CREE

SUPPORT DOCUMENT

Cree® XLamp® LEDs
Solder Joint Reliability Study

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Commercial applications of high-power LEDs have dramatically increased over the last several years because of LEDs' high reliability, long lifetime and energy savings potential. There are high expectations for LED-based luminaires for commercial, indoor, outdoor and residential applications. LED-based luminaires are increasingly required to meet the reliability standards and ENERGY STAR® requirements for long-term lumen maintenance (L70 > 35,000 hours)[1] [1].

The reliability of the solder joint between the LED package and printed circuit board (PCB) is very critical in ensuring the overall reliability of an LED lighting fixture. This application note describes a reliability investigation of solder joints for Cree high-power XLamp® LEDs using thermal shock testing. Thermal shock is a much more rigorous life test procedure than thermal cycling tests and causes a significant acceleration in the evolution of failure mechanisms, thereby precipitating potential failures earlier than thermal cycling tests. Although thermal shock is instructive in identifying the most likely point of system failure under thermal stress, there is no known correlation of thermal shock testing to real-world operating environments and these results should not be used as a predictive indicator of system lifetime or failure rates.

1 That is, after 35,000 hours of operation, the luminaire will still deliver 70% of its initial luminous flux.

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INTRODUCTION

The unique advantages offered by high-power LEDs are driving widespread adoption of this technology in markets previously dominated by traditional lighting technologies. One of the major value propositions of LED-based lighting solutions is long-term reliability. Hence, establishing long-term high-reliability performance with relevant data is critical for LED-based lighting applications. Besides the LED chip, a typical LED package consists of various substrate materials, components, and encapsulants which vary with different manufacturers.

The three joints whose integrity is critical to ensuring thermal transfer from the junction of the LED to the heat sink are illustrated in Figure 1.

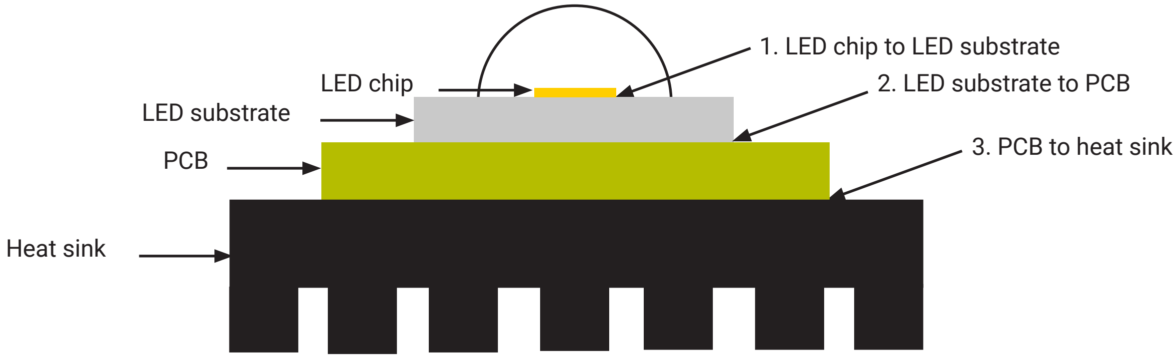


Figure 1: Points critical to ensuring thermal transfer from LED junction to heat sink

The LED manufacturer verifies the integrity of the LED chip to LED substrate joint. The PCB and luminaire assembly firm is responsible for verifying the integrity of the other two joints.

The integrity of the LED substrate to PCB solder joint is one of the key determinants of long-term lumen maintenance and reliability of LED products. Solder joint reliability not only depends on the solder alloys, but also on the metallization of the LED package and PCB. In addition, the reflow profile also has a significant impact on lead-free solder joint performance since it influences the wetting behavior and microstructure of the solder joint. A damaged or faulty solder joint can cause an open circuit failure that in turn can causes the complete electrical failure of the lamp or luminaire.

Thermal shock testing has a much more rapid ramp rate than thermal cycling, thus inflicting much more damage to solder joints. Thermal shock testing results can provide significant insight into the reliability of solder joints [4]. This study uses thermal shock to evaluate the reliability of solder joints for selected high-power XLamp LED packages.

The reliability of a solder joint is defined as the probability that the solder joint can perform the required function under specified operating conditions for a given time interval. Eutectic Sn63Pb37 solder (63% tin, 37% lead), which was historically the alloy of choice for soldering applications, has been replaced by lead-free solder alloys due to health and environmental concerns.

Solder joint failures are a common failure mode observed in electronic packages [2]. The formation of a reliable solder joint depends on several factors such as the ability of the molten solder to rapidly and uniformly wet the surface finish and interact with it to form a consistent intermetallic layer at the interface [3]. The wetting behavior, interface chemistry, and metallurgical microstructure of the solder joint are determined predominantly by the reflow temperature. In addition, overall solder joint reliability is determined by a combination of operating environment and system design. The operating environment determines the temperature extremes which the product must endure, frequency of on/off power cycling and the possibility of mechanical shocks or vibrational stresses [3].

The factors to consider when designing an LED package are as follows. [3]

1. LED chip and LED substrate physical properties
2. Materials selection
3. Solder-joint geometry (pad size and shape, placement of the pad with respect to the solder mask)
4. Bulk solder alloy mechanical properties
5. Nature of the intermetallics formed and their structure at the solder joint/thermal pad interfaces

For LED package to PCB reliability, the key characteristic to consider is the difference in thermal expansion coefficients between the LED package and the PCB material. Changes in operating conditions result in differential forces generated by expansion coefficient mismatch. These forces can be amplified by mechanisms such as LED substrate bending. For a larger LED package on a rigid PCB, the stress generated by expansion mismatch is highest within the solder joints furthest from the center of the LED package.

Figure 2 shows factors typically affecting LED solder-joint integrity. The factors shown in red are relevant to this study.

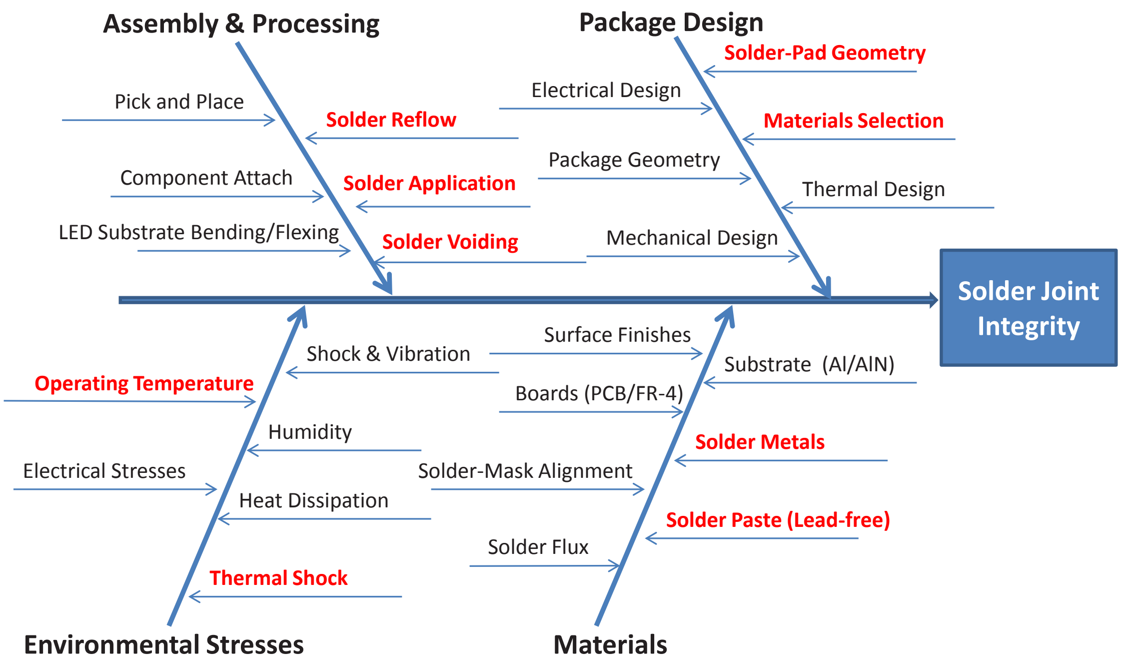


Figure 2: Factors typically affecting LED solder-joint integrity

This application note describes a solder-joint reliability study of lead-free solder joints in seven high-power Cree XLamp LED packages: XB-D, XP-G, XM-L® High Voltage White (HVW)[2], XM-L, MC-E, MT-G and XR-E. Samples of each LED package were mounted on a single-layer metal-core printed-circuit board (MCPCB) and underwent thermal shock testing over a temperature range of -40 °C to 125 °C with a dwell time of 15 minutes and a transfer time less than 20 seconds. The amount of solder voiding between the LED package and the MCPCB was varied to investigate its effect on solder-joint reliability.

2 The XM-L HVW and MT-G LEDs have reached their end-of-life and are no longer available for purchase. The discussions that refer to these LEDs contnue to be valid and mention of these LEDs has not been removed from this application note.

ASSEMBLY OF MATERIALS AND COMPONENTS

Figure 3 illustrates the surface-mount technology (SMT) reflow process used with each LED package in this study.

