Correlation of Material properties to the Reliability performance of High Density BGA Package solder joints:

By
Vasu.S. Vasudevan
Intel Corporation

For
IPC Reliability Summit

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Agenda

- **Introduction**
  - LF Alloy Selection
  - LF Material Properties
  - LF Reliability Concerns and Test Results
  - Reliability Data Analysis
  - Summary
  - Q&A
Scope/Objective

• Objective
  - To provide an overview of Pb-free (LF) material properties, LF challenges, LF and LF reliability results BGA components

• Scope
  - LF challenges and solder joint reliability (SJR) performance of LF alloys for 2\textsuperscript{nd} level interconnect with main emphasize on SAC alloy system
Motivation for LF Transition

• **Government Regulations**
  - The European Union (EU) leads in environmental regulation, but China follows closely
    - California Bill AB 48 would follow UK adoption of RoHS
  - RoHS (EU Directive) restricts the use of the Lead substances in electronic products placed on the EU market after July 1, 2006 or later depending on market segment

• **Deployment Timelines**
  - Consumer electronics, July 2006
  - Sever and Telecom infrastructure exemption to be reviewed by EU in 2008
Position Statement

• Intel recognizes the magnitude and technical complexity involved with converting the world’s board assembly industry from Pb/Sn to LF solders

• Intel has completed a major milestone in driving the LF technology across the industry by closely working with our customers and the supply chain to achieve a successful LF transition in worldwide electronics markets

• Intel has done extensive reliability testing on LF solder and processes for board assembly

• Intel believes its LF products and reference processes to be low risk
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Synopsis
What we know about Pb-free solder joint...

- Solidification characteristics and microstructure
- Mechanical properties
- Impact of material properties on solder joint reliability
  - Improved fatigue performance vs. PbSn
    - Longer fatigue life and better solder joint reliability
  - Reduced shock performance vs. PbSn, but passed board level shock & Vibe test conditions
- Solder joint fatigue can be modulated by
  - Enabling configuration (e.g. w/ vs. w/o heat sink solution)
  - Board design (e.g. pad size & type)
  - Test methods (e.g. dwell time, temp range)

☑ LF (SAC405) showed improved solder fatigue margin
SAC Terminology

• SAC stands for Sn-Ag-Cu solder
• Composition is sometimes written as SACxyz
  – Where
    x.y = Silver (Ag) content in solder by weight
    0.z = Copper (Cu) content in solder by weight
    100-x.y-0.z = Tin (Sn) Content

Examples:
• SAC305 = 96.5%^ Sn / 3.0%^ Ag / 0.5%^ Cu (JIETA)
• SAC405 = 95.5%^ Sn / 4.0%^ Ag / 0.5%^ Cu (Intel)

^ Percentages by weight
Pb-free Solder (Sn-Ag-Cu) SAC alloy


Pb-free SAC alloys range from 1% to 5% Ag

Different SAC alloys have different material properties and microstructure, so variations in performance are expected

SAC405 & SAC305 are similar enough they can be used together (i.e., SAC405 solder balls with SAC305 paste)

➤ Best Practices: SAC305 - SAC405 for most applications
SAC105 – Handheld Equipment
The effect of Ag Content on LF Reliability

Increase in Ag content helps solder fatigue performance

% of Ag₃Sn IMC

% of Compliant Primary Sn phase

% Failures

Better Shock performance

Better Temp Cycle performance

% Ag content in SAC alloy

SAC305-SAC405 alloy showed better long term reliability in temp cycle test (iNEMI Recommendation)

Literature Reference: P. Snugovsky et al: “Failure mechanism of SAC 305 and SAC405 in harsh environments and influence of board defects including black pad” SMTA 2007

Figure 20. Weibull plots for pure SAC 305 (cell 4-1) and SAC 405 (cell4-2) LGA64, -55°C to 125°C

SAC 305

SAC 405

Larger Better
Microstructure

PbSn

Silicon Package

SAC405

PCB

Pb-free & PbSn interfacial intermetallics similar

Bulk solder microstructure different

Performance difference to stem from bulk properties
## Typical Properties: PbSn vs. SnAgCu

