A Solder Joint Reliability Model for the Philips Lumileds LUXEON Rebel LED Carrier Using Physics of Failure Methodology

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Abstract
Light Emitting Diodes (LEDs) are quickly evolving as the dominant lighting solution for a wide variety of applications. With the elimination of incandescent light bulbs and the toxic limitations of fluorescent bulbs, there has been a dramatic increase in the interest in high-brightness light emitting diodes (HB-LEDs). Getting the light out of the die, with reliable color, while maintaining appropriate thermal control over a long service life is a challenge. These issues must be understood and achieved to meet the needs of unique applications, such as solid-state-lighting, automotive, signage, and medical applications. These applications have requirements for 15-25 years of operation making their reliability of critical importance.

The LUXEON Rebel has been accepted as an industry leading LED product, widely used in Mean-Time-Between-Failure (MTBF) sensitive applications. Customers use various mounting platforms, such as FR4 Printed Circuit Board (PCB), FR4 PCB with thermal via's, Aluminum & Copper Metal Core printed Circuit Boards (MCPCB), Super MCPCB, etc. As in other LEDs, when mounting to a platform where a large Coefficient of Thermal Expansion (CTE) exists between the LED & the PCB, Solder fatigue could become an issue that may affect system level lifetime.

In this paper we have examined extreme cases and how a solder joint can impact system level reliability. We have modeled the conditions and formed a means to predict system level reliability. We have compared the prediction modeling with empirical tests for validation of the models.

It is vital to understand system level reliability factors to build lighting solutions that match the application and customer expectations. It is impractical to test LEDs and other components for 50k hours ~5 years since the device evolution is much faster than that – on average one LED generation every 12-18 month. Hence we need models and prediction methods …..

Keywords: Light Emitting Diodes (LED), Solder Joint, Modeling, Validation, Empirical Testing

Introduction

Philips Lumileds, in conjunction with DfR Solutions, developed solder joint reliability models for the LUXEON Rebel LED family with respect to multiple circuit board construction types and material sets. Solder fatigue lifetime was predicted based on strain energy calculations. Finite element models were developed to calculate shear stress and strain range as shown in Figure 1. Since the model is fully 3D boundary conditions were applied to the faces of the printed circuit board (sides) to reflect periodic symmetry. This requires two sides on the origin, the xz face, and the yz face to be constrained in the y and x direction respectively. The opposite xz and yz face have a constraint equation applied to maintain planarity of the nodes. One node of the origin is constrained in the z direction to prevent free-body motion.

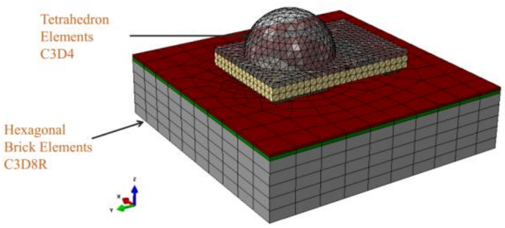


Figure 1 – Example of meshed model developed for LUXEON Rebel LED on a MCPCB

Temperature cycling of the different material sets was performed to validate the models. The experimental results were integrated in DfR's Automated Design Analysis™ software to ascertain the Physics of Failure (PoF) based reliability predictions for the LEDs. In this paper, the model development methodology and validation approach will be described. Additionally, a tool used to demonstrate the long term solder joint reliability characteristics of their LEDs to customers was created for the Philips Lumileds web site.

With the advances in materials, design and manufacture of LED devices, we are seeing a wide spectrum of LEDs that are more colorful, more efficient, more intense, and more reliable.

At the same time the manufacturing capacity increases and market price declines significantly.
Today's main market segments for LEDs are Automotive, Consumer (TVs and Cell Phones), and General Illumination.

Each of these market segments has its specific requirement on reliability:

- Automotive – very high reliability requirements for a "very short" time (<4000 hours)
- Consumer – cost and applications driven – (i.e. cell phones <100 hours)
- General Illumination – very high expectations (>50k hours in some cases for outdoor)

Philips Lumileds, in a proactive approach, decided to develop **solder joint** reliability models for their LUXEON Rebel LEDs enabling customer applications to meet the expected reliability targets.

The LUXEON Rebel has been accepted as an industry leading LED product, widely used in MTBF sensitive applications. Customers use various mounting platforms, such as FR4 PCB, FR4 PCB with thermal via's, Aluminum & Copper MCPCB, Super MCPCB, etc. As in other LEDs, when mounting to a platform where a large CTE exists between the LED & the PCB, Solder fatigue could become an issue that may affect system level lifetime.