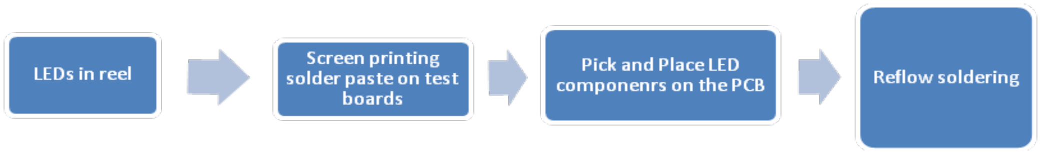


Figure 3: SMT process flow chart

Package dimensions of the high-power XLamp LED packages are given in Table 1.

Table 1: Dimensions of XLamp LED packages selected for solder joint reliability study

XLamp LED Package	Package Dimensions
XB-D	2.45 mm X 2.45 mm
XP-G	3.45 mm X 3.45 mm
XM-L HVW	5.00 mm X 5.00 mm
XM-L	5.00 mm X 5.00 mm
MC-E	7.00 mm X 9.00 mm
XR-E	7.00 mm X 9.00 mm
MT-G	9.00 mm X 9.00 mm

TEST BOARD DETAILS

As shown in Figure 4, the MCPCB selected for the study can accommodate ten LEDs. Twenty or thirty LEDs of each type, i.e., two or three boards for each LED, were included in this study.[3]

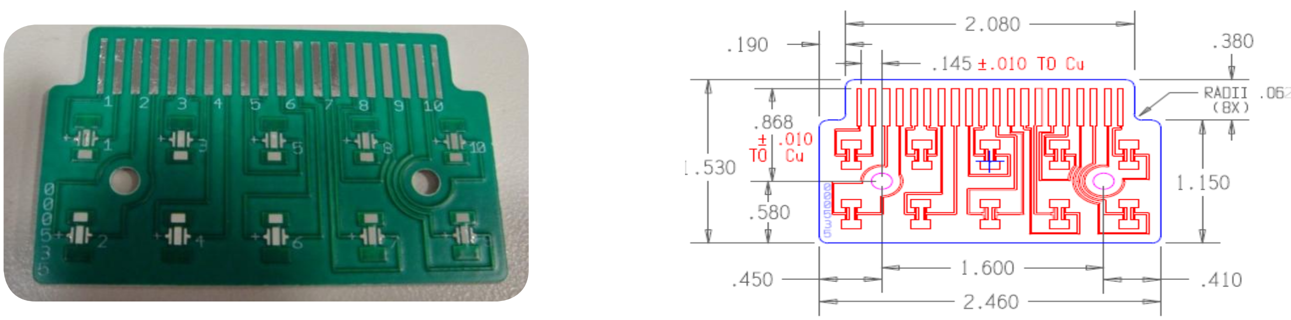


Figure 4: MCPCB board with XLamp XB-D LED package

The MCPCB used in this study is comprised of a solder mask, copper-circuit layer, thin thermally conductive dielectric layer and metal-core base layer. The layers are laminated and bonded together, providing a path for the heat to dissipate. Figure 5 shows a cross section of the MCPCB.

3 MCPCBs were constructed by The Bergquist Company, who produced the drawing in Figure 5.

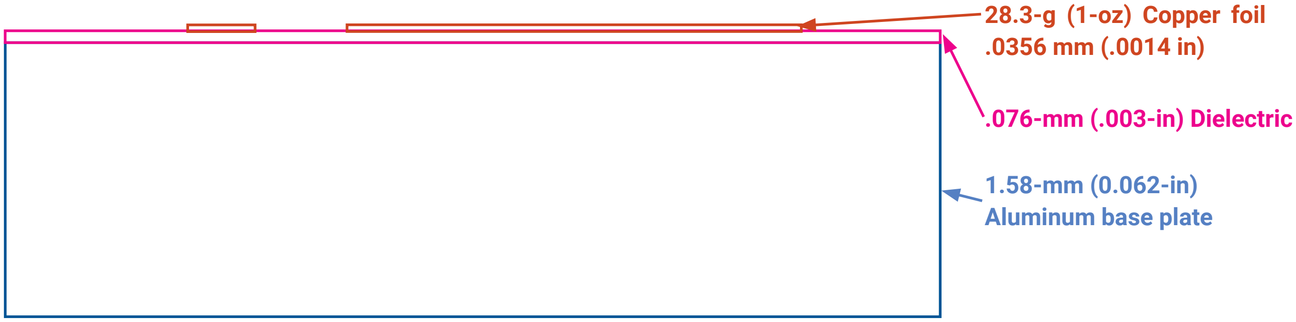


Figure 5: Cross section of MCPCB

MCPCB Finish

The MCPCB has a lead-free hot-air solder-leveled (HASL) surface finish, which provides excellent solderability and longer shelf life than the alternatives like organic solderability preservatives (OSP) and immersion (immersion tin, immersion silver) finishes.

The MCPCB stack-ups used in this investigation are as follows.

XB-D - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) high-temperature (HT) dielectric, 113.4-g (4-oz.) copper foil

XP-G - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) HT dielectric, 170.1-g (6 oz.) copper foil

XM-L HVW - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) HT dielectric, 170.1-g (6-oz.) copper foil

XM-L - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) HT dielectric, 170.1-g (6-oz.) copper foil

MC-E - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) HT dielectric, 170.1-g (6 oz.) copper foil

XR-E - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) HT dielectric, 170.1-g (6 oz.) copper foil

MT-G - 1.58-mm (.062-in) aluminum base plate, 3-mil (.076-mm) HT dielectric, 170.1-g (6 oz.) copper foil

SOLDER DETAILS

Solder Paste

This study used Indium 8.9, an air-reflow, no-clean solder paste specifically formulated to accommodate the high temperature of tin-silver-copper (SAC), lead-free alloy systems.[4] The solder composition is 96.5% tin (Sn), 3.0% silver (Ag) and 0.5% copper (Cu) and is of Type 3 metal loading having 88.75% metal by weight.[5]

4 SAC305, Indium Corporation
5 The metal load is the ratio of powdered solder to flux, expressed as percentage of metal by weight. The metal load depends on the powder type and application.

Assembly Process Equipment

The assembly equipment used in this study is given in Table 2.

Table 2: SMT assembly equipment

SMT Equipment	SMT Equipment Details
Stencil printer	MPM Momentum
Pick and place	JUKI FX – 3
Reflow oven	Heller 1809 MK III

Solder Paste Printing

We performed solder paste printing using an MPM Momentum stencil printer[6] with a 6-mil stencil thickness and a stencil frame size of 73.7 cm x 73.7 cm (29 in x 29 in). The ratio of aperture size to pad size was a 10% pad reduction to achieve the controlled voiding for this study.

LED Placement

A JUKI FX-3 pick and place machine was used for the LED assembly process.

Reflow Soldering

A Heller 1809 MK III convection reflow oven with eight heating zones and one cooling zone was used for the reflow process. All the boards were reflow soldered in a convection air purge environment.

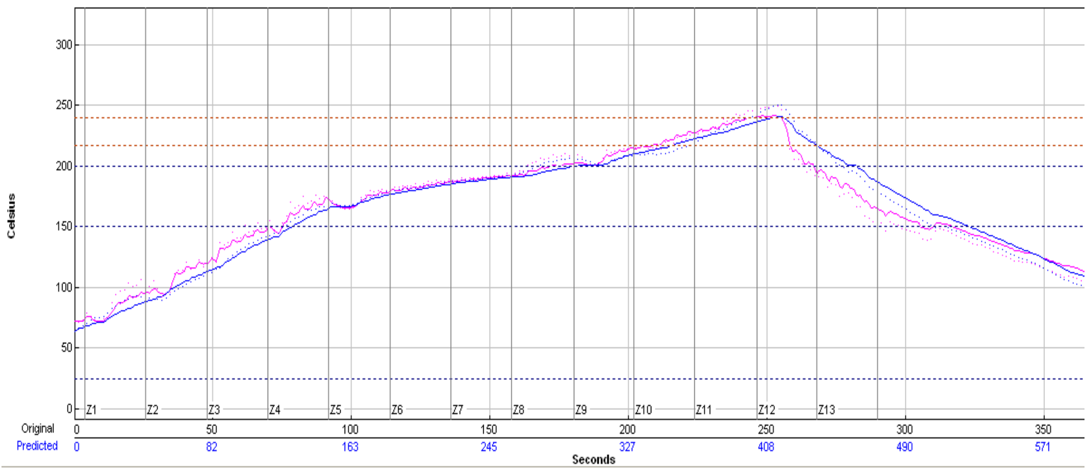
The lead-free solders differ from lead-based solders in their physical and metallurgical properties and process parameters such as melting point, surface tension, pre-heat and peak temperatures, soak and hold times and solder wetting behavior.

