Reliability Tests and Assessment for Electronic Products

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November 2, 2016
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Education:
- Ph.D. in Industrial and Systems Engineering
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- B. S. in Mechanical Engineering
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Previous Experience:
- Assistant Professor at Rose-Holman Institute of Technology, Terre Haute, IN
- Research Associate, AREA Consortium/Universal Instrument Corp., Conklin, NY
Presenter

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Teaching:

Reliability Engineering
Electronics Manufacturing Systems
Quality Design and Control

Research:

Reliability of Electronic Components and Assemblies
Fatigue and Damage Accumulation in Solder Materials
Agenda

- Electronics Manufacturing Industry
- Electronics Reliability Issue
- Reliability Tests for Electronic Products
- Electronics Reliability in Thermal Cycling (Case Study)
- Electronics Reliability Models (Case Study)
- Design of Experiment (DOE) in Electronics Reliability
Electronics manufacturing is unique
- High level of automation, flexibility, and cost optimization
- Affordable sophisticated products

Business challenge: Short product lifecycle
- Rapid Evolution & New Product Introduction
- Intel spent 11.5 billion on R&D in 2014 (21% of Total Revenue)
Electronics Manufacturing

- Electronics everywhere

- Materials, designs and manufacturing processes are optimized as a trade-off between cost, quality and reliability
  - Cell phone: cheap and not reliable
  - Aircraft: very expensive and very reliable
Electronic Products Classification

- **Class I: Consumer products such as TV, cell phone**
  - Service life is less than five years
  - Low cost of failure

- **Class II: Dedicated/Industrial/Telecom products**
  - Service life is longer than class I
  - High cost of failure

- **Class III: Critical products such as aerospace or medical devices**
  - Service life is more than twenty years
  - Failure can be life threatening
Electronic Components

Reliability Issues
What is Reliability?

- Reliability is “the ability of a product to function under given conditions and for a specified period of time without exceeding acceptable failure levels.”

- Reliability is the major issue for electronic assemblies (any single defect leads to complete failure)

- Solder joints are the weakest connection

- Temperature change is the major threat
Temperature Variation Effect

- Temperature changes lead to stresses caused by coefficient of thermal expansion mismatch (CTE)

Heat leads to stresses induced by CTE mismatch
What Does Actually Happen?

- Damage process in thermal cycling:
  - Creation and rotation of dislocation cell structure
  - Global recrystallization and continuous growth
  - Crack along continuous network of grain boundaries
What Does Actually Happen?

- Reliability depends also on the microstructure!
Reliability Tests for Electronic Products

- Thermal Cycling
- Vibration or High Cycling Fatigue (random, fixed frequency, resonance tracking)
- Low Cycling Fatigue
- Mechanical Shock (Drop Test)
- Thermal Shock (air to air, or liquid to liquid)
- Aging (temperature, humidity)
Reliability Tests for Electronic Products

▪ Two common reasons for accelerated life tests:
  • To compare between alternatives (material, design, etc.)
  • To predict life or reliability in real service (requires model)

▪ What could affect on electronic assembly life in accelerated tests?
  1. Component type  
  2. Substrate type  
  3. Solder paste material  
  4. Solder spheres material  
  5. Pad material  
  6. Flux material  
  7. Reflow oven temperature profile  
  8. Aging time  
  9. Aging temperature  
  10. Heatsink  
  11. etc.
Thermal Cycling Accelerated Tests

Typical Thermal Cycling Profile

Temperature (°C)

Time (minutes)
Case Study - Thermal Cycling

- New SBGA (super ball grid array) components
- Three candidate of solder materials (SAC105, SAC305, Innolot)
- Which solder material is better for the thermal cycling reliability?
Case Study - Thermal Cycling

- Thermal cycle test profiles: -40°C to +125°C, 15min dwell, 15min transition
Case Study - Thermal Cycling

- Experimental Setup

Thermal Cycling Test -40 to 125° C
Case Study - Thermal Cycling

- Experimental Setup

Use CAVE’s continuous sampling monitoring system
### Data (number of cycles to failure)

<table>
<thead>
<tr>
<th>SAC305</th>
<th>Innolot</th>
<th>SAC105</th>
</tr>
</thead>
<tbody>
<tr>
<td>1321</td>
<td>1496</td>
<td>1120</td>
</tr>
<tr>
<td>1489</td>
<td>1689</td>
<td>1325</td>
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<td>1694</td>
<td>1889</td>
<td>1789</td>
</tr>
<tr>
<td>1711</td>
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<td>1856</td>
</tr>
<tr>
<td>1769</td>
<td>2015</td>
<td>1976</td>
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<tr>
<td>1840</td>
<td>2092</td>
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<td>1898</td>
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</tr>
<tr>
<td>1965</td>
<td>2260</td>
<td>2478</td>
</tr>
<tr>
<td>1997</td>
<td>2324</td>
<td>2571</td>
</tr>
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</table>