Approach

This paper will compare the prediction modeling with empirical tests for validation of the models.

It is vital to understand system level reliability factors to build lighting solutions that match the application and customer expectations.

It is impractical to test LEDs and other components for 50k hours ~5 years since the device evolution is much faster than that – on average one LED generation every 12-18 months.

Figure 2 is a cross section illustrating the elements of the LUXEON Rebel LED.

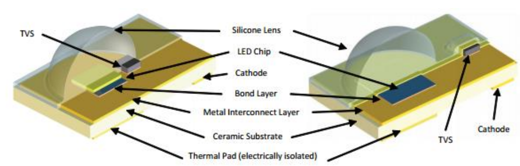


Figure 2 – LUXEON Rebel X-Section

Failure Modes

LUXEON Rebel LEDs are constructed with a single - pre-defined failure mode - electrical short - to limit its system level impact. This is not the case with any other LED on the market as they still have bond wires that can cause an electrical open at LED level.
The solder joints are the only way to have an electrical open failure. The system level impact of an electrical open in a chain of serially connected LEDs are:

- All LEDs in affected string are dark
- Unbalanced current distribution in a serial/parallel architecture

Test Set-Up

The materials set for the experiments consisted of:

- Level 1 Material- Philips Lumileds LUXEON® Rebel
- Level 2 Materials
  - MCPCB-1: Laird Substrate
  - MCPCB-2: Nippatsu Substrate
  - MCPCB-3: Opulent Substrate
  - MCPCB-4: Berquist Substrate
- Test Conditions
  - TC1: -40°C to +125°C, N Cycles
  - TC2: -20°C to 100°C, N Cycles

Figure 3 illustrates the 4 Metal Core PCBs initially evaluated.

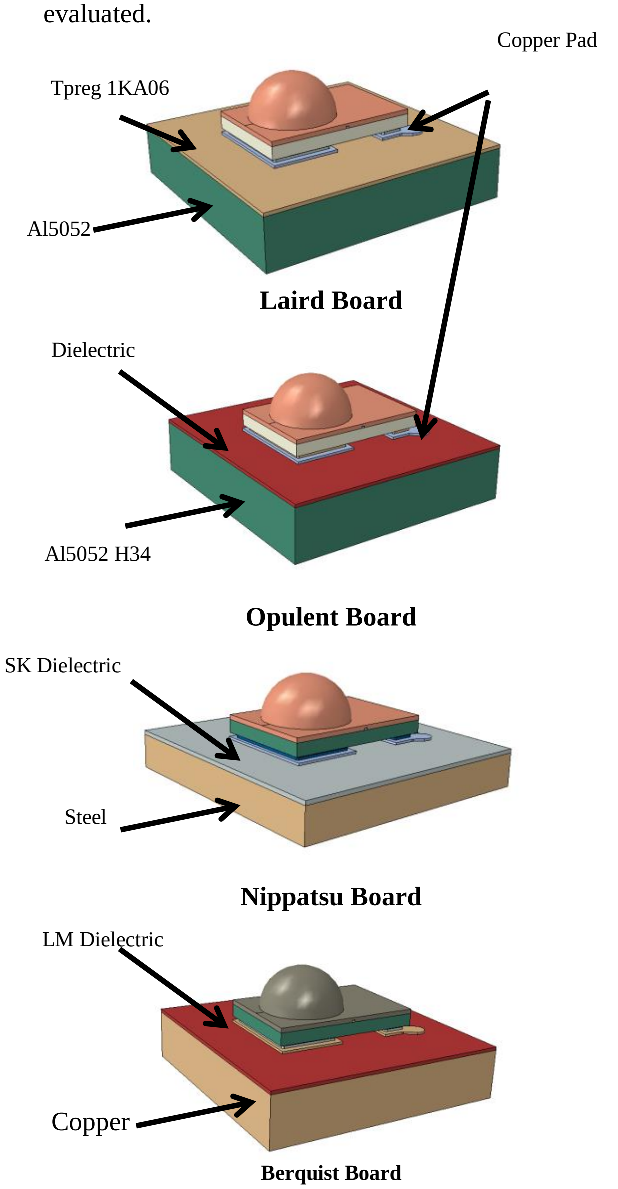


Figure 3 – Board Configurations

The material properties for each element of the construction was incorporated into the models with the following parameters included.

