Light Emitting Diode

Solder Crack Considerations for LEDs for Automotive Applications

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NCxW121x, NCxx131x, Nxxx170x, NJxW270x, NxSx123x, NxSx172x, NCxW093x, NxSx146x, NCxW193x, NxSx572x, NHSx046x, NSSx063x, NxSx064x, NSSx088x, NSSW129, NSSM313x, and NSSM438x refer to Nichia part numbers. These Nichia part numbers within this document are merely Nichia's part numbers for those Nichia products and are not related nor bear resemblance to any other company's product that might bear a trademark.

1. Overview

LEDs are usually mounted on PCBs by using solder. When an LED-mounted PCB is repeatedly turned on and off under operating conditions that lead to a large temperature difference and/or in an environment where the temperature fluctuates significantly, thermal stress may cause cracks in the solder joint (see Figure 1). Solder cracks are more likely to occur when the difference in the coefficient of thermal expansion (CTE) between the package of the LED and the PCB is large. When the solder crack grows, it may cause a solder joint failure, causing the LED not to emit light. Therefore, sufficient verifications must be done before soldering the LEDs.
This application note explains how solder cracks occur and provides examples of reducing the occurrence of solder cracks together with the results of a thermal shock test (temperature cycle test).

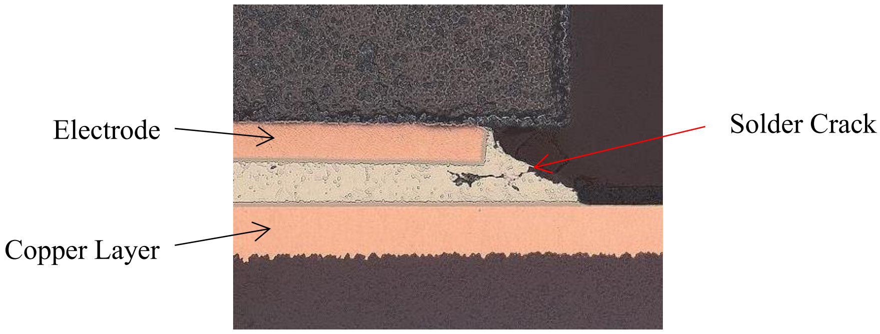


Figure 1. Example of a Solder Crack

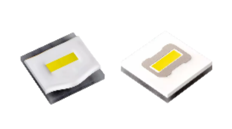
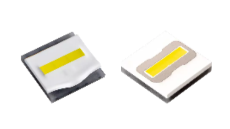
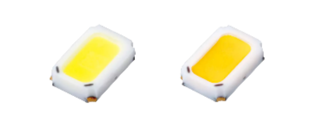
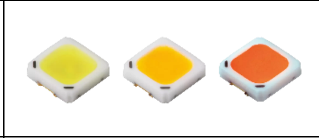
2. Applicable Part Numbers

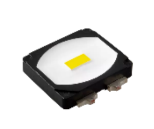
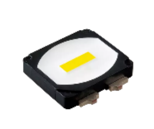
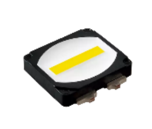
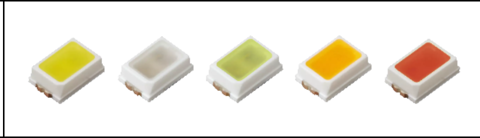
This application note applies to the LEDs shown in Table 1.

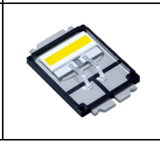
Table 1. Applicable LED Part/Series Numbers

Category	Nichia 121 Series				Nichia 131/170 Series[1]		
Part Number	NC2W121x	NC3W121x	NC4W121x	NC5W121x	NCSx131x NCSx170x	NC2x131x NC2x170x	NJSx170x
Example of Package Appearance							
Package Size (Unit: mm)	3.1×2.6 ×0.75	3.1×3.75 ×0.75	3.1×4.9 ×0.75	3.1×6.05 ×0.75	1.8×1.45 ×0.75	3.0×1.6 ×0.75	1.6×1.2 ×0.75

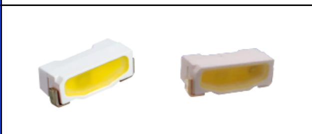
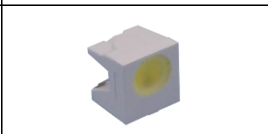
[1] The electrode pattern on the back of the package for the Nichia 131 Series and Nichia 170 Series is different.

Category	Nichia 270 Series		Nichia 123 Series		Nichia 172 Series	
Part Number	NJ2W270x	NJ3W270x	NFSx123x	NJSx123x	NFSx172x	NJSx172x
Example of Package Appearance						
Package Size (Unit: mm)	3.5×3.5×0.75		2.0×3.0×0.7		3.0×3.0×0.8	

Category	Nichia 093 Series				Nichia 146 Series		
Part Number	NC2W093x	NC3W093x	NC4W093x	NC5W093x	NESx146x	NHSx146x	NSSx146x
Example of Package Appearance							
Package Size (Unit: mm)	8.5×8.0×1.5				1.4×2.2×0.7		

Category	Nichia 193 Series					Nichia 572 Series	
Part Number	NCSW193x	NC2W193x	NC3W193x	NC4W193x	NC5W193x	NJSx572x	NSSx572x
Example of Package Appearance							
Package Size (Unit: mm)	11.8×8.0×1.7					3.0×3.0×0.7	

Category	Nichia 046 Series	Nichia 063 Series	Nichia 064 Series		
Part Number	NHSx046x	NSSx063x	NESx064x	NHSx064x	NSSx064x
Example of Package Appearance					
Package Size (Unit: mm)	1.4×2.2×1.3	2.8×3.5×2.0	2.8×3.5×2.0		

Category	Nichia 088 Series	Nichia 129 Series	Nichia 313 Series	Nichia 438 Series
Part Number	NSSx088x	NSSW129	NSSM313x	NSSM438x
Example of Package Appearance				
Package Size (Unit: mm)	1.4×3.5×1.2	3.6×4.0×4.0	3.3×3.3×1.8	1.6×4.7×1.8

The x represents a letter that follows the alphanumeric code of the same LED type. (e.g.: NCSx170x ･･･ NCSW170D, NCSW170F, NCSY170F, NCSA170G, NCSW170G, NCSW170G-SA etc.)