The melting temperature for Sn96.5 Ag3 Cu0.5 solder is between 217 °C and 219 °C, which is significantly higher than the eutectic Sn63 Pb37 solder, which has a melting point of 183 °C. This higher melting temperature requires peak temperatures to achieve wetting and wicking to be in the range of 235-245 °C. Lower peak temperature can only be used for boards with lower overall thermal masses or assemblies and do not have a large thermal mass differential across the board [5]. Lower peak temperature may also require extended soak time above the liquidus (TAL). If the solderability of the component or board is poor, this lower temperature will also translate itself into poor wicking of solder and reduced spread [5]. Thus the formation of a reliable solder joint depends on the time and temperature profile of the solder reflow process, the ability of the molten solder to rapidly and uniformly wet the surface finish and interact with it to form a consistent layer of intermetallic at the interface [3]. All these factors can directly affect the formation and reliable performance of the solder joint. Cree recommends an approximately 3-mil (75-µm) post-reflow solder-joint thickness, which can be verified using an optical microscope with a calibrated scale. This study followed this recommendation.

6 Speedline Technologies

Solder Reflow Profile

The chart in Figure 6 shows the solder reflow profile used in this study.



TCs	Max Rising Slope		Preheat 150-200C		Reflow Time /217C		Peak Temp		Tot Time /217C		Preheat 25-240C-(2)		Tot Time /240
<TC2>	1.93	93%	98.03	-37%	50.64	-31%	241.61	-23%	50.64	-121%	243.89	-294%	11.20
<TC3>	1.25	25%	102.23	-30%	52.48	-25%	240.98	-27%	52.48	-117%	252.56	-279%	3.28
Delta	0.68		4.20		1.84		0.63		1.84		8.67		7.92
P.<TC2>	1.63	63%	151.44	52%	78.27	61%	249.45	30%	78.27	-59%	387.78	-54%	30.84
P.<TC3>	1.06	6%	149.71	50%	77.24	57%	250.85	39%	77.24	-62%	397.48	-38%	25.72
Delta	0.57		1.73		1.03		1.40		1.03		9.70		5.12

Figure 6: Lead-free (SAC) solder reflow profile. Peak temperature: 240.98 °C, time maintained above 217 °C 52.48 sec

Table 3 shows the parameters for the solder reflow process used in this study. The XLamp LEDs in this study are compatible with JEDEC J-STD-020C.

Table 3: Solder reflow profile used in this study.
Note that all temperatures refer to the topside of the LED package, measured on the package body surface.

Profile Feature	Study Profile
Average Ramp-Up Rate (T_{smax} to Tp)	1.25 °C/second
Preheat: Temperature Min (T_{smin})	150 °C
Preheat: Temperature Max (T_{smax})	200 °C
Preheat: Time (t_{smin} to t_{smax})	102.23 seconds
Time Maintained Above: Temperature (T_L)	217 °C
Time Maintained Above: Time (t_L)	52.48 seconds
Peak/Classification Temperature (Tp)	240.98 °C
Time Within 5 °C of Actual Peak Temperature (tp)	3.28 seconds
Ramp-Down Rate	1.78 °C/second

After reflow soldering, the solder joints were visually inspected to look for solder joint defects: cold joint, solder bumps, bridges or tombstoning. We observed none of these defects.

The LED packages were also inspected using real-time X-ray imaging to further evaluate the solder attach quality and to detect the presence of any solder voiding between the LED package and board.

Additional details on pick and place operation, soldering and handling and thermal management of Cree XLamp LEDs can be obtained from application notes available on the Cree website.[7]

X-RAY IMAGING

We used a Cougar Yxlon real-time X-ray imaging station to evaluate the solder attach to locate open contacts, shorts between the anode/cathode contacts and thermal pad, excess solder between the pads and solder voids. Solder voiding is typically caused by:

- Solder paste and solder paste flux formulation - Compared to tin-lead solders, lead-free solder alloys exhibit higher alloy surface tension which increases the propensity of solder voiding. The presence of aggressive flux chemistries in lead-free solders results in increased outgassing which leads to higher voiding.
- PCB surface finish, e.g., OSP, immersion silver, gold/nickel, HASL - Due to the poor wetting of lead-free pastes compared to lead-based solders, PCB surface finish plays a critical role in void formation. Experiments on various PCB surface finishes suggest that immersion tin, immersion silver and lead-free HASL finishes are preferred for use with lead-free assembly [13].

Figure 7 shows the difference in appearance of complete and partial solder coverage. Solder appears green in these images.

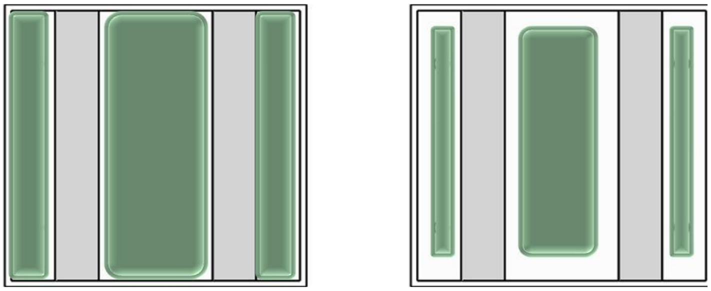


Figure 7: Complete solder coverage (left), partial solder coverage (right)

Cree considers less than 30% solder voiding, i.e., less than 30% of the solderable area void of solder, to be ideal. Cree also considers greater than 50% solder voiding to be conducive to solder-joint failures. For this study, Cree chose to investigate solder-joint reliability when solder voiding is less than 30% and greater than 50%.

The voiding for the XB-D, XP-G and XM-L HVW LED packages ranged from 5% to 30%; greater than 50% voiding was observed for the other LED packages. No evidence of excess solder between the cathode/anode contacts and thermal pads were observed in any of the devices. The presence of excessive solder voids between the LED package and MCPCB is a reliability concern since voiding can compromise the thermal performance and electrical integrity, causing an increase in thermal resistance between the component and PCB.

7 Pick and Place Application Note
Thermal Management Application Note
Soldering and handling details are available in each XLamp LED's Soldering & Handling document.

Figure 8 shows X-ray images of less than 30% solder voiding for XP-G and XM-L HVW LED packages.

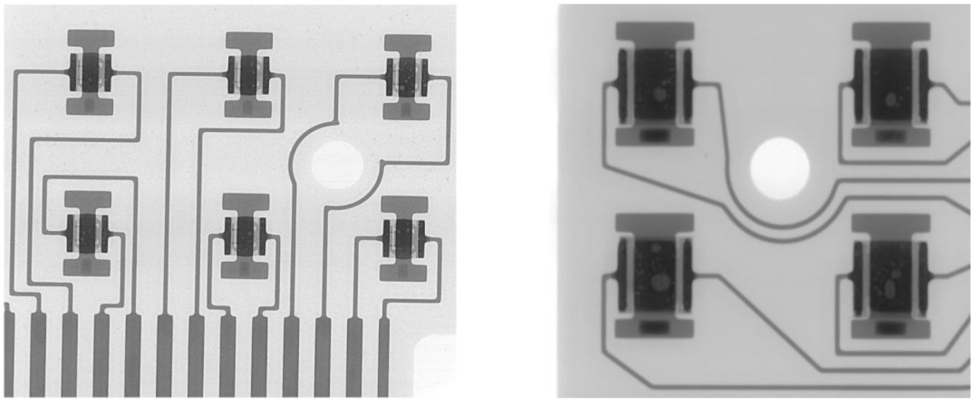


Figure 8: X-ray image of XP-G LED packages on PCB (left) and XM-L HVW LED packages (right) with < 30% solder voiding

We deliberately reduced the XM-L solder stencil design to reduce the area of solder coverage underneath the LED package. This reduction allowed significant voiding under the LED due to lack of solder. This can be seen in Figure 9. This reduction resulted in significant voiding under the LED package due to the lack of solder for wetting purposes.

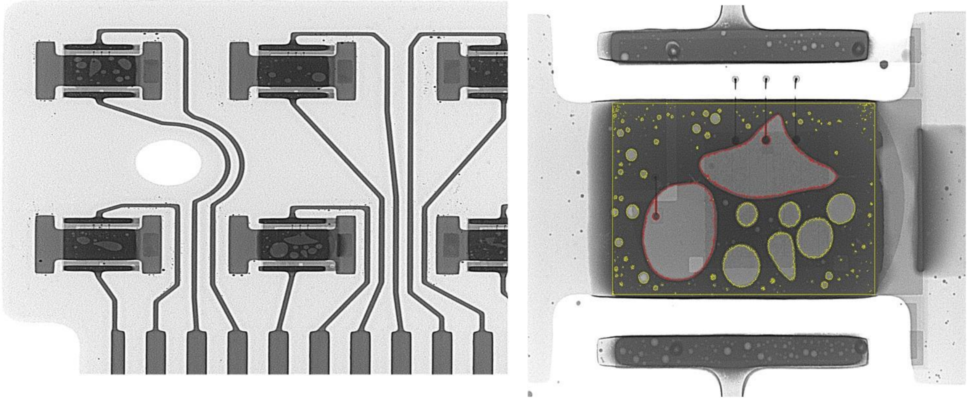


Figure 9: X-ray image of XM-L LED packages on PCB with significant (> 50%) voiding

THERMAL SHOCK TESTS

The most accelerated form of fatigue life testing is thermal shock, which is a type of temperature cycling with a high rate of temperature change [10]. This is realized by conveying the product under test alternately between two "chambers", one at a high temperature, e.g., 125 °C, and another at a low temperature, e.g., -40 °C, over a specified duration of time. During thermal shock tests the solder joint experiences a temperature differential of 165 °C between the high and low temperature extremes. During these rapid temperature changes, large expansion differences are developed between the various parts of an assembled board. This stress is caused not only by differences in expansion coefficients but more importantly by temperature differences between the various parts. Large differential expansions cause large plastic deformations in the soldered joints, much larger than what can occur in real-life applications, where

temperatures change slowly.[8] The shock test therefore produces significant acceleration in the evolution of failure mechanisms thereby precipitating potential failures over a short period of time [10].

