Light Emitting Diode

Solder Crack Considerations for LEDs for General Lighting

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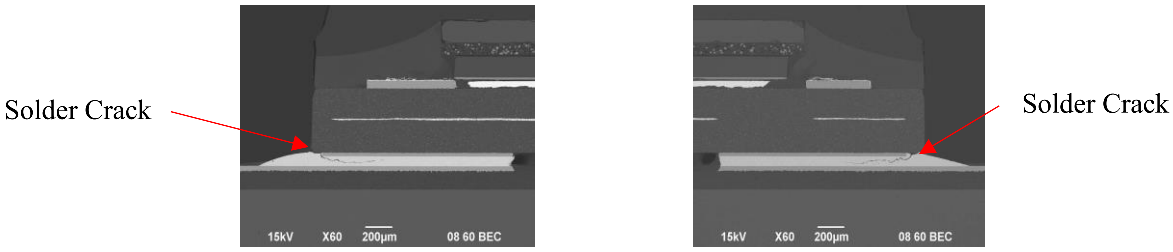
NVSL119B-V1, NVSL219B-V1, NVSL119C, NVSL219C, and NVSW219F-V1 refer to Nichia part numbers. These Nichia part numbers within this document are merely Nichia's part numbers for those Nichia products and are not related nor bear resemblance to any other company's product that might bear a trademark.

1. Overview

In products using LEDs, the LEDs are usually soldered on PCBs, and the applications and environments in which the LED-mounted PCBs are actually used are becoming more diverse. 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, solder cracks may occur depending on the combination of the package of the LED and the PCB used (See Figure 1).
When the difference in the coefficient of thermal expansion (CTE) between the package of the LED and the PCB used is large, solder cracks are more likely to occur and this may cause the LED not to emit light. Therefore, sufficient verifications must be done prior to use to ensure there are no issues for the chosen application.



Electrode: Cathode
Electrode: Anode

Figure 1. Cross-sectional Observation of an LED Solder Joint Area (After a Temperature Cycle Test)

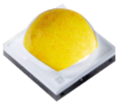
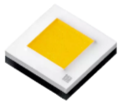
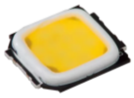
This application note explains how solder cracks occur and provides examples of reducing the occurrence of solder cracks. Solder crack evaluations were conducted through temperature cycle tests using combinations of typical packages of LEDs and PCBs. The evaluation results are also included in this application note.

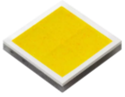
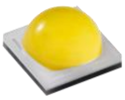
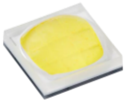
2. Applicable Part Numbers

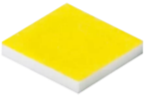
This application note applies to the LEDs shown in Table 1.

Table 1. Applicable LED Part/Series Numbers

Middle Power				
Category	Nichia 757 Series	Nichia 385 Series	Nichia 585 Series	Nichia T02 Series
Part Number	NFxx757x	NF2W385x	NFxW585x	NSSxT02x
Examples of Package Appearance				
Package Size	3.0mm×3.0mm	4.0mm×3.6mm	4.0mm×3.6mm	1.2mm×0.7mm

High Power				
Category	Nichia x19 Series	Nichia 519 Series	Nichia 719 Series	Nichia 48x Series
Part Number	NxSx119/NxSx219	NVSW519x	NVSW719x	NFMW48xx
Examples of Package Appearance				
Package Size	3.5mm×3.5mm	3.5mm×3.5mm	3.5mm×3.5mm	6.5mm×5.8mm

Super High Power			
Category	Nichia B35 Series	Nichia 144 Series	Nichia 149 Series
Part Number	NV4WB35x	NV4x144x	NV9W149x
Examples of Package Appearance			
Package Size	3.5mm×3.5mm	5.0mm×5.0mm	7.0mm×7.0mm

Direct Mountable Chip				
Category	Nichia E11 Series	Nichia E13 Series	Nichia E17 Series	Nichia E21 Series
Part Number	NFSWE11x	NCSWE13x	NCSxE17x	NVSxE21x
Examples of Package Appearance				
Package Size	1.1mm×1.1mm	1.25mm×1.25mm	1.7mm×1.7mm	2.1mm×2.1mm

3. Main Cause of Solder Cracks

3.1 Coefficient of Thermal Expansion (CTE)

Solder cracks are more likely to occur when the difference in CTE between the package of the LED and the PCB is large.

The CTE describes how the length of an object changes with an increase in temperature.