3. Main Cause of Solder Cracks

The following shows how solder cracks occur.
Figure 2 shows an LED soldered to an aluminum-core PCB.

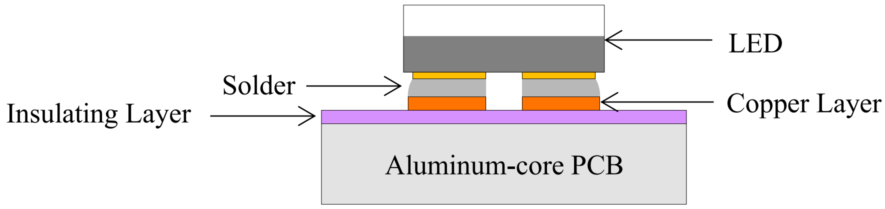


Figure 2. LED Soldered to an Aluminum-core PCB

When the LED-mounted PCB is repeatedly turned on and off under operating conditions that lead to a large temperature difference and/or in an environment where the temperature fluctuates significantly, the difference in the coefficient of thermal expansion (CTE) between the package of the LED and the aluminum-core PCB causes them to expand/contract at different rates and the resulting stress will be applied to the solder joints (see Figure 3).

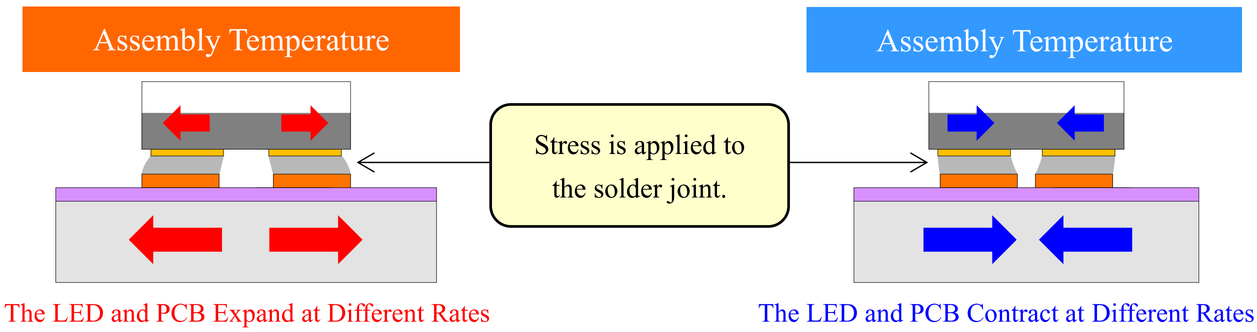


Figure 3. How Stress is Applied to the Solder Joints

If these solder joints are exposed to repeated stress, it will cause a minor crack to occur in the solder joint.
Then when it is exposed to additional stress, if the crack turns into a complete fracture, it stops the flow of electrical current supplied to the LED, the LED will fail to illuminate (see Figure 4).

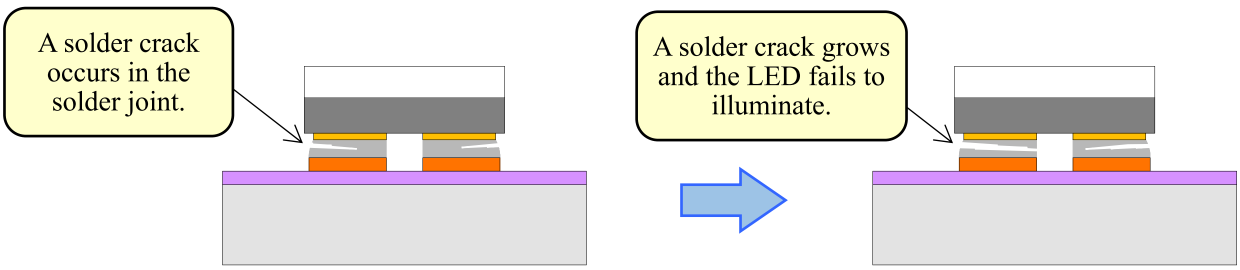


Figure 4. How Solder Cracks Occur

4. Reducing the Occurrence of Solder Cracks

4.1 Effect of the Difference in the CTE between the Package of the LED and the PCB

Solder cracks are more likely to occur when the difference in the CTE between the package of the LED and the PCB is large. The CTE describes how the size of an object changes with an increase in temperature per degree of Celsius (i.e., /°C). Table 2 shows the package materials used in Nichia LEDs. Table 3 below shows the CTEs of the package materials of the Nichia LEDs and the CTEs of typical PCB materials. The CTEs listed in the tables are only the typical values of the materials.