Parameter	Ceramic	Au	Ni	Cu	Silicon	Silicone
Modulus of Expansion	300K MPa	79K MPa	200K MPa	120K MPa	160K Mpa	185K MPa
Poisson's Ratio	.21	.44	.31	.3	.18	.28
CTE x,y	8.2 ppm	14.2 ppm	13.4 ppm	17.6 ppm	2.8 ppm	2.6 ppm

Solder Alloy Properties

The creep behavior properties of SAC405 were also examined using Garafalo's Hyperbolic Creep Model.

$$\dot{\varepsilon} = C[\sinh(\alpha\sigma)]^n e^{\left(\frac{-Q}{RT}\right)}$$

Where:
C = Material Dependent Constant
σ = Applied Stress
T = Temperature in Degrees Kelvin
n = stress exponent
Q = Activation Energy
ε = Strain Rate

Using Schubert Constant (ECTC 2003)

C	α (MPa)$^{-1}$	n	Q (KJ/mol)
2.78E5	0.0245	6.41	54.2

(2)

For the initial test data involved in the reliability model development it was determined that β ~2.9 for the -40C to +125C thermal cycle range and β ~2.6 for the -20C to +100C thermal cycle range.

Using a modified Norris Landzberg equation resulted in an observation of acceleration factors for the two thermal cycle ranges of 2.62 and 2.57 respectively.

$$AF = \frac{N_o}{N_t} = \left(\frac{\Delta T_t}{\Delta T_o}\right)^{\mathbf{a}} \left(\frac{t_t}{t_o}\right)^{\mathbf{b}} \exp\left\{ \mathbf{c} \left(\frac{1}{T_{\max,o}} - \frac{1}{T_{\max,t}}\right)\right\}$$

AF – acceleration factor
N – thermal fatigue life
ΔT - temperature difference
t – dwell time (min)
T_{max} – maximum cycle temperature (K)
o, *t* – operating or test conditions
a, b, c - coefficients 1.84, 0.11, 2167, respectively

Miremadi, et. al., "Lead-Free Solder-Joint-Reliability Model Enhancement", IMAPS 2009.

Again, the model correlated with the test data with regard to solder joint fatigue with a 2nd series of tests showing a β ~4.0 for -40C to +125C and no failures through 3327 cycles at -20 to +100C. The model predicted 17,277 cycles and a β ~3.9.

So, how do we translate the cycles to failure into a life expectancy for the solder joints on various substrates?

Correlation Derivation Process

The purpose of the correlation derivation process is to accelerate and identify the thermo-mechanical mechanisms of solder joint and plated through hole fatigue through utilizing the worst case field environment in the US, that being Phoenix. [3]

Month	Cycles/Year	Ramp	Dwell	Max. Temp (°C)	Min. Temp. (°C)
Jan.+Feb.+Dec.	90	6 hrs	6 hrs	20	5
March+November	60	6 hrs	6 hrs	25	10
April+October	60	6 hrs	6 hrs	30	15
May+September	60	6 hrs	6 hrs	35	20
June+July+August	90	6 hrs	6 hrs	40	25

Utilizing these temperature extremes a methodology was developed to derive how 24 thermal cycles would equate to 1 year in the field. First we used a modified Engelmaier[1] equation to determine the strain range $\Delta\gamma$.

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

Where: C is a correlation factor that is a function of dwell time and temperature, L_D is diagonal distance, α is CTE, ΔT is temperature cycle, h is solder joint height.

We then ascertained the shear force applied to the solder joint using the following formula.

$$(\alpha_2 - \alpha_1)\cdot \Delta T \cdot L = F \cdot \left(\frac{L}{E_1 A_1} + \frac{L}{E_2 A_2} + \frac{h_s}{A_s G_s} + \frac{h_c}{A_c G_c} + \left(\frac{2-\nu}{9 \cdot G_b a}\right)\right)$$

Where: F is the shear force, L is length, E is the elastic modulus, A is the area, h is thickness, G is shear modulus and a is edge length of the bond pad. Subscripts 1 is component, 2 is board, s is the solder joint, c is the bond pad and b is the board.

The formula takes into consideration the foundation stiffness and both the shear and axial loads.

