZAF correction factor) 20 second spot scans since In and Sn are convoluted
- Dot map- 10 keV, 10 kx
  - 8 micro-seconds time constant for 14 minutes.
- In, Ag, and Sn (L$_{\alpha}$)
- Au and Pb (M$_{\alpha}$)
- Ni, Cu (K$_{\alpha}$)
### Results and Discussion-4

<table>
<thead>
<tr>
<th>Spot</th>
<th>Intermetallic Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\text{In}_x \text{Pb}_y \text{Sn}_z$</td>
</tr>
<tr>
<td>2</td>
<td>$\text{In}_x \text{Pb}_y \text{Sn}_z$</td>
</tr>
<tr>
<td>3</td>
<td>$\text{In}_x \text{Pb}_y \text{Sn}_z$</td>
</tr>
<tr>
<td>4</td>
<td>$\text{In}_x \text{Pb}_y$</td>
</tr>
<tr>
<td>5</td>
<td>$\text{In}_x \text{Pb}_y$</td>
</tr>
<tr>
<td>6</td>
<td>$\text{In}_w \text{Pb}_x \text{Au}_y \text{Sn}_z$</td>
</tr>
<tr>
<td>7</td>
<td>$\text{In}_x \text{Au}_y \text{Sn}_z$</td>
</tr>
</tbody>
</table>
Results and Discussion-5

<table>
<thead>
<tr>
<th>Location</th>
<th>Intermetallic Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region A</td>
<td>$\text{In}_x\text{Ag}_y\text{Sn}_z$</td>
</tr>
<tr>
<td>Region B &amp; Spot #7</td>
<td>$\text{In}_x\text{Au}_y\text{Sn}_z$</td>
</tr>
<tr>
<td>Region C &amp; Spot #6</td>
<td>$\text{In}_w\text{Pb}_x\text{Au}_y\text{Sn}_z$</td>
</tr>
<tr>
<td>Region D</td>
<td>Pb area</td>
</tr>
<tr>
<td>Region E &amp; Spot #1</td>
<td>$\text{In}_x\text{Pb}_y\text{Sn}_z$</td>
</tr>
</tbody>
</table>

- Intermetallics at spot location #2 and 3 are also shown in the same areas of the dot map.
- Sn may have formed with $\text{In}_x\text{Pb}_y$ found in the EDS spectra on spots #4 and #5, or it may be unlikely since In and Sn are convoluted on the dot map.
### Results and Discussion-6

*Note: Left side has a higher concentration of Sn
Right side has a higher concentration of Au

<table>
<thead>
<tr>
<th>Location</th>
<th>Estimated Intermetallic Compound</th>
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</thead>
<tbody>
<tr>
<td>Region B</td>
<td>Au-Sn complex</td>
</tr>
<tr>
<td>Region C</td>
<td>Au-Sn complex</td>
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</tbody>
</table>

#### Au-Sn Crystallographic Data

<table>
<thead>
<tr>
<th>Phase</th>
<th>Composition, Pearson symbol</th>
<th>Space group</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Au)</td>
<td>0 to 4.3</td>
<td>(\alpha)HCP, (\gamma)Fm3m</td>
</tr>
<tr>
<td>(\delta) or (\epsilon)AuSn</td>
<td>6.7</td>
<td>b.c.c, (\gamma)Fm3m</td>
</tr>
<tr>
<td>(\zeta) or (\epsilon)AuSn</td>
<td>7 to 12</td>
<td>hP6, (\gamma)Fm3m</td>
</tr>
<tr>
<td>(\gamma) or (\epsilon)AuSn</td>
<td>10.8</td>
<td>hP6, (\gamma)Fm3m</td>
</tr>
<tr>
<td>(\delta) or (\epsilon)Sn</td>
<td>38 to 50.08</td>
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<tr>
<td>(\eta) or (\epsilon)Sn</td>
<td>54.9</td>
<td>hP6, (\gamma)Fm3m</td>
</tr>
<tr>
<td>(\zeta) or (\epsilon)Sn</td>
<td>99.7 to 100</td>
<td>hP6, (\gamma)Fm3m</td>
</tr>
<tr>
<td>(CuSn)</td>
<td>99.990 to 100</td>
<td>hP6, (\gamma)Fm3m</td>
</tr>
</tbody>
</table>

(a) Hexagonal;
(b) Orthorhombic
Results and Discussion-7

- 30 kev, Mag. of 5kx

<table>
<thead>
<tr>
<th>Spot</th>
<th>Intermetallic Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>In_{x}Ag_{y}</td>
</tr>
<tr>
<td>9</td>
<td>In_{x}Pb_{y}Sn_{z}</td>
</tr>
</tbody>
</table>
**Conclusions**

- Nano-connector leads with Sn60Pb40 finish soldered to polyimide PWB with In80Pb15Ag5 failed due to lead lifting between 638 – 863 cycles.
- Primary crack propagation occurred at the lead finish near the heel which is the highest stress location, and secondary crack propagation at the solder/plating interface.
- Crack initiation occurred in the Sn-rich phase at the Sn60Pb40 lead finish, due to the martensitic phase transformation and brittle nature of Sn at low temperatures.
- The failure mode at the In80Pb15Ag5 bulk solder and PWB occurred due to cracking through the brittle intermetallic compounds.
- Sn is integral in intermetallic formation and likely the brittle nature of the Sn-phase caused brittle crack growth.
Additional Current Work

• A more detailed intermetallic analysis of the Sn60Pb40 lead finish is recommended for future work in order to study and confirm the Sn phase involved in the crack initiation site.
• Inspect for possible SnPb grain coarsening as a contributing failure mode.
• Thermal Cycle and study the survivability of nano-connectors with Ni/Au endcap finish and In80Pb15Ag5 solder
• Studying the survivability of other components on the test vehicle boards, e.g. resistors with Ni/Au endcap finish and In80Pb15Ag5 solder, and MOSFETS with heavy Al wire bonds
References

[7] Internal JPL verbal communication- Results of TMA testing
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- Carissa Tudryn began working at JPL in September 2004. She is a Mechanical Engineer in the Advanced Electronic Packaging Group. She has a Bachelor in Mechanical Engineering from The Catholic University of America and a Dual Masters in Mechanical Engineering and Materials Science and Engineering from the Massachusetts Institute of Technology.

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