Table 2 below shows the CTEs of typical package materials of LEDs and the CTEs of typical PCB materials.

Note that the CTEs listed in Table 2 are only the typical values of the materials.

Table 2. CTEs of Typical Package Materials of LEDs and PCB Materials

Package materials of LEDs		Category
Material	CTE (1/°C)	
Ceramic	5～7×10^{-6}	Nichia x19、519、719、B35、144、149 Series
Resin	14～20×10^{-6}	Nichia 757、385、585、T02、48x Series

PCB material	CTE (1/°C)
Ceramic	8×10^{-6}
Iron (Fe)	12×10^{-6}
Glass-reinforced epoxy laminate material (FR-4)	14×10^{-6}
Copper (Cu)	17×10^{-6}
Aluminum (Al)	21×10^{-6}
Composite epoxy material (CEM-3)	25×10^{-6}

3.2 How Solder Cracks Occur

Figure 2 below shows an LED soldered to a 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 CTE between the package of the LED and the PCB causes them to expand/contract at different rates and the resulting stress will be applied to the solder joints (see Figure 3).

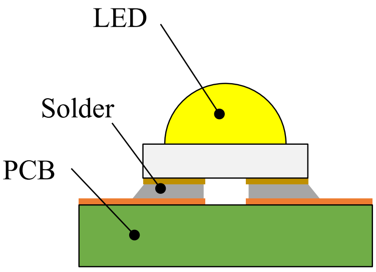


Figure 2. LED Soldered to a PCB

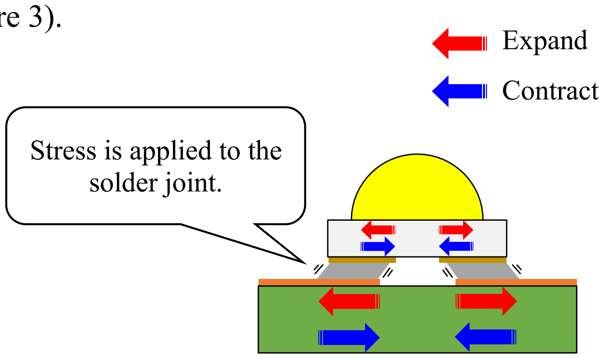


Figure 3. How Stress is Applied to the Solder Joints

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).

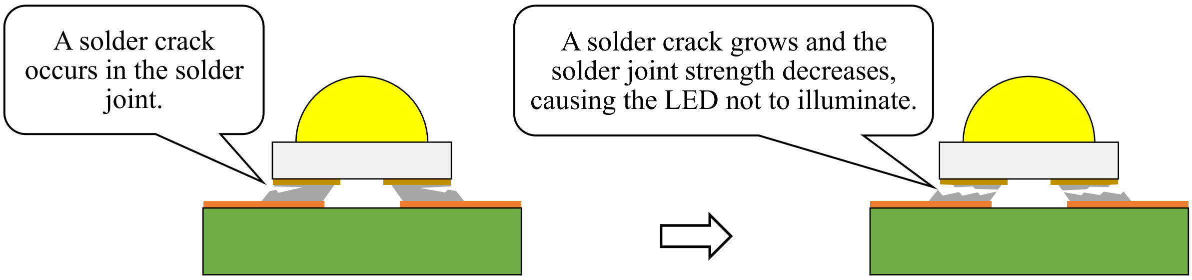


Figure 4. How Solder Cracks Occur

4. Reducing the Occurrence of Solder Cracks

Examples of measures to reduce solder cracks are as follows.

4.1 Using LEDs with a High Solder Crack Resistance

- LEDs with Compact Package Sizes

By using an LED with a compact package size, effects due to the difference in the CTE between the package of the LED and the PCB used under the temperature rise can be minimized, enabling the occurrence of solder cracks to be reduced.

- LEDs with Short Distances between their Electrodes

By using an LED with a short distance between its electrodes, effects due to the difference in the CTE between the package of the LED and the PCB used under the temperature rise can be minimized, enabling the occurrence of solder cracks to be reduced.

- LEDs with Large Areas for their Electrodes

By using an LED with a large area for the electrodes, the strength of the solder joint increases, enabling the occurrence of solder cracks to be reduced.