Thermal Shock Test Profile

The thermal shock testing was based on MIL-STD-202G-Method 107G. In this testing, each solder joint is subjected to at least 1000 cycles of thermal shock from -40 °C to 125 °C instead of 200 cycles.[9] The ramp rate for the thermal shock tests was approximately 1.1 °C/sec. Table 4 gives the thermal shock test profile.

Table 4: Thermal shock test profile

Test	Applicable Standards	Test Conditions & Failure Criteria
Thermal shock	MIL-STD-202G- method 107G	Temperature Range: -40 °C to 125 °C
		Dwell Time: 15 minutes
		Transfer time: < 20 seconds
		Cycles: 1000
		Failure criteria: LED no longer lights up after test

THERMAL SHOCK TEST RESULTS

The individual LEDs on each board were monitored for several different optical (luminous flux, chromaticity coordinates, color shift) and electrical (forward voltage, current, leakage current) parameters after every 100 cycles of thermal shock test cycles. Since “no light emission” was specified as the failure criterion for thermal shock tests, the cycle time at which the device failed to light up was identified. Table 5 shows the results.

8 A plastic deformation is an irreversible, inelastic deformation of a material with the application of stress. A material that has undergone plastic deformation will ultimately fracture and fail.

9 200 cycles of thermal shock testing is considered to be a typical acceptable measure of long-term solder joint reliability for LEDs.

Table 5: Summary of failures after thermal shock tests

LED	LED Size	Number of LEDs Tested	Voiding	Thermal Shock Test Failures	Number of Cumulative Failures
XB-D	2.45 mm X 2.45 mm	30	< 30% voiding	1 at 2600 cycles 1 at 2700 cycles	2
XP-G	3.45 mm X 3.45 mm	30	< 30% voiding	1 at 1800 cycles 1 at 2000 cycles 2 at 2100 cycles 1 at 2200 cycles 1 at 2600 cycles 2 at 2700 cycles 3 at 2800 cycles 1 at 3000 cycles	12
XM-L HVW	5.0 mm X 5.0 mm	30	< 30% voiding	1 at 1200 cycles 1 at 1350 cycles 1 at 1850 cycles 1 at 2000 cycles 2 at 2700 cycles 3 at 2800 cycles	9
XM-L	5.0 mm X 5.0 mm	30	> 50% voiding	1 at 600 cycles 1 at 700 cycles 1 at 800 cycles 1 at 1000 cycles 1 at 1100 cycles 1 at 1200 cycles 1 at 1350 cycles 1 at 1675 cycles 1 at 1850 cycles 1 at 2000 cycles 1 at 2100 cycles 2 at 2200 cycles 2 at 2400 cycles 2 at 2700 cycles	17
MC-E	7.0 mm X 9.0 mm	20	< 30% voiding	0 after 1000 cycles	0
XR-E	7.0 mm X 9.0 mm	20	< 30% voiding	1 at 800 cycles 4 at 1000 cycles 3 at 1400 cycles	8
MT-G	9.0 mm X 9.0 mm	30	< 30% voiding	14 at 400 cycles 12 at 600 cycles 1 at 700 cycles	27

Typically, passing 200 cycles of thermal shock testing is considered to be an acceptable measure of long-term solder joint reliability for LEDs. There is, however, no specified method to directly correlate passing 200 cycles of thermal shock testing with an expected solder-joint lifetime under normal operating conditions. As such, the value of thermal shock testing is to allow a direct comparison of the cycles to failure of different size LED packages and materials. For these tests, all LEDs except the MT-G were subjected to at least 1000 cycles (five times more than normal) of typical thermal shock testing. The number of failures observed for the MT-G LED caused the testing to be stopped before 1000 cycles.

Thermal shock test results showed a linear correlation between the LED package size and the number of cycles to first failure.

Interpretation of Thermal Shock Failure Data Using Weibull Analysis

There are several models for predicting the fatigue life of solder joints. These models are based on one or more of the fundamental mechanisms that can cause solder joint damage. These fundamental mechanisms include plastic-strain based (Coffin-Manson, Solomon, Engelmaier and Miner fatigue models), creep-strain based (Syed model), energy-based (Darveaux fatigue model) and damage-accumulation based [11].

The thermal shock data were analyzed using the Weibull distribution. Weibull probability plots were used to model the failure data for XLamp LED packages in this study. The two-parameter Weibull distribution is defined by the shape and scale parameters. The Weibull cumulative failure distribution was used to fit cycles to the failure data.

The equation is:

$$F(N) = 1 - \exp(-N/N0)^m$$

where F (N) is the cumulative failure distribution function and N is the number of thermal cycles.

N_0 is a scale parameter that is referred to as the characteristic life, and is the number of cycles with 63.2% failure occurrence. The shape parameter m represents the shape of the Weibull curve; as m increases, the spread in cycles to failure decreases. A shape value between two and four is considered somewhat normal. A shape value less than two describes a right-skewed curve and a shape value greater than four describes a left-skewed curve.

Weibull analysis of the failure time data was performed using Minitab statistical software. Figure 10 to Figure 13 show the Weibull probability plot for four LEDs that experienced failures.