Table 2. Package Materials Used in Nichia LEDs

Package of the LED	LED Series
Aluminum Nitride	Nichia 121, 131, 170, 270 Series LEDs
Aluminum Oxide	Nichia 123, 172 Series LEDs
Resin	Nichia 046, 063, 064, 088, 093, 129, 146, 193, 313, 438, 572 Series LEDs

Table 3. CTEs of the Package Materials of the Nichia LEDs and Typical PCB Materials

Package of the LED	
Material	CTE (1/°C)
Aluminum Nitride	5×10^{-6}
Aluminum Oxide	7×10^{-6}
Resin	16×10^{-6}

PCB	
Material	CTE (1/°C)
Ceramic	8×10^{-6}
Iron	12×10^{-6}
Glass Epoxy (FR-4)	14×10^{-6}
Copper	17×10^{-6}
Aluminum	21×10^{-6}

Solder cracks can be reduced by selecting a PCB that has a small difference in CTE between the package material of the LED and the PCB material. For example, the difference in CTE between Nichia 121, 131, 170, 270 series LEDs that use aluminum nitride for the package material and the aluminum-core PCB is 16×10^{-6}/°C. On the other hand, the difference in CTE between those 121, 131, 170, 270 series LEDs and the copper-core PCB is 12×10^{-6}/°C. This indicates that solder cracks are less likely to occur when using a copper-core PCB for Nichia 121, 131, 170, 270 series LEDs (see Figure 5).

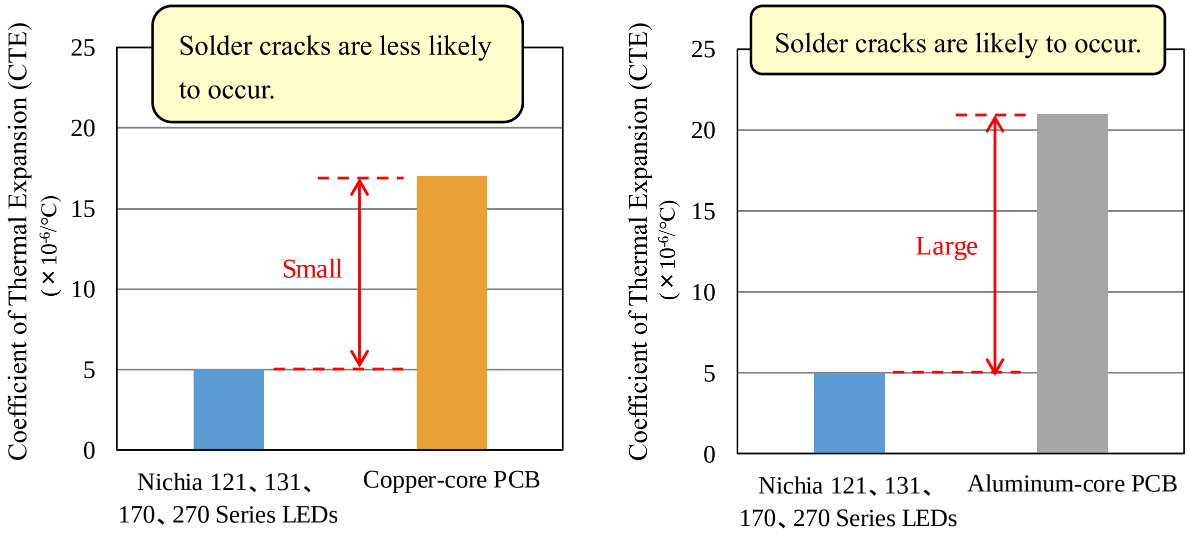


Figure 5. Difference in CTE between Nichia 121, 131, 170, 270 Series LEDs and the Two Different Types of PCBs

4.2 Elastic Modulus of the Insulating Layer of the PCB

In general, the use of a PCB containing an insulating layer with a low elastic modulus is effective in reducing solder cracks. An insulating layer with a low elastic modulus can deform to follow the stress generated by the difference in CTE between the package material of the LED and the PCB material, and thereby reducing stress on the solder joints (see Figure 6).

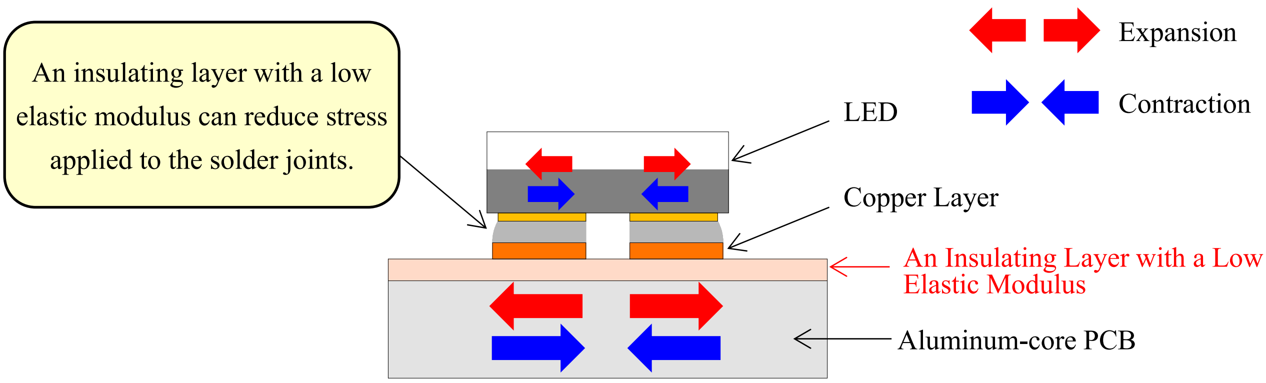


Figure 6. Aluminum-core PCB Containing an Insulating Layer with a Low Elastic Modulus