4.2 Selecting a Combination where the CTE Difference between the Package of the LED and the PCB is Small

As shown in Section 3.2 “How Solder Cracks Occur”, solder cracks can be reduced by selecting a combination where there is a small difference in CTE between the package material of the LED and the PCB material.
For example, when combining a resin package LED and a glass epoxy PCB, the CTE difference is 2x10^{-6}, whereas when combining a ceramic package LED and an aluminum-core PCB, the CTE difference is 16x10^{-6}. It is considered that the combination of a resin package LED and a glass epoxy PCB is effective for reducing solder cracks (See Figure 5).

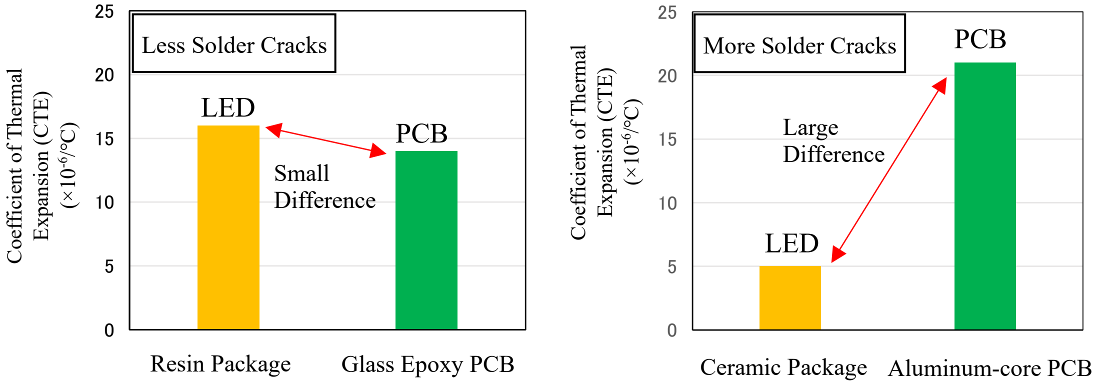


Figure 5. Differences in CTE between the Packages of the LEDs and PCBs

4.3 Using an Aluminum-core PCB Containing a Low Elastic Modulus Insulating Layer

In general, solder cracks can be reduced by using an aluminum-core PCB containing an insulating layer with a low elastic modulus. 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).

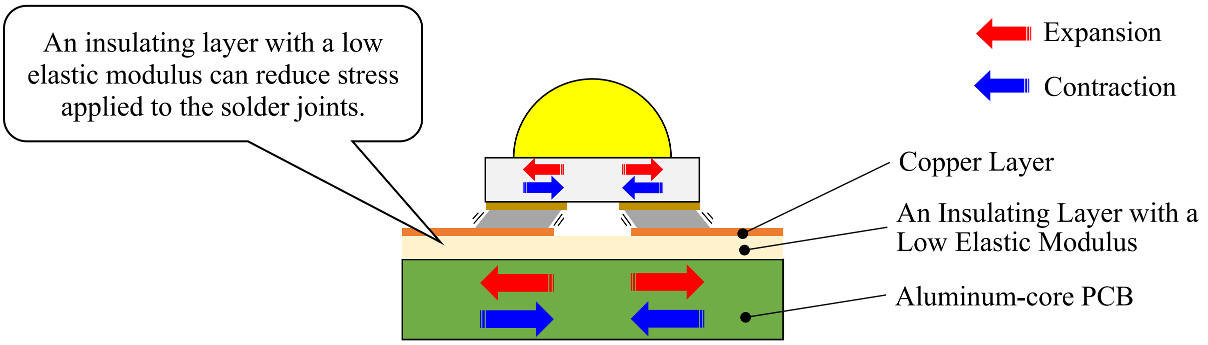


Figure 6. Example of Aluminum-core PCB Containing an Insulating Layer with a Low Elastic Modulus

For reference, Figure 7 shows the deformation rates of the aluminum-core PCB insulating layers against stress.
Under the same stress, the deformation rates of the aluminum-core PCB insulating layers with low elastic moduli are larger than that of a standard aluminum-core PCB.