<table>
<thead>
<tr>
<th>Property</th>
<th>PbSn</th>
<th>SnAgCu</th>
<th>SAC Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point</td>
<td>183 °C</td>
<td>217 – 219 °C</td>
<td>SAC405</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>35 GPa</td>
<td>53 GPa</td>
<td>SAC405</td>
</tr>
<tr>
<td>Tensile Strength (20°C at 0.004s⁻¹)</td>
<td>40 N/mm²</td>
<td>48 N/mm²</td>
<td>SAC387</td>
</tr>
<tr>
<td>Joint Shear Strength (20°C at 0.1mm/min)</td>
<td>23 N/mm²</td>
<td>27 N/mm²</td>
<td>SAC387</td>
</tr>
<tr>
<td>Creep Strength (100°C at 0.1mm/min)</td>
<td>1.0 N/mm²</td>
<td>5.0 N/mm²</td>
<td>SAC387</td>
</tr>
</tbody>
</table>

- SAC405 is stiffer and stronger than PbSn
- Consequences of properties:
  - Improved fatigue performance
  - Reduced shock performance

Compiled from multiple sources
Agenda

- Introduction
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  - LF Reliability Concerns and Test Results
- Reliability Data Analysis
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## LF Reliability Concerns

<table>
<thead>
<tr>
<th>LF Failures Concern</th>
<th>Stress Test</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder fatigue</td>
<td>Temp Cycle</td>
<td>Electrical open/solder crack</td>
</tr>
<tr>
<td>Overstressing</td>
<td>Shock Test</td>
<td>Electrical open/solder crack</td>
</tr>
<tr>
<td>Overstressing</td>
<td>Vib Test</td>
<td>Electrical open/solder crack</td>
</tr>
<tr>
<td>PCB trace, via corrosion</td>
<td>Temp/Humid 85/85°C</td>
<td>Electrical open due to via, trace corrosion</td>
</tr>
<tr>
<td>IMC growth, Diffusion &amp; Solder creep</td>
<td>Bake Test</td>
<td>Electrical open IMC growth, diffusion, &amp; shorts due to solder creep</td>
</tr>
</tbody>
</table>

> LF solder joint reliability requirement established based on expected failure mechanism
1. Lead free is stiffer than PbSn
2. Pad adhesion strength is equivalent for Pb-free and PbSn
3. Board bending pulls apart the opposite surfaces of the solder ball
4. Stiffer Pb-free ball generates higher forces on the pad. The softer PbSn ball deforms to accommodate bending, resulting in lower forces acting on the pad
5. Pb-free ball reaches the critical level of force required to pull the pad out at lower strain. This is a consequence of the ball material property, not the pad property

- Pb-free stiffness reduces transient bend performance, but ICT fixtures redesigned to accommodate the need
Shock Test Performance Comparison Between Sn/Pb vs. LF 2LI

- Stiffer LF solder joint → reduced shock tolerance
- However, passed intensive baseline S&V testing

<table>
<thead>
<tr>
<th>Shock Level</th>
<th>Solder</th>
<th>Crack (%)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Sn/Pb</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>100</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Sn/Pb</td>
<td>50</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>100</td>
<td>100</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Sn/Pb</td>
<td>100</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Design recommendation to include corner sacrificial (NCTF) balls for BGA packages.
Factors Affecting Solder Fatigue

- Component to board CTE mismatch
- Component type: BGA vs. Socket
- Pad size (component and board)
- Pad size ratio
- Metallurgy (PbSn vs. SAC405)
- Component die size (Range: 8 mm to 12 mm)
- Body size (package size ranging from 14 to 42.5 mm sq)
- Body (package) thickness/stiffness
- Ball Array design
- PCB Board thickness/stiffness
- Joint shape
- Load on Solder joint
- Bend mode
- Surface finish compatibility
1 mm LF FCBGA Temp Cycle Test Vehicle Details