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**Probability Plot for SAC105, SAC305, Innolot**

Weibull

![Graph showing probability plot for SAC105, SAC305, and Innolot. The plot includes a table of statistics with parameters such as shape, scale, and confidence levels.](image-url)
In many cases, it’s misleading to compare only based on the characteristic life (scale parameter). It should be based on:

- Reliability at specified life (number of cycles), or
- Number of cycles to accumulate a specified percentile of failure

When you compare only based on the characteristic life, you are comparing based on the number of cycles to accumulate 63% of failure

In electronics, we mainly concern about early failure (~1% or so)
Case Study - Reliability

- Reliability at specified life (number of cycles):
  \[ R(t) = \exp[-(t/\text{scale})^{\text{shape}}] \]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Shape Parameter</th>
<th>Scale Parameter</th>
<th>R(1000)</th>
<th>R(1500)</th>
<th>R(2500)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC105</td>
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<td>1793</td>
<td>0.9977</td>
<td>0.8545</td>
<td>~0</td>
</tr>
<tr>
<td>SAC305</td>
<td>9.09</td>
<td>2034</td>
<td>0.9984</td>
<td>0.9392</td>
<td>0.0015</td>
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<tr>
<td>Innolot</td>
<td>4.76</td>
<td>2041</td>
<td>0.9670</td>
<td>0.7939</td>
<td>0.072</td>
</tr>
</tbody>
</table>

- It is more practical to compare based on the number of cycles to accumulate a certain percentile failure
Case Study - Reliability

- Percentile of failure = 1 – Reliability

\[ R(t) = \exp \left[ - \left( \frac{t}{\text{scale}} \right)^{\text{shape}} \right] \iff t = \text{scale} \left[ \left( \text{-Log } R \right)^{\left(\frac{1}{\text{shape}}\right)} \right] \]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Shape Parameter</th>
<th>Scale Parameter</th>
<th>1% failure</th>
<th>5% failure</th>
<th>10% failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC105</td>
<td>10.37</td>
<td>1793</td>
<td>1151</td>
<td>1346</td>
<td>1443</td>
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<td>2034</td>
<td>1226</td>
<td>1467</td>
<td>1588</td>
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<tr>
<td>Innolot</td>
<td>4.76</td>
<td>2041</td>
<td>776</td>
<td>1094</td>
<td>1272</td>
</tr>
</tbody>
</table>

- Assumption: the best alloy in the test will perform the same in real service
  - Failure mechanism in test should be same as failure in service
Case Study - Failure Analysis

Crack initiate closed to board-side and package side IMC layer

Crack Propagation through the solder bulk
Vibration Test

- Many electronic assemblies are under mild vibration in realistic applications (vehicle applications)

- Accelerated vibration tests are used to assess the reliability of those electronic components

- Typical vibration test equipment:
  - Strain Gage System
  - Laser Vibration Sensor
  - Accelerometer

-70°C to +190°C
Sine Vibration Test – Fixed Frequency

- Sweep test is used to determine the resonance (natural frequency): fixed vibration power (g level) and change frequency

- Then vibration test is performed at fixed g level and fixed frequency (at initial resonance)
Sine Vibration Test – Resonance Tracking

- Resonance typically shifts due to micro-damage in the electronics board or loose of fixture

- Vibration test is performed at fixed g level and at ‘on-time’ resonance
Vibration Test – Random Vibration

- Random Vibration:
  - Excite all the frequencies in a defined spectrum at any given time
- Very realistic
- Not useful for reliability modeling
Low Cycling Fatigue

- Bending (three or four points bending) test
- Tension-compression test
- Shear fatigue
Shock

Thermal Shock (Liquid to Liquid)
Hot Bath: Ambient to +160°C
Cold Bath: Ambient to -75°C

Thermal Shock (Air to Air)
Hot: +200°C
Cold: -73°C

Mechanical Shock Drop Test
Reliability Models

- To predict the fatigue life under conditions of interest
- Most common reliability models are ‘Covariate Models’
- ‘Covariate Models’: Assume a reliability distribution (i.e. Weibull), and define one or more of the distribution parameters as a function of operating variables (operating temperature, voltage, stress, humidity, dimensions, frequency, etc.)
- Thousands of reliability models have been published
- In many cases, accelerated life test is used to find constants/parameters to use such a reliability model
Example: Thermal Cycling Model

