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 \(-120^\circ\text{C}\).
- 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.
Results and Discussion

- 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.
- ΔT = 205 °C
- BeCu lead - 16.7 ppm/°C [6]
- Polyimide PWB - 16.50 ppm/°C (measured in the x, y-dir.) [7]
- In80Pb15Ag5 solder - 28 ppm/°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>

---

**Image Description:**

- **In80Pb15Ag5 Solder**
- **Spot Analysis:**
  - Spot 1
  - Spot 2
  - Spot 3
  - Spot 4
  - Spot 5
  - Spot 6
  - Spot 7
- **Magnification:** 10.10 K X
- **Scale:** 1μm
- **Electron Beam:** 30.00 kV
- **Working Distance (WD):** 12 mm
- **Signal A:** QBSD
- **Photo No.:** 190
- **Date:** 2
- **Time:** 

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**Additional Information:**

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**Note:** The image contains a micrograph of an In80Pb15Ag5 solder with various spots labeled for analysis. The table lists intermetallic compounds identified at different spots.
### 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

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

Au-Sn crystallographic data

<table>
<thead>
<tr>
<th>Phase</th>
<th>Composition, wt% Sn</th>
<th>Symbol</th>
<th>Space group</th>
</tr>
</thead>
<tbody>
<tr>
<td>(aAu)</td>
<td>0 to 4.3</td>
<td>aAu</td>
<td>( \bar{P} \bar{3} )</td>
</tr>
<tr>
<td>( \beta ) or ( \text{Au}_{3} \text{Sn} )</td>
<td>5.7</td>
<td>b216</td>
<td>( \text{Rh} )</td>
</tr>
<tr>
<td>( \alpha ) or ( \text{AuSn} )</td>
<td>10.8</td>
<td>( \text{L} )</td>
<td>( \text{h} )</td>
</tr>
<tr>
<td>( \delta ) or ( \text{AuSn} )</td>
<td>18 to 26.9</td>
<td>( \text{Pm} )</td>
<td>( \text{h} )</td>
</tr>
<tr>
<td>( \varepsilon ) or ( \text{AuSn} )</td>
<td>54.7</td>
<td>( \text{O} )</td>
<td>( \text{Pm} )</td>
</tr>
<tr>
<td>( \eta ) or ( \text{Au}_{2} \text{Sn} )</td>
<td>71</td>
<td>( \text{C20} )</td>
<td>( \text{A2} )</td>
</tr>
<tr>
<td>( \varphi ) or ( \text{AuSn} )</td>
<td>99.7 to 100</td>
<td>( \text{P} )</td>
<td>( \text{A2} )</td>
</tr>
<tr>
<td>( \theta ) or ( \text{AuSn} )</td>
<td>99.99 to 100</td>
<td>( \text{Pl} )</td>
<td>( \text{A2} )</td>
</tr>
</tbody>
</table>

(a) Hexagonal.
(b) Orthorhombic.
Results and Discussion

- 30 kev, Mag. of 5kx

<table>
<thead>
<tr>
<th>Spot</th>
<th>Intermetallic Compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>In\textsubscript{x}Ag\textsubscript{y}</td>
</tr>
<tr>
<td>9</td>
<td>In\textsubscript{x}Pb\textsubscript{y}Sn\textsubscript{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.
- Inspect the co-planarity of the leads
- 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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