Lifetime Prediction and Design Tool Development for Power Electronics Modules

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CMRG of University of Greenwich

- One of largest modelling research groups in the UK
- Started 1984.
- Focus on Manufacturing Processes
- Skills and technology
  - Finite Element Analysis
  - Computational Fluid Dynamics
  - Optimisation
  - Visualisation facilities
- High performance computing facilities
Outline

• Power Electronics Module (PEM)
  – structure failure and reliability prediction
• Computer simulation of PEM
  – Wirebond, solder joint
• Lifetime prediction of a Dynex PEM
• Active cooling
• Design tool development
• Conclusions
Challenges in Power Electronics

- Increased power densities
- High reliability in extreme operating environments
- Lower EM emissions
- Higher levels of integration
  - SOC + SiP
Power Module Structure

Power modules are self-contained power electronics components that contain power semiconductor devices such as IGBT.

- a: wire bond
- b: solder
- c: ceramic substrate
- d: bus bar solder joint
- e: encapsulation

[Diagram of power module structure]
Failures in Power Modules

Key challenges: Accurately predict lifetime and use the information to improve PEM design.
Lifetime Prediction Method

• Wear-out failure is often caused by fatigue
  – mismatch of the coefficient of thermal expansion in PEMs causes fatigue. Vibration is another cause.

• Physics of Failure lifetime prediction is used
  – Damage indicators
    • Dependent on design, materials and loading conditions
    • Obtained using Finite Element analysis.
  – Lifetime models
    • The inputs are damage indicators and material dependent constants
    • Can be obtained through experiment + modelling
Damage Indicators for Lifetime Prediction

• Stress amplitude
  – High cycle fatigue \( \sigma_m = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \)

• Accumulated plastic strain per cycle \( \Delta \varepsilon_p = \int_{t}^{t+\tau} d\varepsilon_p \)
  – Low cycle fatigue

• Accumulated plastic work density \( \Delta W_p = \int_{t}^{t+\tau} \sigma d\varepsilon_p \)
  – Low cycle fatigue
Lifetime Model for Solder Interconnect

- Solder joints are thermal cycled, crack length $L$ after $N$ cycles
- A number of solder joint geometry, or load profiles are used in the experiment to give different $L/N$ values
- Computer run under the same as in the experiments
- Plastic strain per cycle $\Delta \varepsilon_p$ obtained from simulation results.
- The constants in the lifetime model are adjusted to get the best fit
- $a=0.00562$, $b=1.023$

$$\frac{L}{N_L} = a \left( \Delta \varepsilon_p \right)^b$$

Lifetime model

$L$ is in mm
Substrate and Chip Solder Joint
The substrate solder joint is the largest in a PEM. Using average or maximum damage value to calculate lifetime is not accurate. The effect of crack propagation has to be taken into account.

- Aspect ratio: 56/0.1=560!

- The substrate solder joint is the largest in a PEM
- Using average or maximum damage value to calculate lifetime is not accurate
- The effect of crack propagation has to be taken into account
Large Solder Joint Lifetime Prediction

- Divide crack path into small sections
- Number of cycles to failure $N_i$ for each load condition along crack path are calculated
  \[ N_i = \frac{L_i}{a(\Delta \varepsilon_p)_i^b} \]
- The lifetimes, $NF_i$, of each crack section are calculated using $N_i$ and the Miner’s law
- Example:
  \[
  \frac{n_1}{N_1} + \frac{n_2}{N_2} = 1 \quad NF_1 = N_1
  \]
  \[
  n_1 = N_1 \left(1 - \frac{n_2}{N_2}\right) = N_1 \left(1 - \frac{N_1}{N_2}\right)
  \]
  \[
  NF_2 = n_1 + n_2 = n_1 + N_1 \left(2 - \frac{N_1}{N_2}\right)
  \]
  \[
  N_1 < NF_2 < 2N_1
  \]
# Traction Control and Mission Profiles

## Traction Application: Mass Transit

<table>
<thead>
<tr>
<th>Status</th>
<th>$T_{\text{min}}$</th>
<th>$T_{\text{max}}$</th>
<th>Cycles/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shed stops</td>
<td>-40°C</td>
<td>+80°C</td>
<td>1</td>
</tr>
<tr>
<td>Station Stops</td>
<td>+80°C</td>
<td>+100°C</td>
<td>1080</td>
</tr>
</tbody>
</table>