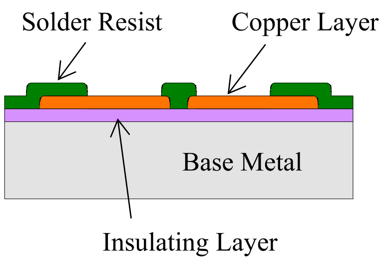
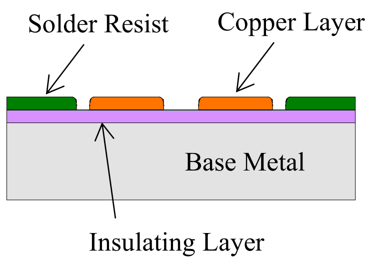
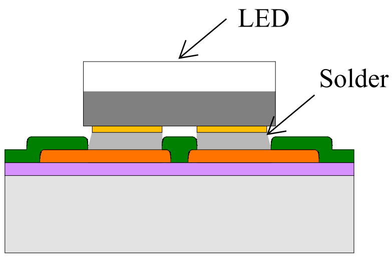
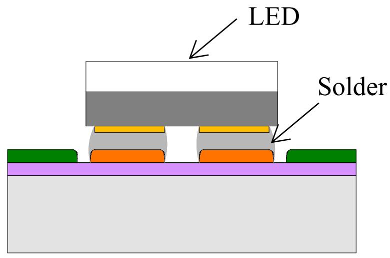
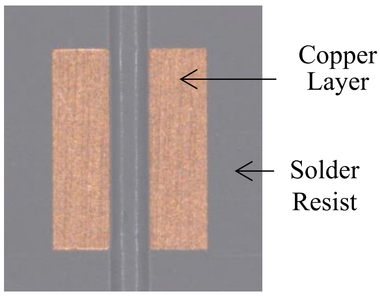
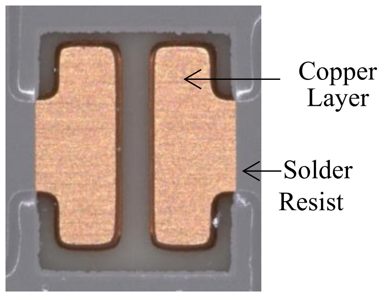
Note that the use of an aluminum-core PCB containing an insulating layer with a low elastic modulus may have a low thermal conductivity. Take this into consideration when selecting a PCB for the chosen application.

4.3 PCB Soldering Pad Patterns

There are two types of soldering pad patterns: Solder Mask Defined (SMD) and Non-Solder Mask Defined (NSMD). For SMD, the shape and location of the soldering pad pattern are defined by the aperture and location of the solder resist. For NSMD, the shape and location of the soldering pad pattern are defined by the shape and location of the copper layer (i.e., the solder resist does not overlap the copper layer).

As shown with the LED-mounted PCBs in Table 4, the SMD pads have the solder joint areas only on the top of the soldering pad pattern (copper layer). On the other hand, the NSMD pads have the solder joint areas not only on the top of the soldering pad pattern (copper layer) but also on the sides of the soldering pad pattern. This indicates that the NSMD pad pattern produces a more reliable solder joint than SMD pads and has a higher resistance against solder cracks.

Table 4. PCB Pad Patterns (SMD and NSMD Pads)

Pad Pattern		SMD	NSMD
PCB			
LED-mounted PCB			
Appearances of Soldering Pad Pattern (Examples)			
Features	Solder Joint Strength	-	Higher than SMD Pads
	Solderability	Harder to Reduce Solder Voids and Solder Balls	Easier to Reduce Solder Voids and Solder Balls
	Accuracy of Soldering Pad Pattern	Not Good (Solder Resist Printing)	Good (Copper Layer Etching)
	Heat Dissipation	Better than NSMD Pads due to the Large Copper Layer	-

When selecting a PCB, take the above features into consideration and perform sufficient verifications on the required properties including solder crack resistance.

4.4 Effects of Solder Voids

If a solder crack occurs in a solder joint where many solder voids exist, the growth of the solder crack can accelerate. When mounting LEDs on PCBs, take measures to reduce solder voids.

Examples of measures to reduce solder voids are as follows:

- Use a PCB with NSMD pads
  NSMD pad configuration allows gases in the soldered joint areas and gases/flux residues within the solder to be easily released to the outside air during reflow soldering (see Table 4 in Section 4.3).

- Adjust the reflow profile
  As a specific measure, gas generation can be reduced by slowing down the pre-heating speed and/or the reflow heating speed; another example is extending the reflow peak time by increasing the reflow peak temperature so that the molten condition of the solder can be kept longer, releasing gases and flux residues to the outside air.

  If the pre-heating temperature is too high or the pre-heating time is too long, the flux will deteriorate and the solder wettability will become poor, leading to an increase in the amount of solder voids.

  Note that adjustment of the reflow profile should be done within both Nichia's recommended reflow conditions and the reflow conditions of the solder used.

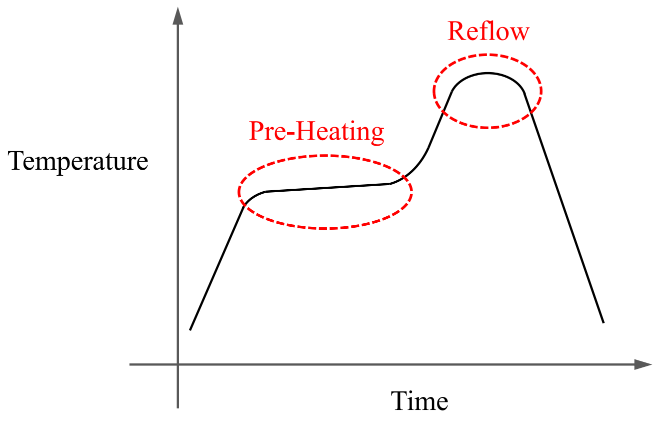


Figure 7. Reflow Profile

  For Nichia's recommended reflow conditions, refer to the applicable specification.

4.5 High Reliability Lead-free Solder

High reliability lead-free solder pastes, which have been specially developed to reduce the risks of occurrence and progression of solder cracks, are available.
Generally, the use of high reliability lead-free solder pastes can improve solder joint strength compared to a standard lead-free solder paste. Due to the increased solder joint strength, stress may become concentrated on the LED, leading to cracks and/or breakage of the LED chip. When selecting a solder paste, sufficient reliability verifications of the chosen application must be performed under the conditions/environments in which the LED will actually be used.