- **Test Vehicle (15 components per board)**
  - 1 mm FCBGA on 0.062 inch thick board (no load)
    - 1 mm pitch FCBGA packages with no heat sinks
      - Package Size: 37.5 mm Sq
      - Ball pattern: Full array and Depop
      - Die Size: 11.7 X 8.0 mm
    - Sample size for each leg: 45 units (3 boards)
  - PCB Pad parameters
    - Pad Type: Mixed (MD & SMD)
  - PCB parameter
    - Im/Ag surface finish, 18 mil PCB pad, & one PCB Supplier
  - Nominal reflow condition (SMT + wave)
  - Control Leg (Sn/Pb solder with HASL SF)
    - Sample size: 45 units (3 boards)
1 mm FCBGA Temp Cycle Test Vehicle
The Effect of Temp Cycle dwell Time on Temp Cycle Performance ( -40 to +85 C)

- Increased dwell → reduced cycles to failure
- Pb-free better than PbSn for 15 and 30 min dwell

Table of Statistics

<table>
<thead>
<tr>
<th>Loc</th>
<th>Scale</th>
<th>AD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.54120</td>
<td>0.0937068</td>
<td>3.657</td>
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<td>7.34854</td>
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<td>118.168</td>
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<td>7.10703</td>
<td>0.0937068</td>
<td>2.897</td>
</tr>
<tr>
<td>6.97849</td>
<td>0.0937068</td>
<td>1.110</td>
</tr>
</tbody>
</table>

Package Size: 37.5 mm sq
Die size: 11.7 X 8 mm, 4 Layer

Graph: Probability Plot for Start
- Lognormal
- Arbitrary Censoring - ML Estimates

Failure Criteria: E-test open

Pb

LF

Normalized Life

Larger is Better

30 < 15 min

Pb-15min
Pb-30min
LF-15min
LF-30min
Dwell Time Concerns

Does SAC405 show poor performance in extended dwell time (use condition) compared to Sn/Pb solder even though better performance seen in short time test?

Does SAC405 cross-over Sn/Pb?
Impact of Temp Cycle Dwell Time

- There is a concern about dwell/soak time performance for LF compared to Sn/Pb
- Does Sn/Pb reliability "cross-over" LF in extended dwell times
- Experimental plan was developed to address this
Dwell Time Impact Study

• **Purpose:** To assess fatigue risk to LF products utilizing two different sockets and FCBGA packages

• **Experimental Description**
  - **Vehicles**
    - Desktop Test Vehicle board (TV1)
      - Sn/Pb and LF
      - Fully enabled
    - Dual-proc server test vehicle board (TV2)
      - Sn/Pb and LF
      - Fully enabled
  - **Thermal Cycling**
    - -25°C to 100°C
    - 1, 4, and 8 hr cycle times
    - *In situ* electrical continuity monitoring

• **Hypothesis:** SAC405 ≥ PbSn
Description of Test Vehicles

Motherboard (TV1) with LGA socket and 0.8 mm pitch FCBGA

Server motherboard (TV2) with LGA sockets and 1.0 mm pitch FCBGA

Thermal solution Assembly
Temp Cycle Profiles

• Temperature range: -25°C to 100°C

<table>
<thead>
<tr>
<th>Cycle Time</th>
<th>Cycle Time</th>
<th>Ramp Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-hour</td>
<td>60min</td>
<td>8min</td>
</tr>
<tr>
<td>4-hour</td>
<td>240min</td>
<td>31min</td>
</tr>
<tr>
<td>8-hour</td>
<td>480min</td>
<td>31min</td>
</tr>
</tbody>
</table>
Dwell Time Study Timeline

Intel/3rd Party DOE Proposal

DOE Plan / TV Build

- 240/480 minute TV1
- 60 TV1
- 60 TV1
- 480 minute TV2
- 240 minute TV2
- 90 minute TV2

Timeline:
- Q2, 05
- Q3, 05
- Q4, 05
- Q1, 06
- Q2, 06
- Q3, 06
- Q4, 06
- Q1, 07
PbSn vs. Pb-free 1.0mm FCBGA
-15 to 125°C, 90 min dwell