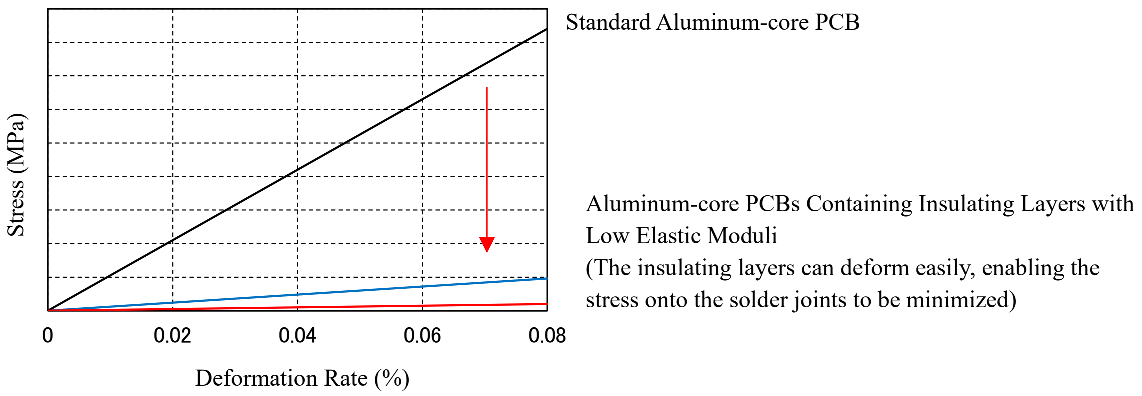


Figure 7. Deformation Rates of the Insulating Layers Contained in Aluminum-core PCBs against Stress

When selecting an aluminum-core PCB, the storage modulus of the insulating layer of the PCB must be checked (see Table 3). The storage moduli of aluminum-core PCBs are temperature-dependent and the values also vary depending on the thicknesses of the insulation layers. Note that lowering the storage modulus may decrease the thermal conductivity that is important for heat dissipation.

Even if an aluminum-core PCB containing an insulating layer with a low elastic modulus is selected, it may not be effective for reducing solder cracks in some LEDs (e.g. LEDs with large package sizes). Therefore, sufficient verifications must be performed by using the selected PCB to evaluate the solder crack resistance.

Table 3. Insulating Layers of the Aluminum-core PCBs

Aluminum-core PCB[1]	Thermal Conductivity (W/m･K)	Storage Modulus (GPa)		
		Low Temperature (-40°C)	Room Temperature (25°C)	High Temperature (125°C)
Standard Insulating Layer	2.1	17	12	2.8
Low Elastic Modulus Insulating Layer - A	3.0	12	1.2	0.7
Low Elastic Modulus Insulating Layer - B	2.5	4.6	0.51	0.04

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[1] These PCBs were used for the solder crack evaluation in Section 5.

4.4 Using a High Reliability Lead-free Solder Paste

Generally, the use of high reliability lead-free solder pastes, which can reduce the risks of occurrence and progression of solder cracks, allows for a delay in the decrease in the solder joint strength. This can delay the onset of solder cracks accordingly when compared with a standard lead-free solder paste (Sn-3.0Ag-0.5Cu).
It is generally known that when a standard lead-free solder paste is used under high temperatures and/or when it undergoes repeated thermal shock, the crystal grains in the solder structure become coarse and the alloy layer grows, resulting in the decrease in the solder joint strength (see Figure 8).

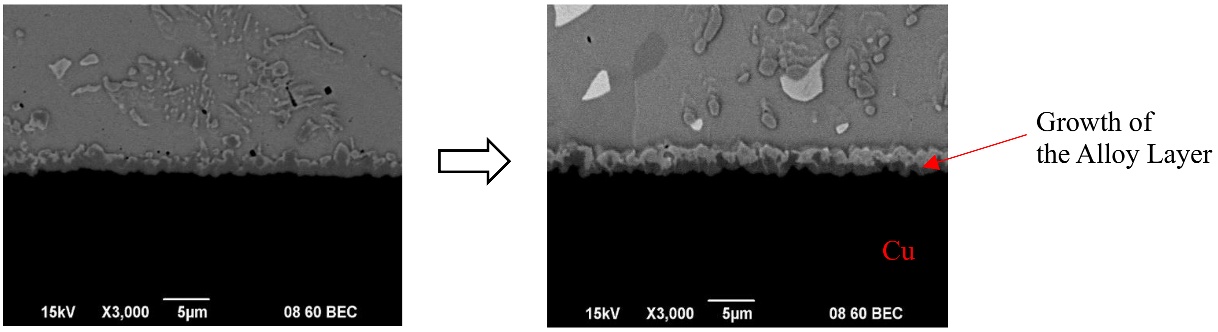

Figure 8. Cross-sectional Views of the Solder Joint Area (Before and After the Temperature Cycle Test)

In recent years, there has been research and development done on solder pastes to maintain the reliability of solder joints even when an LED-mounted PCB is used under high temperatures and/or 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.