- To predict the reliability of SnAgCu solder joints in thermal cycling
- Reliability distribution is Weibull:

  Characteristic Life = \frac{\psi}{1 + \frac{\alpha}{\beta} * t_{dwell}}

  \psi = \text{the dislocation density}

  \alpha = \text{dislocation generation during ‘steady state’}

  \beta = \text{the work done during the initial part of the dwell}

- Accelerated life test is used to find constants/parameters to use such a reliability model

P. Borgesen, L. Wentlent, A. Qasaimeh, D. Schmitz, S. khasawneh and s. shirazi “A Mechanistic model for thermal fatigue of sNagcu solder joints”
How To Develop a Reliability Model
Case Study of Isothermal Cycling of Individual Solder Joint

- There is no one approach to develop a reliability model

- Develop a general model to predict fatigue life of solder joints under varying stress cycling
  - SAC305 Alloy (Sn 96.5%, Ag 3%, Cu 0.5%)
  - Room Temperature
  - Fresh material (no aging)
Experiment

Individual solder joints were soldered onto copper pads on typical BGA substrates.

Isothermal shear cycling using an Instron Micromechanical tester.
Experiment (cont’d)

- The Instron tester records the load and displacement data continuously, providing a hysteresis loop for each cycle.
- Area within loop gives inelastic energy (work).

<table>
<thead>
<tr>
<th>Stress</th>
<th>Replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 MPa</td>
<td>7</td>
</tr>
<tr>
<td>24 MPa</td>
<td>7</td>
</tr>
<tr>
<td>20 MPa</td>
<td>7</td>
</tr>
<tr>
<td>16 MPa</td>
<td>7</td>
</tr>
</tbody>
</table>
Fatigue Life vs. Stress

- Fatigue life is a power equation of Stress (N = a $\sigma^{-c}$)

![Probability Plot for 28 MPa, 24 MPa, 20 MPa, 16 MPa](image)

Weibull - 95% CI

<table>
<thead>
<tr>
<th>Variable</th>
<th>Shape</th>
<th>Scale</th>
<th>AD*</th>
<th>F</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 MPa</td>
<td>5.25567</td>
<td>77.12</td>
<td>0.959</td>
<td>7</td>
<td>0</td>
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<tr>
<td>24 MPa</td>
<td>2.66497</td>
<td>249.88</td>
<td>0.954</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>20 MPa</td>
<td>3.17544</td>
<td>798.63</td>
<td>0.959</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>16 MPa</td>
<td>2.27359</td>
<td>3099.11</td>
<td>0.959</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

Table of Statistics

![Graph showing the relationship between Stress (MPa) and Life (Cycles)](image)

$y = 3E+11x^{-6.553}$

10000

1000

100

10

14

14

20

24

28

Stress (MPa)

Life (Cycles)
Inelastic Work Accumulation is Constant

- The accumulated work to failure is almost constant regardless to stress value or loading conditions
Inelastic Work – Fixed Amplitude

- Inelastic work describes the fatigue life behavior of solder joint:
Inelastic Work – Varying Stress

- Work is amplified in after each excursion to higher amplitude
New Damage Accumulation Rule

- The phenomenon of damage acceleration together with the concept of constant work accumulation has led to a new rule:

\[ 1 = \sum_{i=1}^{s} f(i) \frac{n_{mi}}{N_m} + \frac{n_{hi}}{N_h} \]

- Where \( f(i) \) is the damage acceleration function that can be represented by work amplification

- This rule is for the combination of two alternating amplitudes

- Realistic applications include more than two amplitudes

- Still need to generalize to combinations of more than 2 amplitudes
Combinations of Three Amplitudes

- Due to the variability: measured the effect of sequence of amplitudes on the same solder joint (paired comparison)

- Example: Repeating the sequence

![Graph showing work per cycle (Joule) vs. number of cycles for different combinations of amplitudes: 16MPa + 24MPa + 16MPa + 20MPa]
Based on the constant accumulated inelastic work to failure a general damage accumulation model is proposed:

\[ 1 = \sum_{i} M_i \frac{n_i}{N_i} \]

- \( M_i \) is a multiplier representing the loading history, calculated:

\[ M_i = \prod_{r=1}^{r=i-1} A_{i,i-r} \]

\( A_{i,i-r} \) is the damage acceleration factor at stress \( \sigma_i \) due to the effect of stress \( \sigma_{i-r} \).
General Model (cont’d)

- Behavior of the damage acceleration factor ($A_{i,i-r}$):
Final Isothermal Damage Interaction Model