5. Solder Crack Evaluation

Nichia conducted solder crack evaluations using Nichia NCSW170G LEDs. This Nichia LED was chosen for the evaluations since it is one of the products from the Nichia 131/170 series LEDs that has an operating temperature range between -40°C to 135°C (see Figure 8). Note that the solder crack evaluation results are only reference data based on Nichia's test conditions.

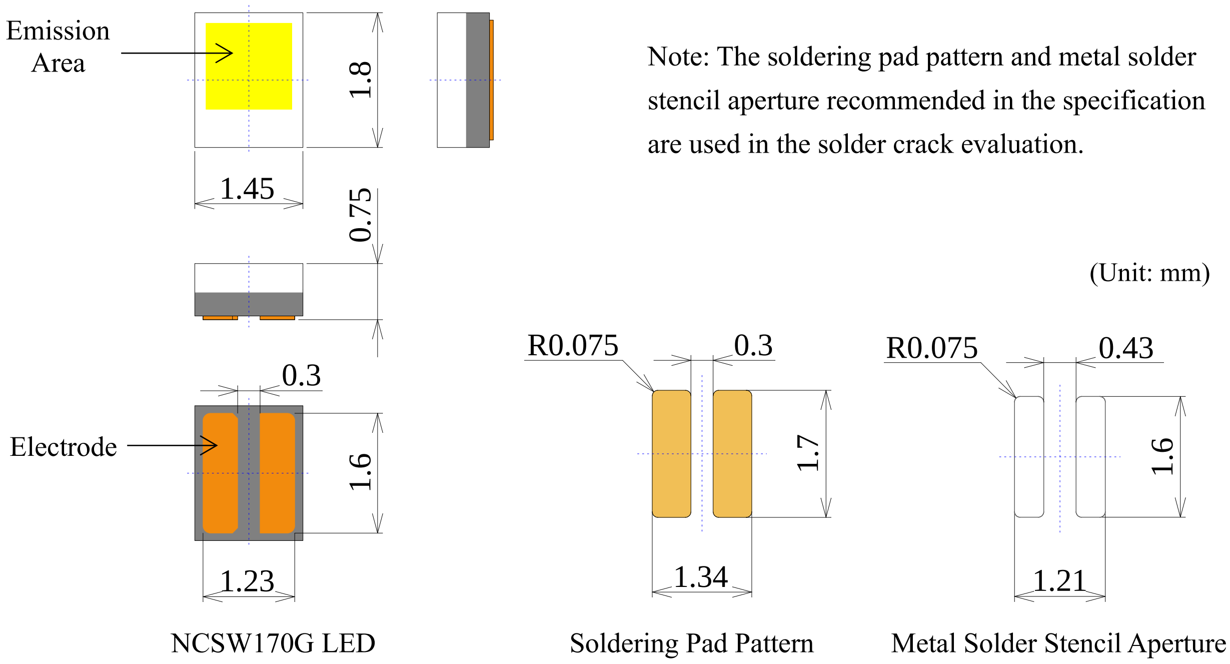


Figure 8. Dimensions Detailed in the Specification

Nichia mounted the NCSW170G LEDs on PCBs under the different conditions shown below and conducted a thermal shock test (temperature range: -40°C to 135°C) on the LED-mounted PCBs to investigate the increase rate in the forward voltage (ΔV_F)[2] and the lighting failure[3] rate. In this test, evaluations were conducted on different evaluation samples by changing the combination of the PCB base metal, PCB insulating layer, soldering pad pattern, and solder paste used (see Table 5).

Test Conditions:

LED Part No.:	NCSW170G
PCB:	Aluminum-core PCBs containing different types of insulating layers and a copper-core PCB containing a standard insulating layer (see Table 6)
Thickness:	Base metal 1.5mm, insulating layer 100μm, copper layer: 70μm

[2] When solder cracks occur in an LED, the electrical resistance at the solder joints becomes large and the forward voltage (V_F) tends to increase; the V_F is used as a reference value for occurrence of solder cracks. The increase rate of the forward voltage (ΔV_F) represents in percentage how much of V_F increases from the initial V_F.

[3] The lighting failure stated in this application note means that an LED does not illuminate due to an open circuit.

Soldering Pad Pattern:	SMD or NSMD pad pattern (see Table 7)
Solder Paste:	Standard lead-free solder (Sn-3.0Ag-0.5Cu)
Thickness of the Metal Solder Stencil:	100µm (see Figure 8 for the aperture)
Solder Void Percentage:	<10% (Percentage of the total area of voids to the solder joint area, the areas are examined by X-ray)
Conditions of the Temperature Cycle:	-40°C (15 min) ⇔ 135°C (15 min), up to 3,000 cycles, not in operation
Number of LEDs Tested:	10 or 20 LEDs per evaluation condition

The evaluation test results are shown in Sections 5.1 to 5.3. The tables in these sections show comparisons of number of the evaluation samples with $\Delta V_F \geq 10\%$[4] and the lighting failure at each stage up to 3000 cycles. The graphs in these sections show how the lighting failure increases and how the average ΔV_F, which were obtained from the evaluation samples that did not fail to emit light, increases as a reference of occurrence timing of solder cracks.