However, when a high reliability lead-free solder paste is used as a measure to reduce solder cracks, stress may become concentrated onto the LED due to a large difference in CTE between the package of the LED and the PCB, leading to cracks and/or breakage of the LED chip. Take this into consideration when selecting a solder paste. Table 4 shows the types of solder pastes and the precautions.

Table 4. Types of Solder Pastes and the Precautions

Solder Paste[2]	Composition	Precaution
Standard Lead-free Solder	Sn-3.0Ag-0.5Cu	―
High Reliability Lead-free Solder	Sn-3.4Ag-0.7Cu-3.2Bi-3.0Sb-Ni-X	Avoid using this solder paste for Nichia's E11, E13, E17, E21 Series.

When a high reliability lead-free solder paste is used for the PCB assembled in the chosen application, ensure that there are no issues with the solderability, solder voids, and reliability etc. prior to use.

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[2] These solder pastes were used for the solder crack evaluation in Section 5.

5. Solder Crack Evaluation

5.1 Temperature Cycle Test 1

Nichia conducted temperature cycle tests on LED-mounted PCBs in different combinations of the packages of LEDs and PCBs that were explained in Section 4. The test conditions and types of the LEDs and PCBs used, and the test results are as follows.

5.1.1 Test Conditions and Evaluation Materials

Conditions of the Temperature Cycle:	-40°C (15 min) ⇔ 100°C (15 min), 2,000 cycles, not in operation
LEDs and PCBs Used:	See Tables 5 and 6, and Figure 9
Solder Paste Used:	Sn-3.0Ag-0.5Cu
Thickness of the Metal Solder Stencil:	100µm
Verification Method:	Lighting inspection, check for ΔV_F [3], cross-sectional observation

Table 5. Evaluated LEDs

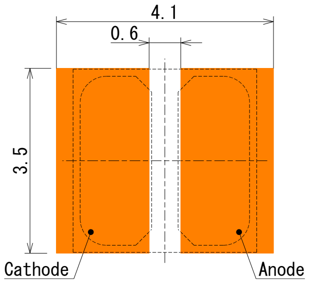
LED Part No.	Package Material	CTE (1/°C)	Qty. of Electrodes	Area of the Electrodes (mm^2)
NVSL119B-V1	Ceramic (Al_2O_3)	(7×10^{-6})	2	8.3
NVSL119C	Ceramic (AlN)	(5×10^{-6})	2	8.3
NVSL219B-V1	Ceramic (Al_2O_3)	(7×10^{-6})	3	6.2
NVSL219C	Ceramic (AlN)	(5×10^{-6})	3	6.2

NVSL119B-V1 and NVSL219B-V1
Size: 3.5mm × 3.5mm

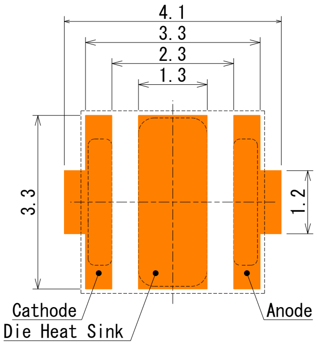
NVSL119C and NVSL219C
Size: 3.5mm × 3.5mm

NVSL119B-V1 and
NVSL119C
Bottom Surface
(Two Electrodes)

NVSL219B-V1 and
NVSL219C
Bottom Surface
(Three Electrodes)



NVSL119B-V1 and NVSL119C
Soldering Pad Pattern (Two Electrodes)



NVSL219B-V1 and NVSL219C
Soldering Pad Pattern (Three Electrodes)

Figure 9. Evaluated LEDs and the Soldering Pad Patterns

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[3] 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.
$\Delta V_F \geq 10\%$, which has been used for Nichia's reliability tests as the judgement criterion, is also used in the solder crack evaluations.

Table 6. PCBs Used

PCB	CTE (1/°C)	PCB Thickness (mm)	Copper Layer Thickness (µm)	Insulating Layer Thickness (µm)
Iron (Fe)	12×10^{-6}	0.5	35	120
Glass Epoxy (FR-4)	14×10^{-6}	1.0	35	-
Aluminum (Al)	21×10^{-6}	1.0	35	120

5.1.2 Test Results

The temperature cycle tests were conducted up to 2000 cycles. As a result, no lighting failure[4] occurred in any of the combinations of the packages of LEDs and PCBs; however, the forward voltage did increase at 1000 cycles onward for the combination of the aluminum-core PCB and the LEDs with small areas for their electrodes, where the CTE difference is large (see Tables 7 and 8).

