System Level Effects on Solder Joint Reliability

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Outline

➢ Thermo-mechanical Fatigue of solder interconnects
➢ Shear and tensile effects on Solder Fatigue
➢ Effect of Glass Style on Solder Fatigue
➢ Effect of Improper Conformal Coating
➢ Effect of Mirroring
➢ Influence of Board Mounting and Housing
➢ Physics of Failure Methodology
➢ Solder Alloy Selection Approach
Solder Fatigue in Microelectronics

- Solder fatigue in electronics components is the result of temperature fluctuations or mechanical loads transmitted to the components through the assembly.
- Lead and package geometry influences solder joint response to mechanical loads. Solder geometry will dictate the stress distribution at the interface.
- Temperature fluctuations in field environments are not the same as accelerated thermal cycling conditions as defined by many standards.
Thermo-mechanical Fatigue of solder interconnects

- Idealized CTE mismatch

\[ \gamma = \frac{C L \Delta T \Delta \alpha}{h} \]

- Realistic CTE mismatch

Thermal expansion and warping of the substrate or FR4. Copper to solder CTE mismatch
Thermomechanical Fatigue of Solder Interconnects: Underfill

- Reduced fatigue life in BGA packages with underfill
- Axial strain and shear strain contribution to thermo-mechanical fatigue life
- How does axial loading contribute to reduction in fatigue life of BGA components

\[ \Delta \gamma = \frac{C L_h \Delta T \Delta \alpha}{h} \]

Without underfill

\[ T = 20^\circ C \]

With underfill

\[ T = 20^\circ C \]

Shear strain

Shear + Axial strain

\[ T = 120^\circ C \]
Shear and tensile effects on Solder Fatigue
Shear and tensile effects on Solder Fatigue

- Fatigue sensitivity of bulk solder alloys to loading direction translates to thermomechanical fatigue of solder interconnects of electronic components.
- Ratcheting strain accumulation due to secondary strain accumulation significantly reduces cycles to failure.

Shear and tensile effects on Solder Fatigue

- Lower cycles to failure observed for underfill with certain materials properties
- Partial flow underfill - slightly lower fatigue life.
- CSP package – 12x12, 228 I/O, 0.5mm pitch, SAC305 solder, 0.3mm ball diameter, 1 mm thick FR4 PCB.
- -40°C to 125°C, 10 min dwell, 15°C/min ramp thermal cycles

<table>
<thead>
<tr>
<th>Underfill</th>
<th>Viscosity at 25°C (mPa.s)</th>
<th>Tg (°C)</th>
<th>CTE (ppm/°C)</th>
<th>Modulus (GPa)</th>
<th>Typical curing performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>375</td>
<td>69</td>
<td>52</td>
<td>188</td>
<td>3.080</td>
</tr>
<tr>
<td>B</td>
<td>2000~4500</td>
<td>85</td>
<td>60</td>
<td>200</td>
<td>3.500</td>
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</table>

Effect of Glass Style on Solder Fatigue
Effect of Glass Style on Solder Fatigue

➢ Different glass style type will result in different CTE which in turn affects solder fatigue
➢ Larger component are more sensitive to changes in the board CTE

7628 – 7 layers (63 mil PCB)

1080 – 19 layers (63 mil PCB)
Effect of Glass Style on Solder Fatigue

- Incremental change in temperature and CTE range are directly proportional to shear strain range experienced by solder interconnects.
- Glass style and board thickness can drastically influence thermo-mechanical fatigue life as illustrated using Physics of Failure models.

\[ \Delta \gamma = C \frac{L_D}{h_s} \Delta \alpha \Delta T \]