## Traction Application: high speed.

<table>
<thead>
<tr>
<th>Status</th>
<th>$T_{\text{min}}$</th>
<th>$T_{\text{max}}$</th>
<th>Cycles/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shed stops</td>
<td>-40°C</td>
<td>+80°C</td>
<td>1</td>
</tr>
<tr>
<td>Station Stops</td>
<td>+80°C</td>
<td>+100°C</td>
<td>20</td>
</tr>
<tr>
<td>Speed Control</td>
<td>+80°C</td>
<td>+85°C</td>
<td>3240</td>
</tr>
</tbody>
</table>

Failure definition: crack length= 2.8mm, this is equivalent to about 20% area crack.

There are 4 unique load profiles

**Shed stop:**
over night storage in extremely cold environment

**Station stops:**
stop at station during service

**Speed control:**
action of the automated speed control system
Traction Control PEM Lifetime prediction

Predicted lifetime for each single load temperature profile.

<table>
<thead>
<tr>
<th>Solder Thickness</th>
<th>shed</th>
<th>speed</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 mm</td>
<td>6.94E+03</td>
<td>1.25E+09</td>
<td>2.24E+05</td>
</tr>
<tr>
<td>0.2 mm</td>
<td>8.26E+03</td>
<td>1.50E+09</td>
<td>2.64E+05</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>8.99E+03</td>
<td>1.61E+09</td>
<td>2.84E+05</td>
</tr>
</tbody>
</table>

Calculated lifetime for railway traction control applications

<table>
<thead>
<tr>
<th>solder thickness</th>
<th>high speed (years)</th>
<th>mass transit (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 mm</td>
<td>11.61</td>
<td>0.55</td>
</tr>
<tr>
<td>0.2 mm</td>
<td>13.76</td>
<td>0.65</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>14.93</td>
<td>0.70</td>
</tr>
</tbody>
</table>

- Lifetime for PEM for the high speed application is much longer than for the mass transit because of the number of station stops.
- Solder joint thickness effects

\[ y = 3.0306 \ln(x) + 18.601 \]
Sensitivity Analysis: Effects of Solder Joint Geometry

- Solder joint life is determined by the geometric parameter
- Their effects are investigated using computer modelling and a 3-parameter DOE
- DOE method: Composite Method
- Number of points in design space: 15
DOE and Response Equation

- Solder thickness is the most important design parameter for reliability
- Substrate size has very little effect
- Optimization can be carried out using the response equation

\[ \Delta \varepsilon_p = c_0 + c_1 x_1 + c_2 x_2 + c_3 x_3 + c_{12} x_1 x_2 + c_{13} x_1 x_3 + c_{23} x_2 x_3 + c_{11} x_1^2 + c_{22} x_2^2 + c_{33} x_3^2 \]

<table>
<thead>
<tr>
<th>x1</th>
<th>x2</th>
<th>x3</th>
<th>damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>0.015824</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>0.014357</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>0.015823</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>0.014353</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0.01536</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0.009185</td>
</tr>
<tr>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0.009183</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0.009409</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0.008704</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.009184</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.007004</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>0.006602</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>0.007003</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0.0066</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.006876</td>
</tr>
</tbody>
</table>
Crack Propagation Based on The Disturbed State Concept

• Damage accumulates in solder under cyclic loading
• Material is divided into two parts: intact and damaged
• Continuous damage parameter $D$ is used to quantify the fraction of the damaged solid

\[ D = 0 \quad 0 < D < 1 \quad D = 1 \]

7000 cycles
D and Young’s Modulus E

• Assumption: damage is linked to the Young’s modules $E$ through:

$$E_{\text{avg}} = (1 - D)E_{\text{intact}}$$

• $D$ is a function of the accumulated plastic strain $\varphi_{\text{acc}}$

$$D = 1 - e^{-B\varphi_{\text{acc}}} \quad B \text{ is a material parameter}$$

- From an earlier work on chip resistors the $B$ value has been estimated to be 0.05
Experiments and Simulations