Finally, we determined the strain energy dissipated by the solder joint:

$$\Delta W = 0.5 \cdot \Delta\gamma \cdot \frac{F}{A_s}$$

We then calculated the cycles to failure (N_{50}), using the energy based fatigue models for SAC developed by Syed[4] at Amkor.

$$N_f = (0.0019 \cdot \Delta W)^{-1}$$

Using these calculations the total damage to the solder joint for 10 years in the Phoenix environment was determined to be 0.02604. The total damage in 1 cycle of -40C to +85C test environment is 0.00012. This translates into 222 cycles equates to 10 years in the field, or that 1 cycle/hour testing, approximately 1 day of test equals 1 year in the field.

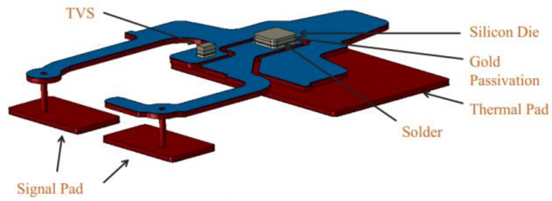
Model Development

LUXEON Rebel ODB++ files for a carrier having an InGaN LED and also a AllGaP LED were used for the devices. Ceramic and metal based carrier compositions were also utilized as were two Heraeus solder compositions F640-IL-89M30 and F640HT1-89M30.

The thermal requirements were across each board type modeled and also across the following thermal cycle ranges.

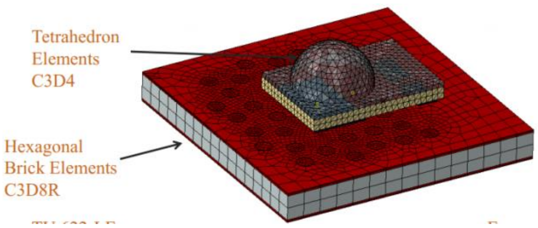
- -30 to 110ºC, 30 min dwells, 30 sec transitions, 2 chambers
- -40 to 125ºC, 30 min dwells, 30 sec transitions, 2 chambers
- -50 to 140ºC, 30 min dwells, 30 sec transitions, 2 chambers

Figure 4 illustrates the typical submount modeled.

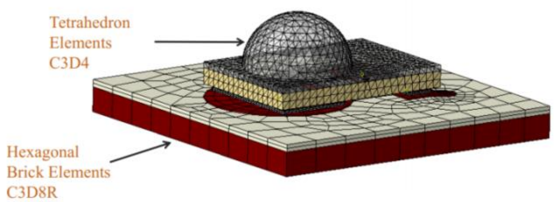


Layers view

Figure 1 is an example of the meshed model created for each construction. Figure 5 shows additional examples of the different constructions which also included FR-4 configurations.



Multek FR-4



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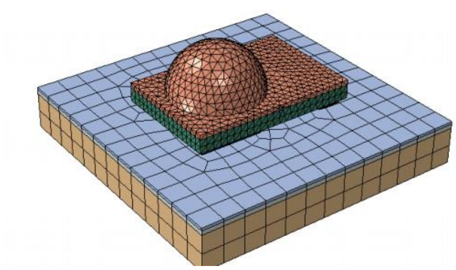
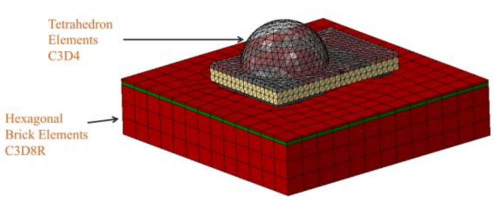


IMS Nippatsu



IMS Berquist

Figure 5 – Different Meshed Models

Von Mises Stresses were modeled at both the hot and cold dwells for each configuration. In this case, a material is said to start yielding when its von Mises stress reaches a critical value known as the yield strength, σ_Y. The von Mises stress is used to predict yielding of materials under any loading condition from results of simple uniaxial tensile tests.

Figure 6 illustrates the Von Mises Stresses determined for the cold dwell extreme.

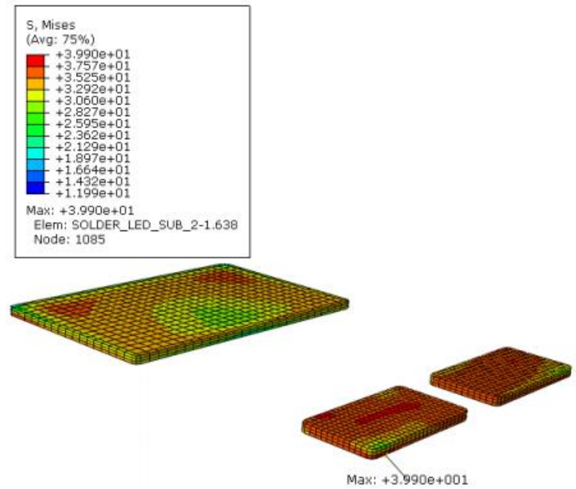


Figure 6 – Von Mises Stresses (Cold Dwell)

Similarly, the Creep Strain Energy was generated for each thermal cycle. Figure 7 is an example of this calculation (also cold dwell).