Table 7. Temperature Cycle Test Results (Number of the LEDs that Failed to Emit Light)

PCB Material	Iron (Fe)				Glass Epoxy (FR-4)				Aluminum (Al)			
Number of Cycles	500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000
NVSL119B-V1	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
NVSL119C	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
NVSL219B-V1	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
NVSL219C	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

Table 8. Temperature Cycle Test Results (Number of the LEDs with $\Delta V_F \geq 10\%$)

PCB Material	Iron (Fe)				Glass Epoxy (FR-4)				Aluminum (Al)			
Number of Cycles	500	1000	1500	2000	500	1000	1500	2000	500	1000	1500	2000
NVSL119B-V1	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
NVSL119C	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
NVSL219B-V1	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	1/10	7/10	7/10
NVSL219C	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10	5/10	7/10	8/10

The combinations of the LED and the iron PCB and of the LED and the glass epoxy PCB, where the CTE difference is small, no $\Delta V_F \geq 10\%$ occurred. When comparing the LEDs based on the different electrode areas, the LEDs with large areas for their electrodes are more effective in reducing solder cracks than those with small areas for their electrodes (see Table 9).

Table 9. Combination of the LEDs and PCBs
(CTE differences in red indicate that the combinations led to $\Delta V_F \geq 10\%$)

LED Part No.	Qty. of Electrodes	Area of the Electrodes (mm^2)	CTE Difference between the LED and the PCB (1/°C)		
			Iron (Fe)	Glass Epoxy (FR-4)	Aluminum (Al)
NVSL119B-V1	2	8.3	5×10^{-6}	7×10^{-6}	14×10^{-6}
NVSL119C	2	8.3	8×10^{-6}	10×10^{-6}	17×10^{-6}
NVSL219B-V1	3	6.2	5×10^{-6}	7×10^{-6}	**14×10^{-6}**
NVSL219C	3	6.2	8×10^{-6}	10×10^{-6}	**17×10^{-6}**

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

5.2 Temperature Cycle Test 2

In Section 4, Nichia explained examples of measures to reduce solder cracks: selecting a PCB containing an insulating layer with a low elastic modulus and using a high reliability lead-free solder paste. For these measures, Nichia performed temperature cycle tests and the test results are shown below.

5.2.1 Test Conditions and Evaluation Materials

Conditions of the Temperature Cycle:	-40°C (15 min) ⇔ 100°C (15 min), 2,000 cycles, not in operation
LEDs and PCBs Used:	See Tables 10 and 11, and Figure 10
Solder Paste Used:	See Table 12
Verification Method:	Lighting inspection, check for ΔV_F [3], cross-sectional observation

Table 10. Evaluated LED

LED Part No.	Package Material	CTE (1/°C)	Qty. of Electrodes	Area of the Electrodes (mm^2)
NVSW219F-V1	Ceramic (AlN)	5×10^{-6}	3	6.2

NVSW219F-V1
Size: 3.5mm × 3.5mm

NVSW219F-V1
Bottom Surface
(Three Electrodes)

NVSW219F-V1
Soldering Pad Pattern
(Three Electrodes)

Figure 10. Evaluated LED and the Soldering Pad Patterns

Table 11. PCBs Used

Type of Aluminum-core PCB	Storage Modulus at 25°C (GPa)	Thickness of the Aluminum (mm)	Thickness of the Copper Layer (µm)	Thickness of the Insulating Layer (µm)
Standard Insulating Layer	12	1.0	35	120
Low Elastic Modulus Insulating Layer - A	1.2	1.0	35	120
Low Elastic Modulus Insulating Layer - B	0.51	1.0	35	100

Table 12. Types of Solder Pastes and Thickness of the Metal Solder Stencil

Solder Paste	Composition	Thickness of Metal Solder Stencil (µm)
Standard Lead-free Solder	Sn-3.0Ag-0.5Cu	100
High Reliability Lead-free Solder	Sn-3.4Ag-0.7Cu-3.2Bi-3.0Sb-Ni-x	100

5.2.2 Test Results

Using an Aluminum-core PCB Containing a Low Elastic Modulus Insulating Layer

When the standard aluminum-core PCB was used, the forward voltage increased at 1000 cycles onward, whereas when the aluminum-core PCB containing an insulating layer with a low elastic modulus (A) was used, the increase in the forward voltage was delayed to 2000 cycles. When another aluminum-core PCB containing an insulating layer with a low elastic modulus (B) was used, no increase in the forward voltage occurred within 2000 cycles (see Figure 11 and Table 13).