At 90 min dwell Pb-free performed better than PbSn

Vasudevan et al. “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007
<table>
<thead>
<tr>
<th>Test Vehicle</th>
<th>Cycle Time</th>
<th>Solder Alloy</th>
<th># of Cycles Completed</th>
<th>E-test Cumulative Solder Joint Fails</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV Design 1</td>
<td>1 hr</td>
<td>Pb</td>
<td>2480</td>
<td>5/10 fails</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LF</td>
<td>2480</td>
<td>1/10 Fails</td>
</tr>
<tr>
<td></td>
<td>4 hr</td>
<td>Pb</td>
<td>2407</td>
<td>2/9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LF</td>
<td>2407</td>
<td>1/9</td>
</tr>
<tr>
<td></td>
<td>8 hr</td>
<td>Pb</td>
<td>1121</td>
<td>0/8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LF</td>
<td>1121</td>
<td>0/8</td>
</tr>
<tr>
<td>TV Design 2</td>
<td>1.5 hr</td>
<td>Pb</td>
<td>846</td>
<td>8/16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LF</td>
<td>846</td>
<td>5/16</td>
</tr>
<tr>
<td></td>
<td>4 hr</td>
<td>Pb</td>
<td>1044</td>
<td>0/8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LF</td>
<td>1044</td>
<td>0/10</td>
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<tr>
<td></td>
<td>8 hr</td>
<td>Pb</td>
<td>925</td>
<td>9/10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LF</td>
<td>925</td>
<td>4/10</td>
</tr>
</tbody>
</table>

LF (SAC405) solder showed improved fatigue performance and no early LF failures observed in all legs of the DOE

Vasudevan et al. “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007

Intel Corporation
Socket “Y” Temp Cycle Results
(-25°C to 100°C 1 hr cycle time)

Probability Plot for Start
Lognormal
Arbitrary Censoring - ML Estimates

Failure Criteria:
E-test open

Larger Better

% Failures

Normalized Life

Table of Statistics

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Location</th>
<th>Scale</th>
<th>AD*</th>
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</thead>
<tbody>
<tr>
<td>LF</td>
<td>8.06939</td>
<td>0.254316</td>
<td>26.596</td>
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<td>Pb</td>
<td>7.65566</td>
<td>0.254316</td>
<td>1.274</td>
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</tbody>
</table>

Socket Size: 37.5 mm sq
PCB pad size: 20 mm

Pb-free solder showed better solder fatigue performance compared to PbSn

Vasudevan et al. “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007
Vasu
Intel Corporation
Socket X 480 Minute Temp Cycle Results

Probability Plot for Start
Lognormal
Arbitrary Censoring - ML Estimates

- Failure Criteria: E-test open
- Larger is Better
-25 to + 100°C

Socket Size: 37.5 mm sq
PCB pad size: 20 mm

- LF (SAC405) solder showed improved fatigue performance at 8 hrs cycle time
- No reliability issues observed with LF fatigue creep

Vasudevan et al. “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007

Vasu

Intel Corporation
Socket Y 480 Minute Cycle Time After 1121 Cycles

Sn/Pb Sample

Max solder crack
~75%

LF Sample

Max solder crack
< 40%

LF samples showed smaller solder crack size (worst case) compared to Sn/Pb at extended dwell

Vasudevan et al. “Solder fatigue creep performance of LF (SAC) solder,” ECTC 2007
Socket Y 240 Minute Cycle Time
Dye Penetrant Results After 1900 Cycles

Sn/Pb Sample

Max solder crack
~90%

LF Sample

Max solder crack
~70%

- LF samples showed smaller solder crack size (worst case) compared to Sn/Pb at extended dwell
Effect of Dwell time, SJ X-section

1399 Cycles, LF 90 min

1300 Cycles, Pb-Sn, 90 min

1320 Cycles, LF, 480 min

1248 Cycles, Pb-Sn, 480 min

Vasudevan etal “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007
### FCBGA Temp cycle results (0 to +100 °C)

#### Probability - Weibull

<table>
<thead>
<tr>
<th>Model</th>
<th>Weibull</th>
<th>Eutectic</th>
<th>Life</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.5mm-1752 FCBGA</td>
<td>Eutectic</td>
<td>6153</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pb-Free</td>
<td>8696</td>
<td>10.1</td>
<td></td>
</tr>
</tbody>
</table>