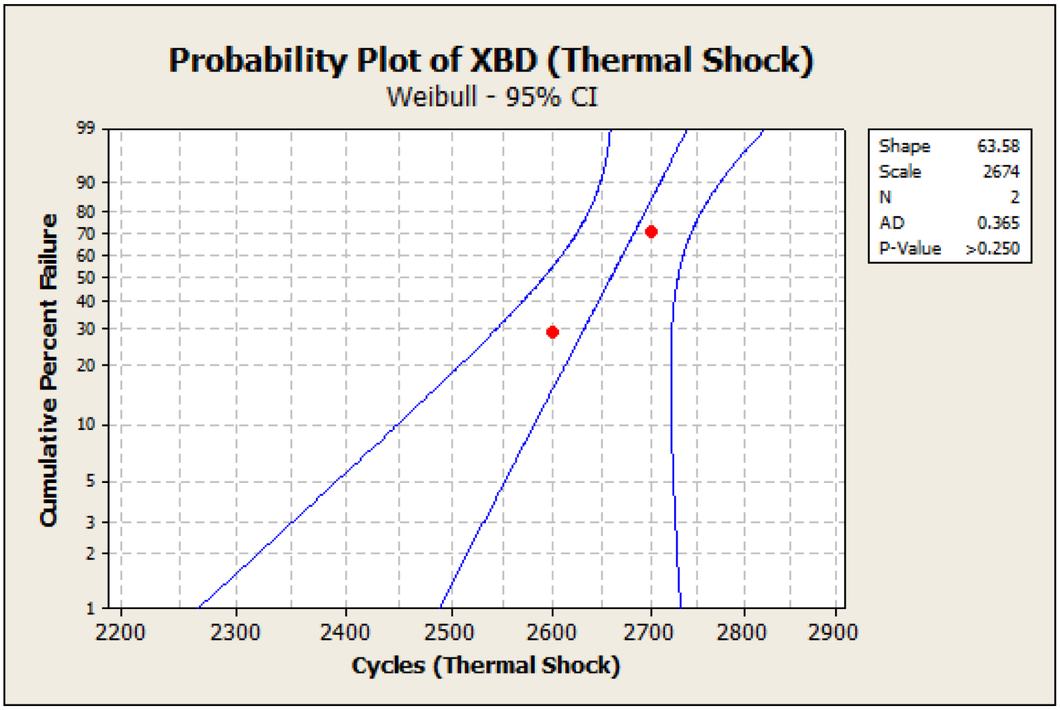


Figure 10: XB-D thermal shock tests, -40 °C to 125 °C, up to 2700 cycles

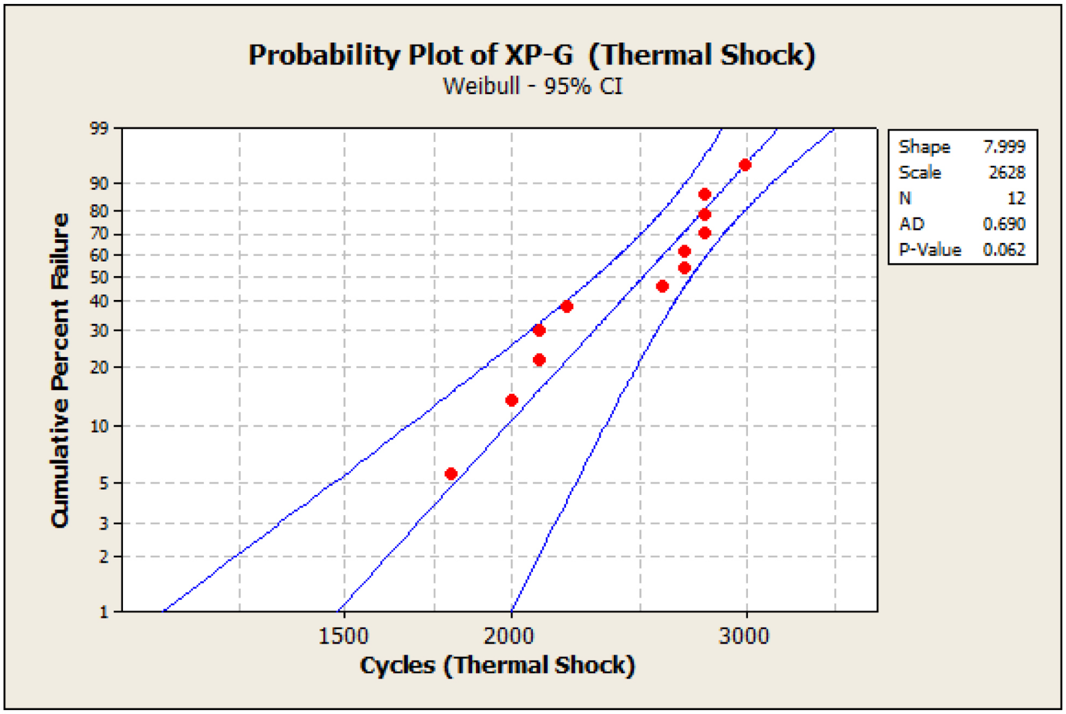


Figure 11: XP-G thermal shock tests, -40 °C to 125 °C, up to 3000 cycles

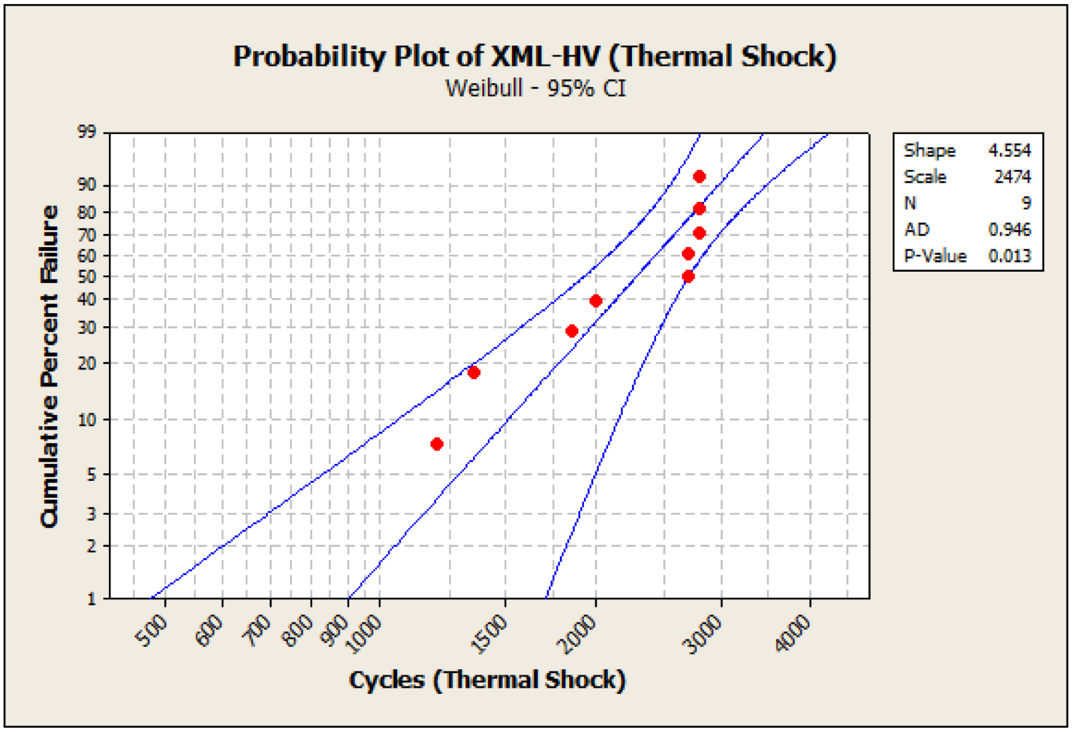


Figure 12: XM-L HVW thermal shock tests, -40 °C to 125 °C, up to 2800 cycles

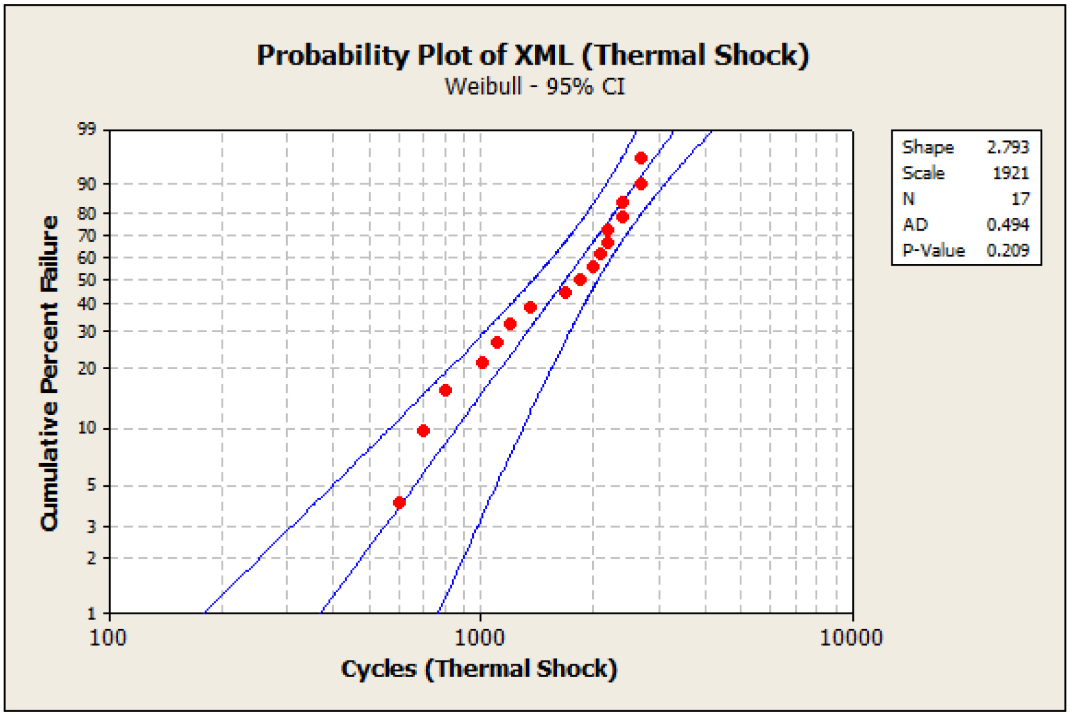


Figure 13: XM-L thermal shock tests, -40 °C to 125 °C, up to 2700 cycles

The Weibull probability plots show that the solder joints under smaller LED packages with less than 30% voiding performed better than the solder joints under larger LED packages with less than 30% voiding. Conversely, increasing the percentage of voiding to greater than 50% resulted in inferior solder joint performance. The characteristic life of the solder joints also showed a strong dependence on the degree of voiding with a smaller voiding percentage correlating to a higher characteristic life.

Thermal Shock Induced Failure Modes

It is well known that thermal management is one of the most important factors that determine the long-term reliability of high-power LED packages. The majority of electronic failures are thermomechanically related, i.e., by the result of thermally induced stresses and strains or accelerated transport phenomena at higher temperatures. These thermomechanical failures are categorized as extrinsic failures because they often involve the electronic packaging [8].

In non-operating life tests like thermal shock, the sudden temperature changes cause concurrent degradation of the solder joint, resulting in intermetallic compound (IMC) growth and thermal fatigue damage. Thermal fatigue failures are one the most common failure modes associated with lead-free solder joints attributed to the differences in materials' coefficient of thermal expansion (CTE). These CTE differences are responsible for the development of stresses and mechanical strains at the material interfaces which results in fatigue-crack initiation and propagation in solder joints. CTE is a key material property that quantifies the degree to which a material will expand or contract as a result of a change in temperature [8].

We examined the solder joint interfaces in this study using scanning electron microscopy (SEM), energy dispersive X-ray (EDX) analysis and optical microscopy to evaluate the integrity of the joints and potential fatigue failure modes.

The cross sections of the failed solder joints exhibited cracks within the bulk solder on the component side. These samples exhibited a microstructure that is typical of thermomechanical fatigue failures in lead-free solder alloys.

SOLDER JOINT EVALUATION

Solder Joint Microstructure

Cross sectional analysis was performed to analyze the behavior of solder joints after thermal shock tests and is shown in Figure 14 to Figure 17. The cross sections of the failed joints, show that the fatigue fracture starts at the edge of the solder in all four LED packages. Most of the fatigue cracks exist between tin and silver grains in the bulk of the solder trace and propagated throughout the length of the solder in the direction of highest strain [9].