Table 5. Evaluation Samples Prepared Under Different Conditions

Sample	PCB		
	Base Metal	Insulating Layer (See Table 6)	Soldering Pad Pattern (See Table 7)
1	Aluminum	Standard	SMD
2	Copper	Standard	SMD
3	Aluminum	Low Modulus Elasticity	SMD
4	Aluminum	Standard	NSMD

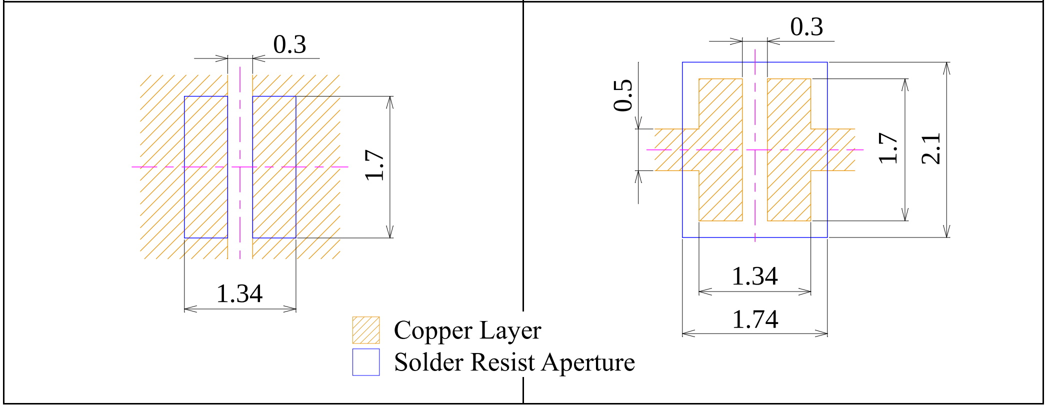
Table 6. Insulating Layers

Insulating Layer	Modulus Elasticity (Storage Modulus) (GPa)
Standard	13
Low Modulus Elasticity	0.16

4 $\Delta V_F \geq 10\%$, which has been used for Nichia's reliability tests as the judgement criterion, is also used in the solder crack evaluations.

Table 7. Soldering Pad Patterns

Soldering Pad Pattern	
SMD	NSMD



5.1 Comparison of Evaluation Samples with Different PCB Base Metals

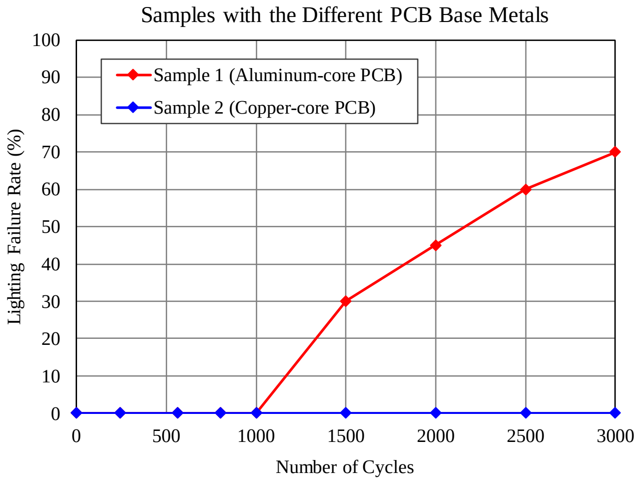
Comparisons were made between the evaluation samples that were prepared under the same conditions except for using different PCB base metals (see Table 8).
As a result, sample 1 using an aluminum-core PCB has a high occurrence of $\Delta V_F \geq 10\%$ and a high rate of lighting failure at 1500 cycles. On the other hand, sample 2 using a copper-core PCB has no occurrences of those even at 3000 cycles (see Table 9). As shown by the average ΔV_F in Figure 9, almost no ΔV_F increment occurred in sample 2 up to 2500 cycles.
The findings indicate that when considering the difference in the CTE between the PCB and the package material (Aluminum Nitride) of the NSWE170G LED, the use of a copper-core PCB is more effective for reducing solder cracks than the use of an aluminum-core PCB because the difference in the CTE between them is small.

Table 8. Evaluation Samples Prepared Under Different Conditions

Sample	PCB		
	Base Metal	Insulating Layer	Soldering Pad Pattern
1	Aluminum	Standard	SMD
2	Copper	Standard	SMD

Table 9. Occurrence Numbers of $\Delta V_F \geq 10\%$ and Lighting Failure

Sample	Judgement Criteria	Number of Cycles							
		240	560	800	1000	1500	2000	2500	3000
1	$\Delta V_F \geq 10\%$	0/20	0/20	0/20	0/20	3/14	6/11	6/8	6/6
	No Light	0/20	0/20	0/20	0/20	6/20	9/20	12/20	14/20
2	$\Delta V_F \geq 10\%$	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
	No Light	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10



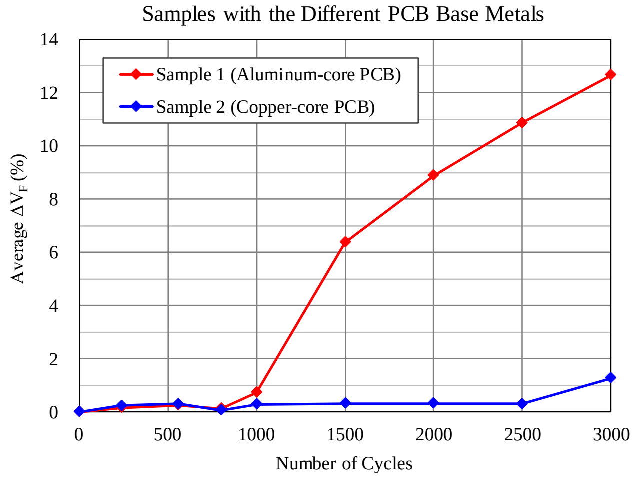


Figure 9. Lighting Failure Rate and Average ΔV_F

5.2 Comparison of Evaluation Samples with Different PCB Insulating Layers

Comparisons were made between the evaluation samples that were prepared under the same conditions except for using different PCB insulating layers for the aluminum-core PCBs (see Table 10).