<table>
<thead>
<tr>
<th>Glass Style</th>
<th>Resin Content [Weight %]</th>
<th>Resin Content [Vol %]</th>
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<tbody>
<tr>
<td>1027</td>
<td>75%</td>
<td>86%</td>
</tr>
<tr>
<td>1037</td>
<td>75%</td>
<td>86%</td>
</tr>
<tr>
<td>1056</td>
<td>72%</td>
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</tr>
<tr>
<td>1067</td>
<td>71%</td>
<td>84%</td>
</tr>
<tr>
<td>1035</td>
<td>70%</td>
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<tr>
<td>1078</td>
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<td>1080</td>
<td>64%</td>
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</tr>
<tr>
<td>1086</td>
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<tr>
<td>2313</td>
<td>57%</td>
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<tr>
<td>2113</td>
<td>55%</td>
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<td>3313</td>
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<td>3070</td>
<td>50%</td>
<td>68%</td>
</tr>
<tr>
<td>1647</td>
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<td>66%</td>
</tr>
<tr>
<td>1651</td>
<td>48%</td>
<td>66%</td>
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<tr>
<td>2165</td>
<td>48%</td>
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<td>66%</td>
</tr>
<tr>
<td>7628</td>
<td>48%</td>
<td>64%</td>
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</table>

Fatigue life of a 2512 resistor mounted on a PCB with different glass styles and board thickness.

Calculated elastic modulus and CTE for different glass styles.

Effect of Improper Conformal Coating
Effect of Improper Conformal Coating

- Components used are 17x17mm, 256 IO BGA
- Test vehicle was a 2.05 mm (81mil) thick, 8 layer PCB that was populated with 60 BGAs
- ‘Thick’ coating was applied to components on one side of the board with a syringe to ensure that it wicked under the BGAs
- ‘Standard’ coating was then sprayed on the other half of the board
- Multiple test vehicles were produced for different conformal coatings and test conditions

Test Vehicle after Thick conformal coating had been applied to the right side (coating visible due to UV light)
Effect of Improper Conformal Coating

➢ Temperature Profile 1: temperature range of -55°C to +125°C
   ➢ 620 cycles total cycles
➢ Temperature Profile 2: temperature range of -20°C to +80°C
   ➢ 2020 cycles total cycles.
➢ Temperature profiles per IPC-9701
   ➢ minimum 15 minute dwell time at each temperature extreme
   ➢ ramp rate of 5-10°C per minute
Effect of Improper Conformal Coating

- Effect of conformal coating on stress distribution in BGA during thermal cycling.
  Worst case: Conformal coating flowed underneath component. 17x17 mm 256 IO BGA
- Mechanical behavior of solder alloy is sensitive to simulation methodology. Interaction of deformation mode needs to be considered by accurately modeling material behavior at each condition

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Effect of conformal coating on stress distribution in BGA during thermal cycling. Worst case: Conformal coating flowed underneath component. 17x17 mm 256 IO BGA

Mechanical behavior of solder alloy is sensitive to simulation methodology. Interaction of deformation mode needs to be considered by accurately modeling material behavior at each condition.
Effect of Improper Conformal Coating

- Corner joint with Pb-free solder exhibits slight distance to neutral effect. Die shadow joint exhibits a more uniform axial strain distribution.
- Peak strain occurs at the interface of the solder and copper pad.
- Maximum axial strain location shifts from the top to bottom copper pads throughout the thermal profile and dwell periods.

Von Mises stress distribution in SAC305 BGA with Thick conformal coating at 125°C
Effect of Improper Conformal Coating

- Von Mises stress of corner Pb-free solder joints was similar to stress profile of SnPb solder joint at both temperature extremes and profiles.

- Higher magnitude of stress with Thick conformal coating is shown at the cold dwell temperature than at the hot dwell temperature.

- Due to the higher stiffness and lack of creep and relaxation in Pb-free solder joints at the cold temperature.

- Mechanical deformation alternates between creep and plasticity with transition of the temperature extremes.