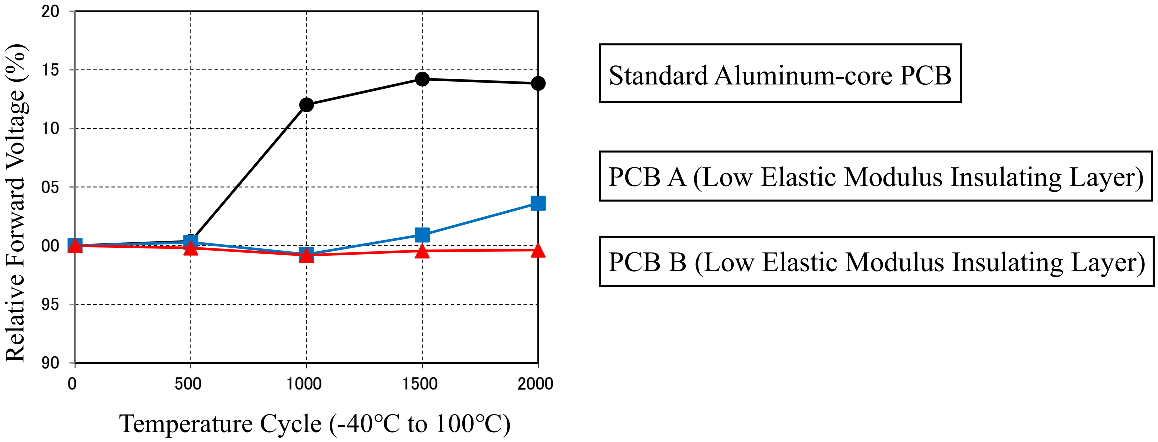


Figure 11. Temperature Cycle Test Results (Average Forward Voltage)

Table 13. Temperature Cycle Test Results (Number of the LEDs with $\Delta V_F \geq 10\%$)

Aluminum-core PCB	Solder Paste	500 Cycles	1000 Cycles	1500 Cycles	2000 Cycles
Standard Insulating Layer	Standard Lead-free Solder Paste	0/20	18/20	20/20	20/20
Low Elastic Modulus Insulating Layer - A	Standard Lead-free Solder Paste	0/20	0/20	0/20	2/20
Low Elastic Modulus Insulating Layer - B	Standard Lead-free Solder Paste	0/20	0/20	0/20	0/20

Using a High Reliability Lead-free Solder Paste

When the standard lead-free solder paste was used, the forward voltage increased at 1000 cycles onward, whereas when a high reliability solder paste was used, the increase in the forward voltage was delayed to 1500 cycles (see Figure 12 and Table 14).