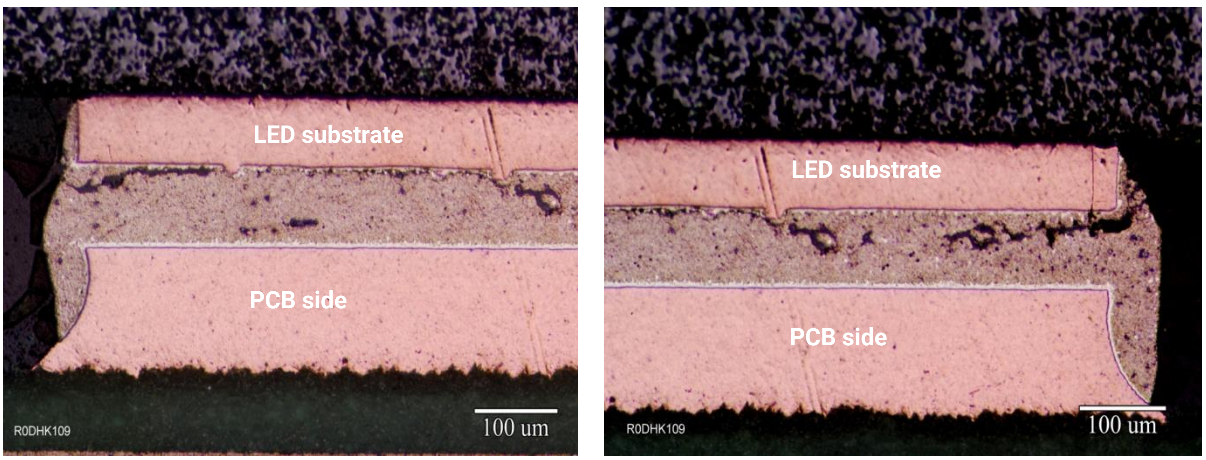


Figure 14: Solder joint between PCB and XLamp XB-D LED package after thermal shock tests

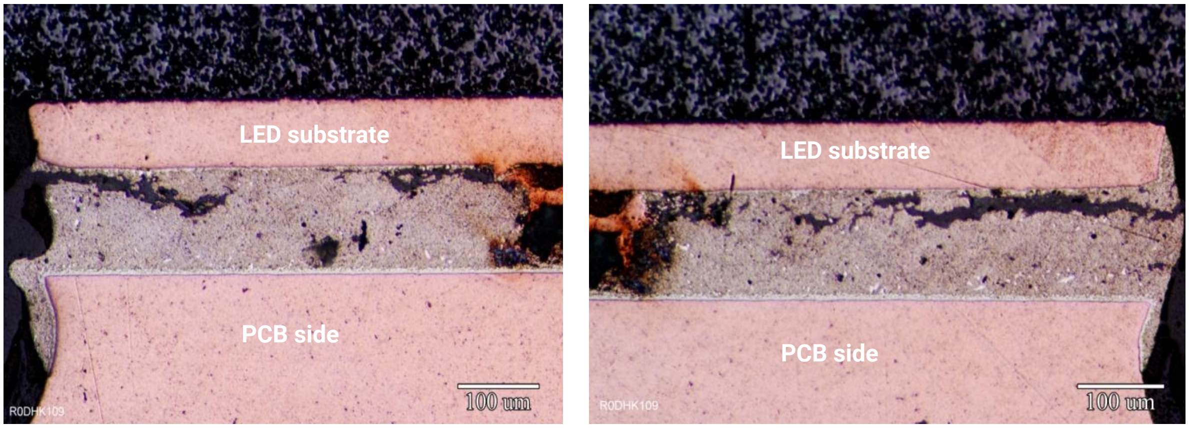


Figure 15: Solder joint between PCB and XLamp XP-G LED package after thermal shock tests

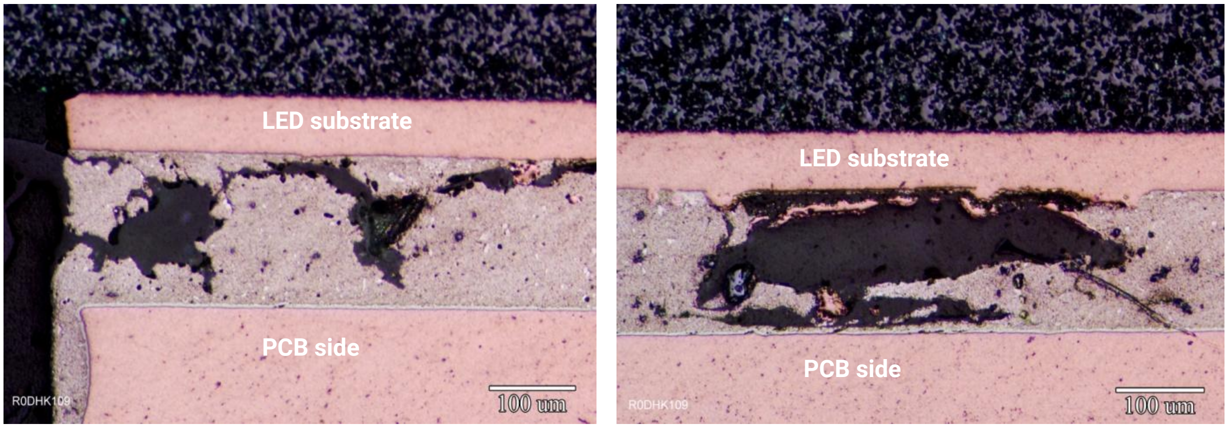


Figure 16: Solder joint between PCB and XLamp XM-L LED package after thermal shock tests. More than 50% voids were present underneath the XM-L LED package after the reflow soldering process.

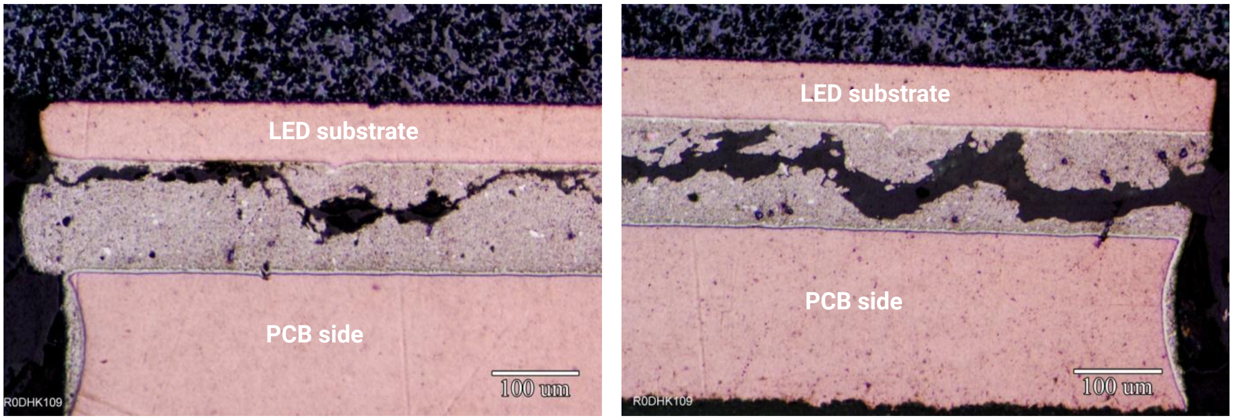


Figure 17: Solder joint between PCB and XLamp XM-L HVW LED package after thermal shock tests

Cross-sectional studies showed the presence of solder cracks extending to the edges of the solder joint, which is the location of greatest stress concentration. These cracks occurred in the bulk of the solder extending from one edge of the solder joint to the other edge, decreasing the electrical performance and potentially causing mechanical failure of the solder joint. Although both LEDs had less than 30% voiding, the solder joint cracks underneath the XB-D LED package, the smallest LED in the study, were less severe than those under the XM-L HVW, whose substrate has more than four times the surface area of the XB-D. The cracks observed were all representative of solder-joint fatigue fracture typically associated with thermal-shock-induced stress which is attributed to the differences in the CTE between the mating/joining materials.

Based on these observations, we concluded that the size of the LED package has a significant impact on the development of cracks in the solder joints. Although both LEDs had less than 30% voiding, the solder joints underneath the XM-L HVW showed a higher number of solder joint failures compared to the XB-D, the smallest LED package in the study.

Solder joint cracks underneath the larger LED packages appeared to be continuous, extending from one edge of the solder to the opposite edge without discontinuities. Cross-section imagery revealed the appearance of cracks on the component and PCB sides. However the extent of cracks on the component side was more severe.

Figure 18 shows an SEM micrograph of the cross section of the XB-D LED package showing solder-joint cracks after thermal shock tests. Solder joint cracks toward the component side can be observed in the image.