#### Metallurgy

<table>
<thead>
<tr>
<th>Metallurgy</th>
<th>Characteristic Life</th>
<th>Beta</th>
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</thead>
<tbody>
<tr>
<td>Eutectic</td>
<td>6153</td>
<td>10.6</td>
</tr>
<tr>
<td>Pb-Free</td>
<td>8696</td>
<td>10.1</td>
</tr>
</tbody>
</table>

### 15mm-196

<table>
<thead>
<tr>
<th>Model</th>
<th>Weibull</th>
<th>Eutectic</th>
<th>Life</th>
<th>Beta</th>
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</thead>
<tbody>
<tr>
<td>15mm Eu ED</td>
<td>Eutectic</td>
<td>7649</td>
<td>14.2</td>
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</tr>
<tr>
<td></td>
<td>Pb-Free</td>
<td>10273</td>
<td>12.1</td>
<td></td>
</tr>
</tbody>
</table>

#### Characteristic Life

- **Beta**: Statistical parameter of the Weibull distribution.
- **Life**: Expected time to failure for a given percentile.

#### Notes

- Beta values indicate the shape of the failure rate distribution.
- The Eutectic solder life is compared to Pb-Free solder life for reliability assessment.

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**Graph Details**

- Probability - Weibull plots for different models with Beta and Life values.
- Graphs show the reliability of soldering over temperature cycles.

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Agenda

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  ➢ Reliability Data Analysis
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Pb-free performed better in normal temp cycle testing which is typical of use condition, but performed worse in extreme test condition unrealistic for telecom central offices & data centers.
Ceramic LCC Solder fatigue Results (*)


- In head-to-head tests:
  - Pb-free performed better than SnPb with Tmax up to 100°C
  - SnPb performed better than Pb-free with Tmax over 120°C
Temp Cycle Test Recommendation: $T_{\text{max}} < 110^\circ\text{C}$ and ramp rate < 15°C/min (IPC spec)

Mixed or Poor Reliability Results for LF Compared to Sn/Pb

Thermal Shock Region
($ > 15^\circ\text{C}$ ramp & Delta T > 125°C)

Recommended LF temp cycle test range (LF better than Sn/Pb)

Storage Region

Typical use condition

~120°C

Mixed Reliability Results

* J. Barleto et al
Ceramic BGA
* M. Osterman et al
Ceramic LCC

**Y, Qi et al
Agenda

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  ➢ Summary
  ➢ Q&A
## Reliability Tests for Pb-free Solder Joints

<table>
<thead>
<tr>
<th>Stress Test</th>
<th>Reason</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp Cycle at -40 to 85°C, ΔT = 125°C, -25 to +100°C, ΔT = 125°C</td>
<td>Solder fatigue</td>
<td>Completed/Passed</td>
</tr>
<tr>
<td>Bake 150°C for 1000 hrs</td>
<td>Diffusion and IMC growth</td>
<td>Completed/Passed</td>
</tr>
<tr>
<td>Temp/Humidity (85°C/85% RH) unbiased For 1000 hrs</td>
<td>Corrosion for Trace and via</td>
<td>Completed/Passed</td>
</tr>
<tr>
<td>Board Level Shock (50 g) &amp; Vibration (3.13 g Rms)</td>
<td>Shipping and handling</td>
<td>Completed/Passed</td>
</tr>
</tbody>
</table>

- Pb-free solder passed the established baseline reliability testing
Summary

- Extensive reliability testing has been done for Intel LF packages
- Intel LF packages showed improved fatigue performance compared to eutectic solder
- Intel recommends the use of SAC405 for applications where long-term reliability is a critical factor
- Temp cycle test data indicates that LF (SAC 405) outperforms eutectic solder even with long dwell time thermal cycling
- SAC405 products with proper process control exceeds the reliability of SnPb products
- Temp cycle test conditions can modulate the LF performance and convergence in temp cycle test needed
- Recommended temp cycle condition for LF: Temperature range between -40 and + 100 °C and ramp rate less than <15 °C/Min.
Q & A