As a result, sample 3 using an insulating layer with a low elastic modulus has no occurrence of $\Delta V_F \geq 10\%$ up to 2500 cycles and has no lighting failure up to 3000 cycles (see Table 11). As shown by the average ΔV_F in Figure 10, sample 3 has approx. 1% ΔV_F increment in average up to 2500 cycles.

The findings indicate that the use of an aluminum-core PCB with an insulating layer with a low elastic modulus is more effective for reducing solder cracks than the use of an aluminum-core PCB with a standard insulating layer.

Table 10. Evaluation Samples Prepared Under Different Conditions

Sample	PCB		
	Base Metal	Insulating Layer	Soldering Pad Pattern
1	Aluminum	Standard	SMD
3	Aluminum	Low Modulus Elasticity	SMD

Table 11. Occurrence Numbers of $\Delta V_F \geq 10\%$ and Lighting Failure

Sample	Judgement Criteria	Number of Cycles							
		240	560	800	1000	1500	2000	2500	3000
1	$\Delta V_F \geq 10\%$	0/20	0/20	0/20	0/20	3/14	6/11	6/8	6/6
	No Light	0/20	0/20	0/20	0/20	6/20	9/20	12/20	14/20
3	$\Delta V_F \geq 10\%$	0/10	0/10	0/10	0/10	0/10	0/10	0/10	1/10
	No Light	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

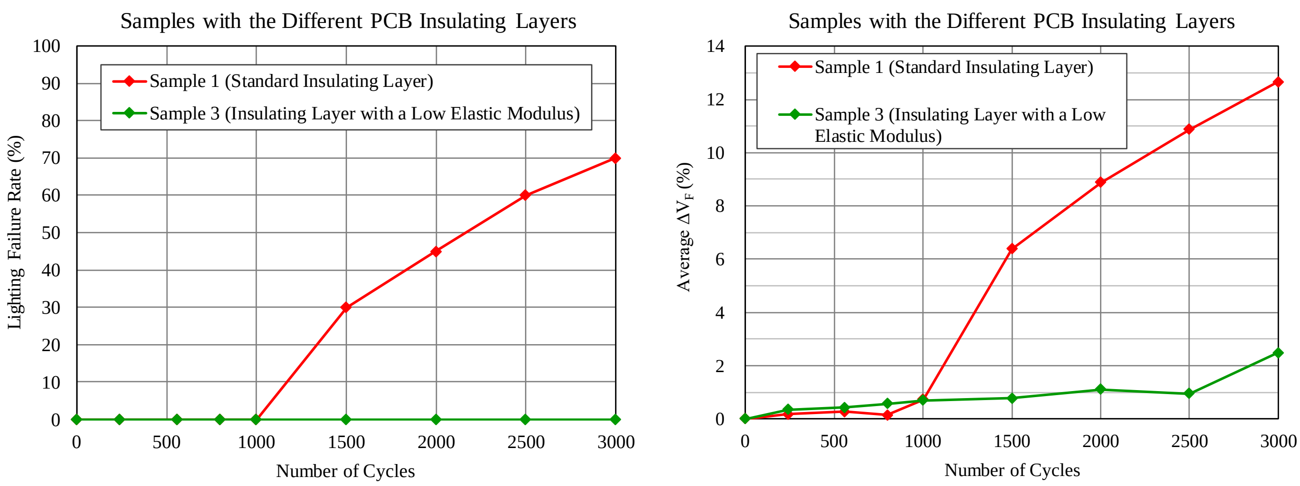


Figure 10. Lighting Failure Rate and Average ΔV_F

5.3 Comparison of Evaluation Samples with Different PCB Soldering Pad Patterns

Comparisons were made between the evaluation samples that were prepared under the same conditions except for using different PCB soldering pad patterns for the aluminum-core PCBs (see Table 12).

As a result, sample 4 using the NSMD pad pattern has no occurrence of $\Delta V_F \geq 10\%$ up to 1500 cycles and has no lighting failure occurred up to 3000 cycles (see Table 13). As shown by the average ΔV_F in Figure 11, sample 4 has less than 1% ΔV_F increment in average up to 1500 cycles.

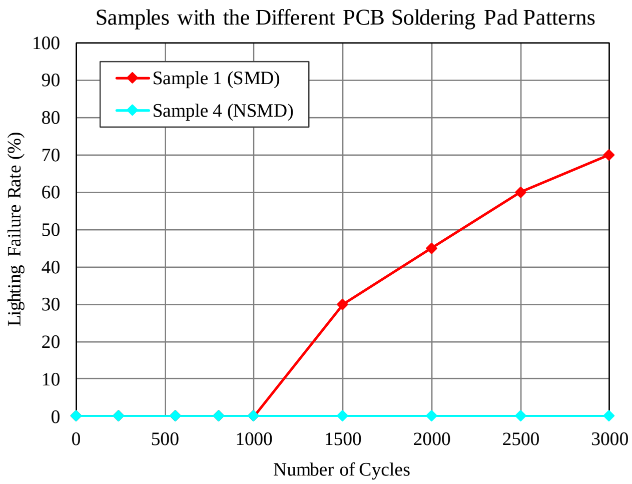
The findings indicate that the use of the NSMD pad pattern for the aluminum-core PCBs is more effective for reducing solder cracks than the use of the SMD pad pattern for the aluminum-core PCBs.