Von Mises stress for corner joint with thick conformal coating at (a) 125 °C (b) -55°C

Von Mises stress for corner joint with thick conformal coating at (a) 80°C (b) -20°C
Effect of Improper Conformal Coating

- Similar strain distribution for SnPb corner joint with Standard and Thick conformal coating at high dwell temperature
- Larger diagonal shear strain accumulation for corner joints with the Thick conformal coating
- Control sample showed a more uniform strain distribution at the cold temperature dwell with high magnitude

SnPb37 BGA Min. principal strains at 125°C for corner joint (a) with Thick coating (b) without Thick coating.

SnPb37 BGA Min. principal strains at -55°C for corner joint (a) with Thick coating (b) without Thick coating.
Effect of Improper Conformal Coating

- Acrylic conformal coating carries compressive pre-strain on Pb-free and SnPb solder joints to the subsequent thermal cycles.
- The amount of compressive pre-strain applied by the acrylic depends on the glass transition temperature (Tg) and the thermal profile. Difference in thermal conduction between materials can introduce lag in mechanical response which could affect numerical results.
- Strain in the axial direction dominates loading mode and places solder joints under mean compressive strain during thermal cycling.

Maximum principal strain with and without conformal coating

Axial stress with and without conformal coating.

SAC305 corner solder joint with Thick Conformal Coat, Temperature Profile 1
Effect of Improper Conformal Coating

- Distinct difference in solder joint failure mechanism between standard and heavy conformal coating processes
- Distance to Neutral Point (DNP) effect contributes to failure location and is dependent on temperature profile

SnPb BGA with acrylic Standard coating showing cracking in upper left size of solder joint at 1600 cycles.

SnPb BGA with Thick acrylic coating survived 1600 cycles a) corner joint b) joint in middle row

SnPb BGA with Thick conformal coating failed at 1055 thermal cycles (-20 to 80°C) a) corner joint b) joints in the middle of a row.
Effect of Improper Conformal Coating

- Results show a distinct difference in solder joint failure mechanism between Standard and Thick conformal coating processes.
- Higher loads transfer to Pb-free solder resulting in severe plastic deformation.
- Pb-free solder is less compliant than SnPb solder, which led to shorter fatigue life under similar test conditions.

SAC305 Control sample (no coating) showing cracking along bottom pad.

Failure of SAC305 BGA with acrylic conformal coating (-55 to 125°C):
- a) Standard
- b) Thick coating
Effect of Improper Conformal Coating

- BGA with SAC305 (Pb-Free) solder joints under temperature profile 2 with thick coating found to have lowest fatigue life
- High $\beta$ value for the thick coating indicates influence of failure mechanism on transition from wear-out dependent failure
- BGA with SnPb solder joints with standard and thick application of acrylic conformal coating shows greater fatigue resistance compared to the Pb-free components under equivalent test conditions

$$
F(n) = 1 - \exp\left(-\left(\frac{n}{\theta}\right)^\beta\right)
$$

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<tr>
<th>Alloy</th>
<th>Application method</th>
<th>Temp Profile</th>
<th>$\beta$</th>
<th>$\theta$</th>
<th>First failure</th>
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<td>7.9</td>
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<td>173</td>
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<td>5.7</td>
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<td>245</td>
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<td>Thick</td>
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<td>16.7</td>
<td>197</td>
<td>171</td>
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<td>2600</td>
<td>1532</td>
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<td>4.8</td>
<td>1554</td>
<td>756</td>
</tr>
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Effect of Mirroring
Effect of Mirroring

- Previous researchers have shown the negative effect of double sided configuration on the thermo-mechanical fatigue life of area array components.
- A 2x to 3x decrease in reliability can occur in mirror image assemblies compared to single sides configurations.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Reliability (cycles)</th>
<th>Measured</th>
<th>Predicted</th>
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<td>Single-Sided BGA</td>
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<tr>
<td>(20 mil pad)</td>
<td>8,284</td>
<td>8,153</td>
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</tr>
<tr>
<td>Single-Sided BGA</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(22 mil pad)</td>
<td>7,897</td>
<td>7,991</td>
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<tr>
<td>Single-Sided BGA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(24 mil pad)</td>
<td>7,736</td>
<td>7,814</td>
<td></td>
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<tr>
<td>Mirror Image BGA</td>
<td>1,576</td>
<td>2,890</td>
<td></td>
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<tr>
<td>Single-Sided CSP</td>
<td>7,611</td>
<td>6,140</td>
<td></td>
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<tr>
<td>Mirror Image CSP</td>
<td>3,174</td>
<td>2,300</td>
<td></td>
</tr>
<tr>
<td>50% Offset CSP</td>
<td>3,026</td>
<td>3,000</td>
<td></td>
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Effect of Mirroring