- $T=40$ to $120^\circ C$
- Number of cycles = 1800

Test results

Nottingham university
Crack Propagation

12.25 cycles, $B_{\text{sim}} = 30$

$N_f = N_{f_{\text{sim}}} \frac{B_{\text{sim}}}{B} = 12.25 \times \frac{30}{0.05} = 7350$

Final damage distribution almost fully cracked
\[ N_f = N_{f_{sim}} \frac{B_{sim}}{B} = 9 \times \frac{15}{0.05} = 2700 \]
Improving Wirebond Reliability

Lifetime model

\[ N_f = 1.18 \varepsilon_p^{-3.492} \]
Wirebond formation and failures

Wirebond lifting

Fatigue crack after 1500 thermal cycles for wire bonds
Wirebond Reliability

- Failure mechanism
  - Wirebond lifting
  - Heel cracking
- Causes
  - fatigue fracture (results of CTE mismatch, wire flexing, vibration)
- Improvement of reliability:
  - increasing fatigue resistance
    - bonding at elevated temperatures
  - selection of materials
- Reduce stress
  - selection of materials and geometry (loop height, wire size) and
  - use of globtop
Effect of Wire Diameter

Wire diameters: 150, 225, 300, and 375 microns
No globtop is included

<table>
<thead>
<tr>
<th>D (microns)</th>
<th>150</th>
<th>225</th>
<th>300</th>
<th>375</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max plastic strain nodal</td>
<td>0.17</td>
<td>0.24</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>increase</td>
<td>0</td>
<td>41%</td>
<td>82%</td>
<td>106%</td>
</tr>
</tbody>
</table>

Strain doubles as D changes from 150 to 375 microns!
Effect of Loop Height

Loop height has to be much greater to have significant effect on reliability.

<table>
<thead>
<tr>
<th>Loop height H(mm)</th>
<th>1.1875</th>
<th>1.5625</th>
<th>1.9375</th>
<th>2.3125</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max plastic strain nodal</td>
<td>0.372</td>
<td>0.362</td>
<td>0.357</td>
<td>0.35</td>
</tr>
<tr>
<td>increase</td>
<td>0%</td>
<td>-2.7%</td>
<td>-4%</td>
<td>-6%</td>
</tr>
</tbody>
</table>

\[ y = 0.3775x^{-0.088} \]
\[ R^2 = 0.9894 \]
Globtop

- Globtop has been used in power modules (Dynex, Semelab..) to
- Improve reliability through stress reduction

- Its effects have not been analysed in detail
Effect of Globstop Geometry

10 micron gap in model 9. It is filled with globstop in other models.
Effect of Globtop Geometry: Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness(μm)</td>
<td>430</td>
<td>346</td>
<td>280</td>
<td>194</td>
<td>0</td>
</tr>
<tr>
<td>$\sigma_{vm}$ (Gpa)</td>
<td>172</td>
<td>177</td>
<td>183</td>
<td>190</td>
<td>191</td>
</tr>
<tr>
<td>Change %</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>10.4</td>
<td>11</td>
</tr>
</tbody>
</table>

Models 5 to 8 have almost the same maximum stress = 230 MPa

Model 9 (no globtop) Max stress = 464 MPa

- The thin gap below the heel is the most important location to be filled
- It’s also important that both ends should have globtop
Effect of Globtop Material Properties

Properties that have been investigated:
- Young’s modulus $E$
- Coefficient of thermal expansion (CTE)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al metalization</td>
<td>10 microns</td>
</tr>
<tr>
<td>AlN</td>
<td>0.32 mm</td>
</tr>
<tr>
<td>Cu</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>SnAg solder</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Die</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Al wire diameter</td>
<td>0.375 mm</td>
</tr>
</tbody>
</table>
Effect of Globtop Young’s Modulus (E)

For fixed CTE, optimal E is about 2GPa

Failure mode may change from bond lifting to heel cracking for high E globtop
Effect of CTE @ E=2GPa

• CTE from 20 to 50 ppm, E=2GPa

• 26% decrease in plastic strain as CTE increases from 20 to 40 ppm.