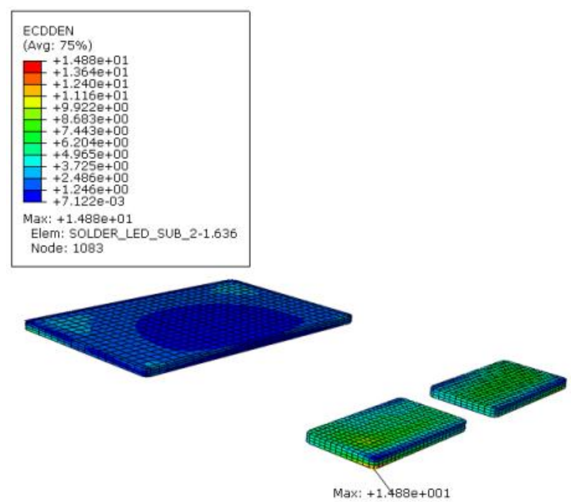


Figure 7 – Strain Energy Density Contour Plot (Cold Dwell)

Validation Approach

General Illumination (outdoor lighting) if used in a street light (timer controlled/activated) application would last for 47 years as the 17,277 cycles from (-20C) to +80C (delta change of 80C) would translate to this life expectancy. If two cycles a day were used for the calculation, then the street lamps would last 24 years, as the number of cycles per day decreases the life expectancies accordingly.

As -20C to +100C is a relatively severe environment for anything but an automotive application the models project excellent life expectancies for the LUXEON Rebel LEDs on several MCPCB constructions. Even the automotive scenario looks good due to the lower life expectancies for those applications previously noted.

Fatigue Calculator

This model development was then used to create a fatigue calculator that is now on the Philips web site. Figure 8 shows the appearance of the model on the site.

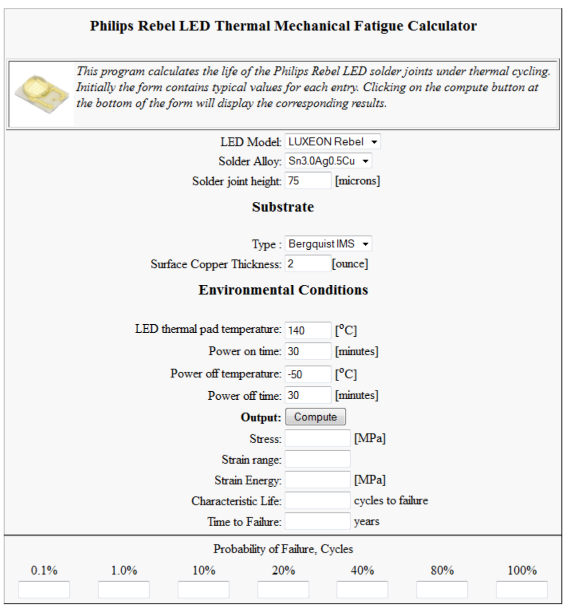


Figure 8 – Calculator on Philips Lumileds Web Site

Summary

Models were constructed for the LUXEON Rebel LED on a total of 15 different substrates with Thermo Mechanical Analyses performed on nine for 3 different environments using the SAC405 solder alloy.

The results from the FEA analysis indicated an excellent correlation between the models and experimental data.

A tool was developed for use in predicting the solder joint reliability of Philips LUXEON Rebel LEDs on a variety of substrates to facilitate their customer's ability to select the most viable approach for their particular application.

References

1) Blattau, Nathan; Hillman, Craig, "An Engelmaier Model for Leadless Ceramic Chip Devices with Pb-free Solder, 2006
2) Schubert, et al, ECTC 2003
3) Hillman, Craig, "True Design for Reliability (DfR): Understanding What is and What is Not DfR", 2009 IPC Conference and Enphase Solar Inverter data
4) Syed, A., "Accumulated Creep Strain and Energy Density Based Thermal Fatigue Life Prediction Models for SnAgCu Solder Joints," ECTC 2004, pp. 737-746 – corrected.