Table 12. Evaluation Samples Prepared Under Different Conditions

Sample	PCB		
	Base Metal	Insulating Layer	Soldering Pad Pattern
1	Aluminum	Standard	SMD
4	Aluminum	Standard	NSMD

Table 13. Occurrence Numbers of $\Delta V_F \geq 10\%$ and Lighting Failure

Sample	Judgement Criteria	Number of Cycles							
		240	560	800	1000	1500	2000	2500	3000
1	$\Delta V_F \geq 10\%$	0/20	0/20	0/20	0/20	3/14	6/11	6/8	6/6
	No Light	0/20	0/20	0/20	0/20	6/20	9/20	12/20	14/20
4	$\Delta V_F \geq 10\%$	0/10	0/10	0/10	0/10	0/10	4/10	8/10	9/10
	No Light	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10



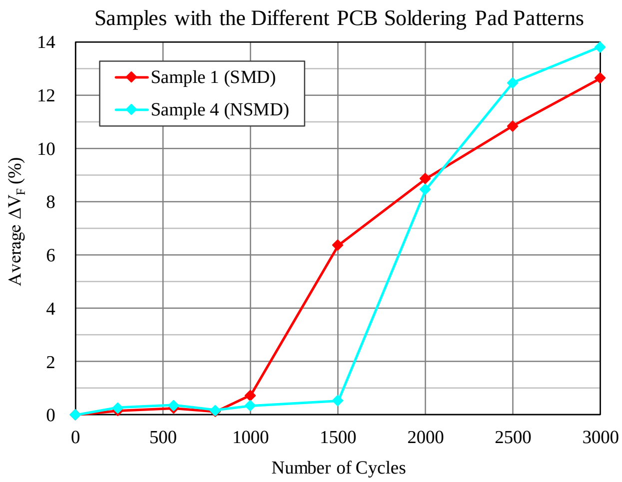


Figure 11. Lighting Failure Rate and Average ΔV_F

5.4 Cross-sectional Observation (Reference)

For reference purposes, Table 14 shows examples of cross-sectional observation results of the LEDs that underwent a thermal shock test (3000 cycles). The cross-sectional abrasion locations and observation directions are shown in Figure 12.

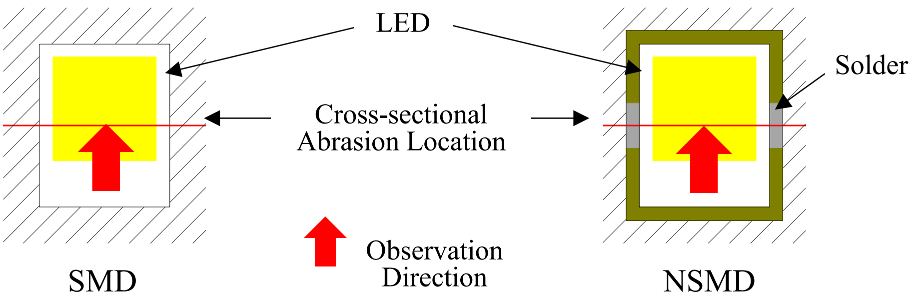
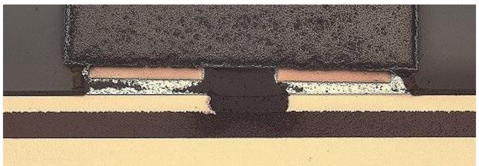


Figure 12. Cross-sectional Abrasion Location and Observation Direction

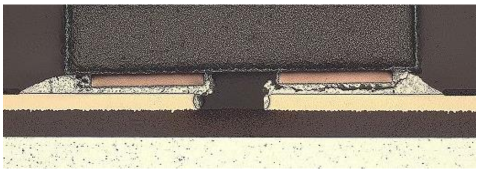
Table 14. Examples of the Cross-sectional Observation Results of the LEDs after a Thermal Shock Test (3000 cycles)

Sample 1		
PCB		Cross-sectional Observation Image
Base Metal	Aluminum	
Insulating Layer	Standard	
Soldering Pad Pattern	SMD	
Ratio of Solder Crack[5]		57%

Sample 2		
PCB		Cross-sectional Observation Image
Base Metal	Copper	
Insulating Layer	Standard	
Soldering Pad Pattern	SMD	
Ratio of Solder Crack[5]		48%

[5] Ratio of Solder Crack (%) = The total length of solder cracks in the horizontal direction / The total length of the solder joints of both electrodes in the horizontal direction × 100

Sample 3		
PCB		Cross-sectional Observation Image
Base Metal	Aluminum	
Insulating Layer	Low Modulus Elasticity	
Soldering Pad Pattern	SMD	
Ratio of Solder Crack[5]		19%

Sample 4		
PCB		Cross-sectional Observation Image
Base Metal	Aluminum	
Insulating Layer	Standard	
Soldering Pad Pattern	NSMD	
Ratio of Solder Crack[5]		55%

6. Summary

When an LED is mounted on a PCB by using solder, especially when the package of the LED is made of ceramics (aluminum nitride or aluminum oxide), care should be taken because solder cracks are likely to occur and to grow when the LED-mounted PCB is repeatedly turned on and off under operating conditions that lead to a large temperature difference and/or in an environment where the temperature fluctuates significantly.

As examples of measures to reduce solder cracks, this application note explains the selection of a PCB material considering thermal expansion (CTE), use of an aluminum-core PCBs containing a low modulus elasticity insulating layer, use of a PCB with NSMD pads, and use of a high reliability lead-free solder. The solder crack evaluation results in this application note are only reference data based on Nichia's test conditions. Before using LEDs, sufficient solder crack evaluations must be performed by using the PCB and solder pastes that are used for the chosen application with consideration of conditions/environments in which the LED will actually be used.

A cross-sectional observation of the solder joints and a solder joint strength evaluation (e.g. shear test) etc. are also effective to evaluate solder cracks.

The measures to reduce solder cracks stated in this application note may affect the heat dissipation and/or solderability. Moreover, the LED characteristics and reliability may be adversely affected depending on the materials used.

A light-up test, sufficient verifications etc. of the chosen application must be performed prior to use under the conditions/environments in which the LED will actually be used to ensure that the expected performance is maintained.

The cross-sectional images in Figure 1 and Table 14 were provided by Qualtec Co., Ltd.

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