- FEA modeling on 17x17mm BGA with 256 IO.
- Over-constraining of the PCB resulting in reduced package compliance and larger strain transfer to solder joints along with the DNP effect.

Figure 1. Displacement magnitude of control board at 125°C (20x mag).

Figure 2. Displacement magnitude of control board at -55°C (20x mag).

Figure 3. Displacement magnitude of mirrored board at 125°C (20x mag).

Figure 4. Displacement magnitude of control board at -55°C (20x mag).
➢ Corners joints for mirrored BGA package show a 25% increase in strain magnitude compared to single sided configuration at the start of the first high temperature dwell of 125°C.

➢ After 3 thermal cycles, peak difference between mirrored and control boards indicate 2x increase in strain energy density.
Influence of Board Mounting and Housing
Influence of Board Mounting and Housing

➢ Mounting points directly influence board strains during thermal expansion and vibration loading.
➢ Proximity of mounting points and connectors to components should be factored in reliability assessment with the intended use environment.
➢ Interaction of potting compounds with housing and thermal management of assembly should be considered.
Physics of Failure Methodology
Physics of Failure (PoF) Approach

- Accuracy of the models depend on simplifying assumption of material properties.
- PoF models are deterministic in nature and cannot be applied to all failure mechanisms.
- PoF approach enables us to track effects of material change on component reliability under wear out failure mechanisms.
- Models offer the ability to evaluate reliability performance based on both extrinsic and intrinsic parameters of electronic components.
- An accurate PoF approach consists of a combination of analytical equations, numerical simulations.
Physics of Failure Approach

- Case study: Reliability of Quad-flat no-lead (QFN) packages.

Steps:
1. Create geometric dependency with material properties
2. Simplify material properties dependence on loading conditions
3. Apply constitutive models with material properties to calculate mechanical behavior of interconnects.
4. Introduce appropriate damage parameter to fatigue behavior of solder interconnects.
Solder Alloy Selection Approach
Solder Alloy Selection Approach

- With an increase variety of electronic packages there is an inherent decrease in overall board reliability.
- Reliability of solder alloys depends on a combination of package type, board properties, operational environment and manufacturing quality.
- Fatigue crack propagation path is sensitive to as reflowed solder grain morphology and loading orientation.

Solder Alloy Selection Approach

- Example of drop and thermal cycling performance of BGA with SAC alloys of different silver content.
- Reliability of solder alloys greatly depends on the test type and alloy content.

- Global loading conditions dominate thermal Mechanical Fatigue loading which overcome the benefits of increase fatigue Resistance of some high temperature solder alloys

Tools for Solder Fatigue

➢ Free solder fatigue calculator available at dfrsolutions’s website along with extensive resources for electronics reliability.

http://www.dfrsolutions.com/reliability-calculators
Conclusion & Recommendations

➢ Thermomechanical fatigue of solder interconnects largely depends on configuration and material properties of the components used.

➢ PCB selection for qualification tests and production should consist of the same materials and geometries to avoid inconsistencies in failure rates. Board selection should take into consideration the CTE and modulus of the final assembly.

➢ Avoid acrylics with glass transition temperature within operating or environmental temperature change.

➢ PoF approach should be implemented along with solder alloy selection procedures.

➢ Simulation results should be assessed with evaluation of test data to prevent early fatigue failures.
Thank you for your attention!!!

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