- To predict the fatigue life of SnAgCu solder joints in varying amplitude cycling at room temperature:

\[
1 = \sum_{i} \left( \frac{n_i}{N_i} \times \prod_{r=1}^{r=i-1} (A_{i,i-r}) \right)
\]

\[
A_{i,i-r} = \begin{cases} 
1 \\
1 + \min \left\{ f(\sigma_i) \left( \frac{n_{i-r}}{N_{i-r}} \right), c_1 \left( \frac{\sigma_{i-r} - \sigma_i}{\sigma_i} \right)^{d_1} \right\} & , \sigma_i \geq \sigma_{i-r} \\
1 & , \sigma_{i-r} \leq \sigma_{i-r-1} \\
\end{cases}
\]

- Accelerated life test is used to find constants/parameters to use such a reliability model
Design of Experiment (DOE) Case Study
Thermal Cycling Accelerated Test

Study the life of CABGA (Chip Array Ball Grid Array) in thermal cycling with temperature (-40C to 125C)

Response: Life (cycles)

Factors (6 Factors):

<table>
<thead>
<tr>
<th>Factor</th>
<th>Type</th>
<th>Levels</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Fixed</td>
<td>2</td>
<td>FR406, Megtron6</td>
</tr>
<tr>
<td>Solder Paste</td>
<td>Fixed</td>
<td>3</td>
<td>Innolot, SAC305, SnPb</td>
</tr>
<tr>
<td>Reflow Profile</td>
<td>Fixed</td>
<td>2</td>
<td>TC1-Bot, TC1-Top</td>
</tr>
<tr>
<td>Aging (Months)</td>
<td>Fixed</td>
<td>4</td>
<td>0, 6, 12, 24</td>
</tr>
<tr>
<td>Aging Temp. (Celsius)</td>
<td>Fixed</td>
<td>3</td>
<td>25, 50, 75</td>
</tr>
<tr>
<td>Solder Spheres</td>
<td>Fixed</td>
<td>5</td>
<td>Innolot, SAC-Y, SAC105, SAC305, SnPb</td>
</tr>
</tbody>
</table>
Solder Sphere & Solder Paste

Solder Paste Material: Innolot, SAC305, SnPb
Solder Sphere Material: Innolot, SAC-Y, SAC105, SAC305, SnPb
Printed Circuit Board (Substrate)

Substrate Type (PCB): FR406, Megtron6
Reflow Temperature Profile

Reflow Profile: TC1-Bot, TC1-Top
TC1-Bot: Max Temp = 250°C
TC1-Top: Max Temp = 240°C
Aging Time and Temperature

- Aging time: 0, 6, 12, 24 months
- Aging Temperature: 25, 50, 75°C
<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Adj SS</th>
<th>Adj MS</th>
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<th>P-Value</th>
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<tbody>
<tr>
<td>Substrate</td>
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<td>54188884</td>
<td>702.44</td>
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<td>1241922</td>
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<td>Reflow Profile*Aging Temp. (Celsius)</td>
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<td>12826</td>
<td>6413</td>
<td>0.08</td>
<td>0.920</td>
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</table>
## Main Effect Plots

### Main Effects Plot for Failed At

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Solder Paste</th>
<th>Reflow Profile</th>
<th>Aging (Months)</th>
<th>Aging Temp. (Celsius)</th>
<th>Solder Spheres</th>
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</thead>
<tbody>
<tr>
<td>FR406</td>
<td>Megtron6</td>
<td>Innolot</td>
<td>SAC305</td>
<td>TC1-Top</td>
<td>TC1-Bot</td>
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<tr>
<td></td>
<td>SAC105</td>
<td>SAC-Y</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>SAC-Y</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>SnPb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
P = 0.503\]
Interaction Effect Plots

Interaction Plot for Failed At Data Means

Substrate: FR406

Solder Paste: Innolot

Reflow Profile: 

It does not matter

Aging (Months)

Aging Temp. (Celsius)
Best Combination

- Innolot Solder paste and Innolat solder sphere on FR406 Substrate

- Innolot is more expensive!!!
Summary

- Electronics Manufacturing Industry
- Electronics Reliability Issue
- Reliability Tests for Electronic Products
- Electronics Reliability in Thermal Cycling (Case Study)
- Electronics Reliability Models (Case Study)
- Design of Experiment (DOE) in Electronics Reliability
Research Group

Dr. Hamasha

Dr. Evans

Left to right: Anto, Francy, Thomas, Sinan, Sharath, Seth, Cong, Sa’d, Gayatri

Industrial & Systems Engineering
Reliability Tests and Assessment for Electronic Products

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