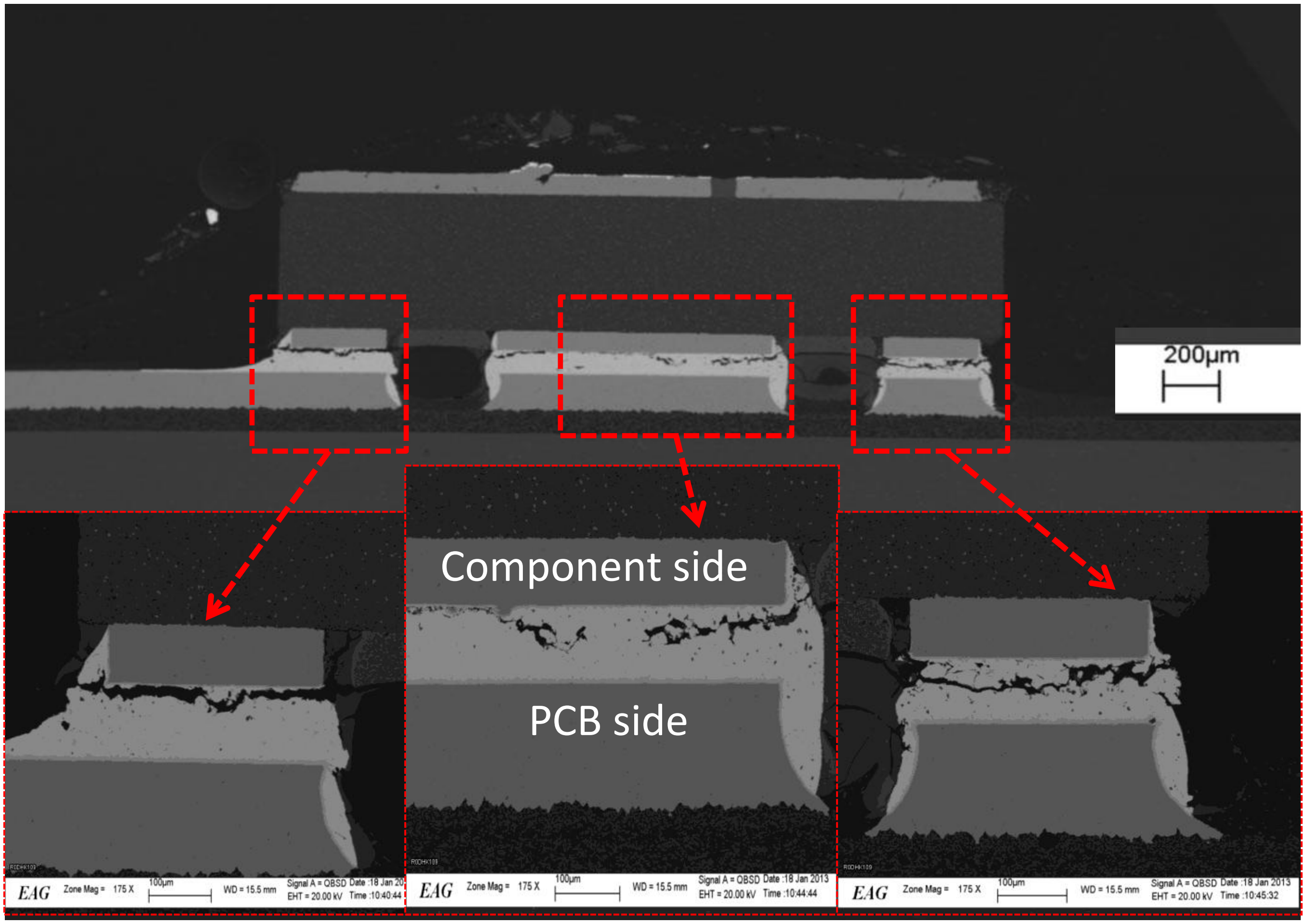


Figure 18: SEM micrograph of cross section of XB-D LED package showing solder joint cracks after thermal shock tests

Figure 19 shows an SEM micrograph of the cross section of the XM-L HVW LED package showing solder-joint cracks after thermal shock tests are more prevalent on the component side.

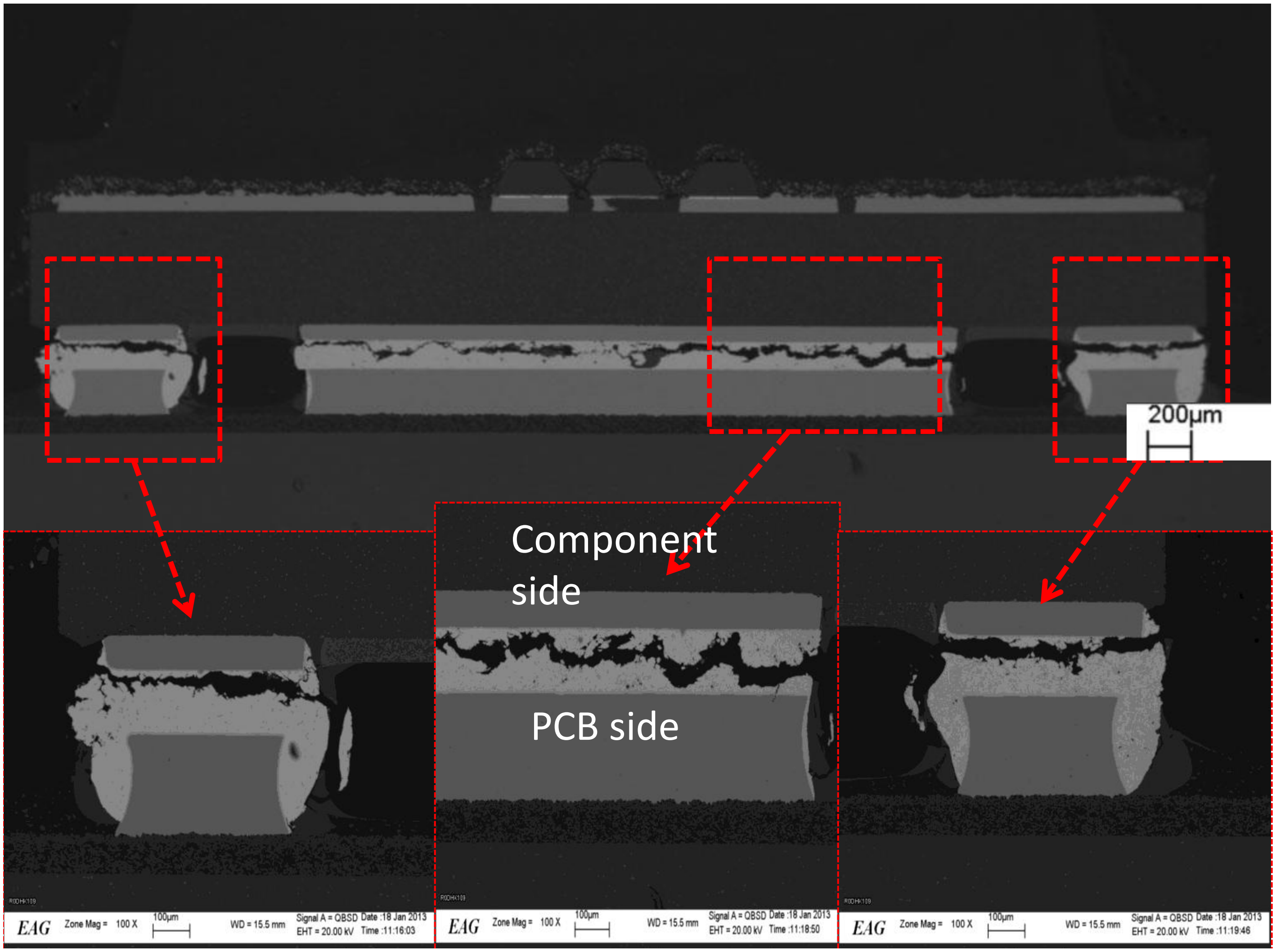
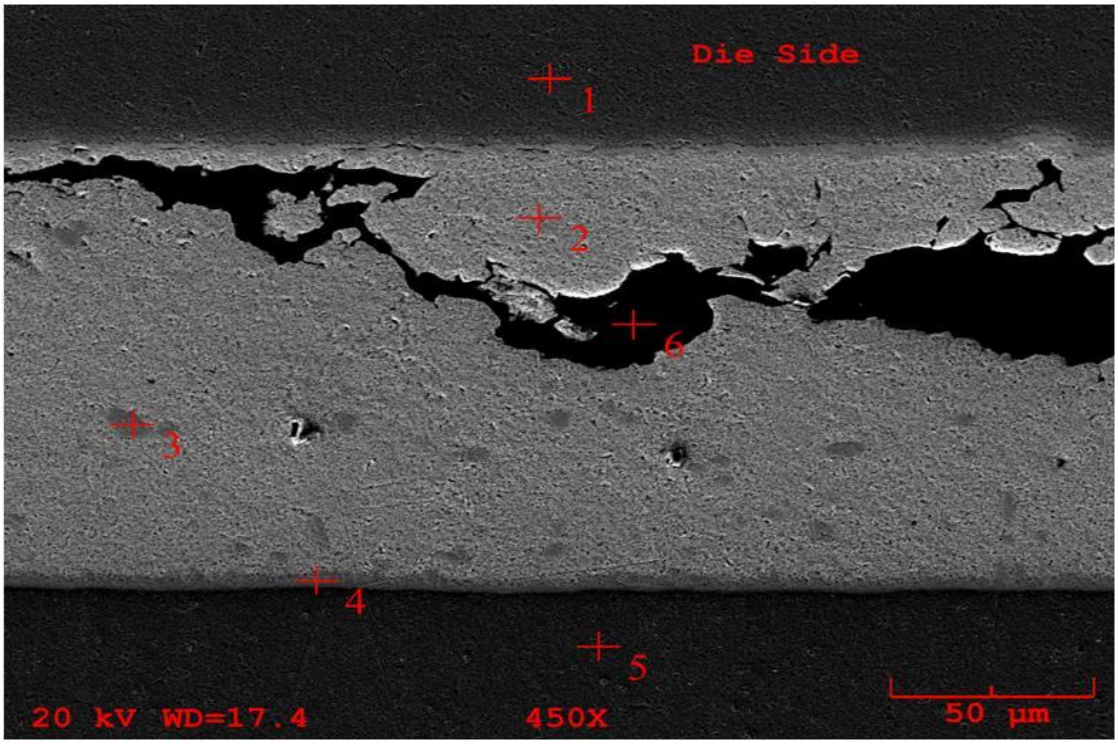
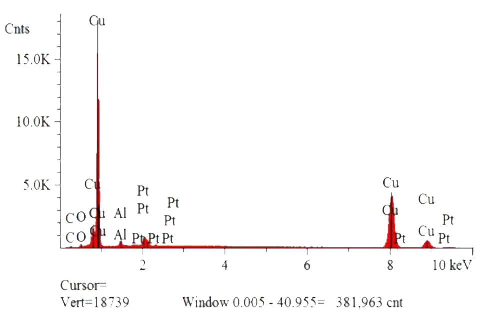