• CTE > 40 ppm, strain increases slightly and the maxima moves from the heel to the interface

• Strain at the interface increases as CTE increases
Effect of CTE: Summary

- Increase the globtop CTE will
  - Increases strain at bonding interface
  - Decrease strain at the bond heel
  - May change maxima location (and therefore crack location)
  - An optimal combination of E and CTE can achieve the lowest plastic strain in Al wire

<table>
<thead>
<tr>
<th></th>
<th>CTE=20</th>
<th>CTE=30</th>
<th>CTE=40</th>
<th>CTE=50</th>
</tr>
</thead>
<tbody>
<tr>
<td>E=1</td>
<td>0.08624</td>
<td>0.08806</td>
<td>0.089159</td>
<td>0.0899</td>
</tr>
<tr>
<td>E=2</td>
<td>0.093054</td>
<td>0.078694</td>
<td>0.06615</td>
<td>0.06893</td>
</tr>
<tr>
<td>E=3</td>
<td>0.14526</td>
<td>0.119015</td>
<td>0.095667</td>
<td>0.07611</td>
</tr>
</tbody>
</table>

Yellow: heel cracking
Green: wire lifting
Power Module Lifetime Prediction

- Predict the lifetime of the Dynex power module under qualification test condition
Simulations

Plastic strain in solder layers
Lifetime Prediction Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>busbar</td>
<td>946</td>
</tr>
<tr>
<td>wirebond</td>
<td>10489</td>
</tr>
<tr>
<td>chip</td>
<td>14889</td>
</tr>
<tr>
<td>substrate</td>
<td>29996</td>
</tr>
</tbody>
</table>

- Busbar has significantly lower lifetime than other components
- The busbar that will fail first is the one that
Active Cooling Technologies

Definition: Requires energy input to drive the cooling system

- Micro-Channels
- Jet-Impingement / Spray Cooling
- Micro-Channels/Staked System
- Fans
- Thermoelectric and Thermionic Devices
Jet Impingement Cooling for Power Modules

Baseplate Cooler

Flow Profiles

Temperature

Inlet
Outlet

Baseplate Design

Model Courtesy: University of Nottingham
Prognostics and Health Monitoring

• Assessing extent of deviation or degradation from its expected state and predicting remaining useful life.

Model Driven: Physics-of-Failure

• **Fusion prognostics** combines precursor monitoring and trending (data-driven models) and the use of physics of failure models.
Generate & Analysis of Load Profile

**Current vs. time**

![Current vs. time graph](image1)

**Temperature vs. time**

![Temperature vs. time graph](image2)

**Transfer function**

![Transfer function graph](image3)

**Rainflow analysis**

![Rainflow analysis graph](image4)

- **Number of cycles**
  - ΔT (°C)
  - Peaks from signal

- **Temp. estimates (°C)**
  - Peaks, counted from 0
Lifetime Prediction for Solder Interconnect

• **Lifetime prediction model**

\[
\frac{L}{N_L} = 0.00562 \left( \Delta \varepsilon_p \right)^{1.023}
\]

\( N_L : \text{Cycles} \)

\( L : \text{Crack length (20\% Area: Failure Criteria)} \)

• **Lifetime Consumption (Palmgren-Miner rule)**

\[
D = \frac{N_1}{N_{f1}} + \frac{N_2}{N_{f2}} + \frac{N_3}{N_{f3}} + \ldots = \sum \frac{N_i}{N_{f_i}}
\]

• **Illustrative example**

<table>
<thead>
<tr>
<th>( \Delta T(\text{C}) )</th>
<th>5-15</th>
<th>15-25</th>
<th>&lt;5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Temp</strong></td>
<td>50</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>No. Cycles (Rainflow Algorithm)</td>
<td>3000</td>
<td>2000</td>
<td>6000</td>
</tr>
<tr>
<td>Predicted (PoF) Cycles to Failure</td>
<td>300,000</td>
<td>20,000</td>
<td>60,000,000</td>
</tr>
<tr>
<td>Life Consumed (D)</td>
<td>1%</td>
<td>10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Life Consumed after 11,000 cycles</td>
<td>11.01%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Real-Time Prognosis

• Real time electro-thermal models
• Real time thermo-mechanical models
• Precursor Models
• Life consumption
Module Design
Load Condition & Predict Lifetime
Conclusions

- Physics of Failure approach to reliability is essential in accurate lifetime prediction.
- Lifetime models have been developed to predict the lifetime of power modules.
- Integrated, PEM design tool has been developed. This will make physics of failure reliability analysis easy to use.