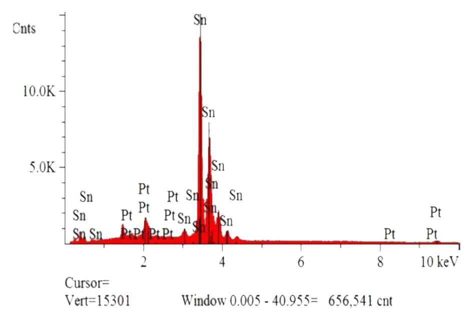
Figure 19: SEM micrograph of cross section of XM-L HVW LED package showing solder joint cracks after thermal shock tests

EDX analysis of the XM-L HVW solder joint showed the presence of intermetallic phases with silver and tin (Ag_3Sn) and copper and tin (Cu_6Sn_5) [7]. These intermetallics are brittle in nature and solder joint failure will occur in these regions.

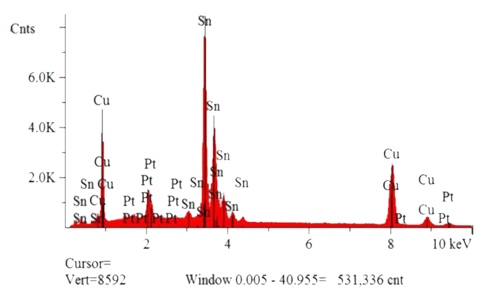




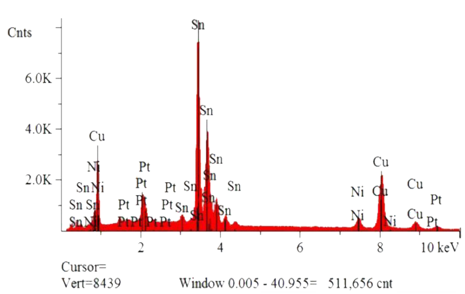
(1)



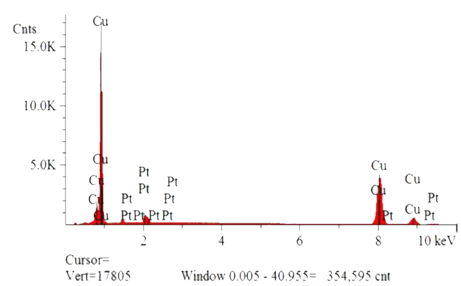
(2)



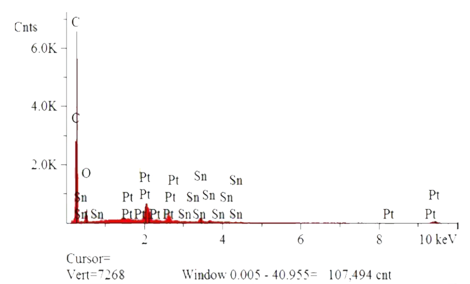
(3)



(4)



(5)



(6)

Figure 20: XM-L HVW solder joint (top) with EDX analysis locations

CONCLUSION

This study investigated the reliability of lead-free solder joints between various-sized XLamp LED packages and PCBs using thermal shock tests from -40 °C to +125 °C. SEM analysis of solder-joint microstructure identified cracks in the bulk of the solder joint toward the LED component side attributed to solder-joint fatigue failure. EDX analysis showed the formation of various silver-tin and copper-tin intermetallic phases. These are brittle intermetallics that can weaken the solder joints depending on the specific operating conditions. Thermal fatigue failure modes are associated with lead-free solder joints attributed to the differences in materials' CTE. These CTE differences are responsible for the development of stresses and mechanical strains at the material interfaces which result in fatigue-crack initiation and propagation in solder joints.

The method used for these evaluations follows JEDEC specification JESD22-A104D, Test Condition G (-40 °C to +125 °C), Soak Mode 4 (15 minutes). The test results showed a strong dependence on the LED package size and solder void percentage on solder-joint reliability. More solder voiding is worse than less solder voiding and larger substrate sizes are measurably worse than smaller substrate sizes. It must be noted that while this investigation allows a direct comparison to be made between different product types, processes, or materials, this JEDEC method does not allow the user to extrapolate the results into what are often called "real-world" conditions where temperature extremes and cooling/heating rates are much less aggressive.

Lastly, Cree recommends that, to avoid premature solder-joint failures, always use the recommended solder-pad layout, solder paste and solder-reflow profile for XLamp LEDs as can be found in Cree's soldering and handling documents.

REFERENCES

1. Ellen Tormey, Rahul Raut, Westin Bent, Ranjit Pandher, Bawa Singh and Ravi Bhatkal, "Low Voiding Reliable Solder Interconnects for LED Packages on Metal Core PCBs", alphacpmd.com/~/media/Files/CooksonElectronics/ETormey%20et%20al%20SMTAI%202011%20Final%2008082011.pdf

2. Robert W. Herrick, *FA Handbook*, Chapter 5, Special Devices, Failure Analysis and Reliability of Opto Electronic Devices, pp 248-250

3. "Solder Joint Reliability", www.rohmhaas.com/electronicmaterials/interconnect_technical_site/attachments/Tech%20comm_%20Jul%2008%20English.pdf

4. J. Pan, J. Wang and D.M. Shaddock, *Lead-free Solder Joint Reliability - State of the Art and Perspectives*, International Microelectronics and Packaging Society-JMEP, Vol.2, No. 1, 1st Qtr, 2005

5. P. Biocca, "Lead-free Defects in Reflow Soldering", www.smta.org/chapters/files/smta-gdl_Lead_free_Reflow_Defects__How_to_Prevent_Them.pdf

6. L.P Lehman, R.K. Kinyanjui, L. Zavalij, A. Zribi, and E.J. Cotts, *Growth and Selection of Intermetallic Species in Sn-Ag-Cu No-Pb Solder Systems Based on Pad Metallurgies and Thermal Histories*, IEEE 2003 Electronic Components and Technology Conference, pp 1215-1221.

7. Janick Ihringer, "Reliability of LEDs and LED Based Luminaires for Outdoor Applications", LED Symposium Expo.

8. Alex MacDiarmid, *Thermal Cycling Failures- Part One of Two*, Quanterion Solutions, Inc - The Journal of the Reliability Information Analysis Center-January 2011.

9. Peter Ratchev, Bart Vandelvelde and Ingrid de Wolf, *Reliability and Failure Analysis of Sn-Ag-Cu Solder Interconnections of PSGA packages on Ni/Au Surface Finish*

10. R.J. Klein Wassink, Soldering in Electronics, Second Edition, *A Comprehensive Treatise on Soldering Technology for Surface Mounting and Through-Hole Techniques*, Electrochemical Publications Limited, 1989.

11. W. D. van Driel, X.J.Fan (Ed), *Solid State Lighting Reliability, Components to Systems*, Solid State Lighting Technology and Application Series

12. Mohammad Yonus, K.Srihari, J.M.Pitarresi, Anthony Primavera, *Effect of Voids on the Reliability of BGA/CSP Solder Joints*, Microelectronics Reliability 43(2003) p 2077-2086.

13. David Bernard and Keith Bryant, “Does PCB Pad Finish Affect Voiding Levels in Lead-free assemblies?”, www.nordson.com/en-us/divisions/dage/support/Literature/Documents/Pad_finish.pdf