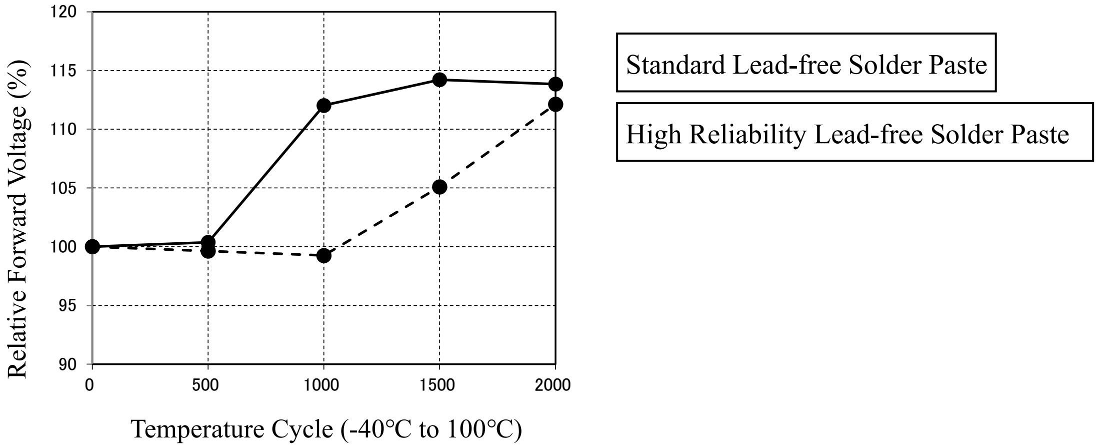


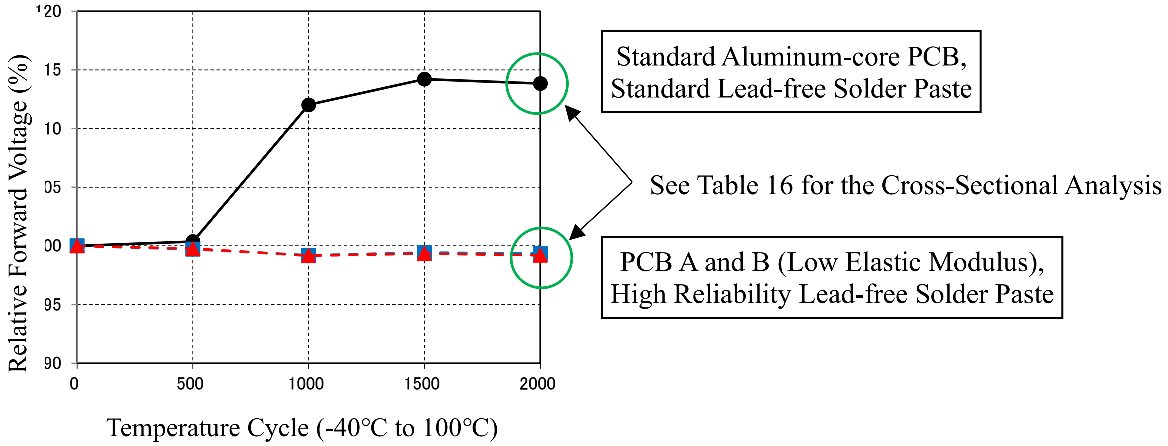
Figure 12. Temperature Cycle Test Results (Average Forward Voltage)

Table 14. Temperature Cycle Test Results (Number of the LEDs with ΔV$_F$ ≥10%)

Aluminum-core PCB	Solder Paste	500 Cycles	1000 Cycles	1500 Cycles	2000 Cycles
Standard Insulating Layer	Standard Lead-free Solder Paste	0/20	18/20	20/20	20/20
Standard Insulating Layer	High Reliability Lead-free Solder Paste	0/20	0/20	2/20	14/20

Using an Aluminum-core PCB Containing a Low Elastic Modulus Insulating Layer and a High Reliability Lead-free Solder Paste

When aluminum-core PCBs containing a low elastic modulus insulating layers and a high reliability lead-free solder paste were used, no increase in the forward voltage occurred within 2000 cycles (see Figure 13 and Table 15).



Standard Aluminum-core PCB, Standard Lead-free Solder Paste

See Table 16 for the Cross-Sectional Analysis

PCB A and B (Low Elastic Modulus), High Reliability Lead-free Solder Paste

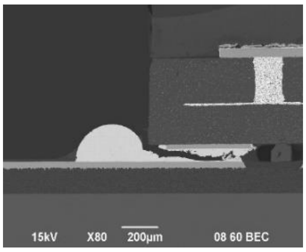
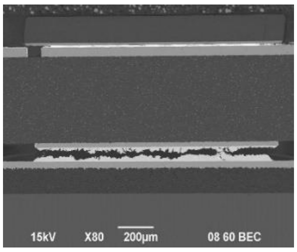
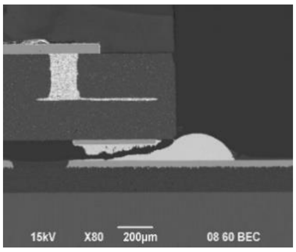
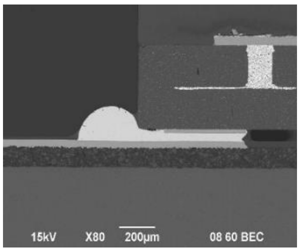
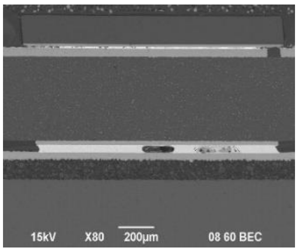
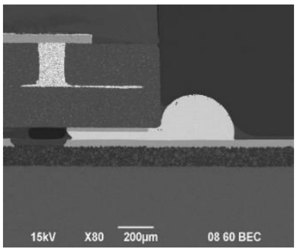
Figure 13. Temperature Cycle Test Results (Average Forward Voltage)

Table 15. Temperature Cycle Test Results (Number of the LEDs with ΔV$_F$ ≥10%)

Aluminum-core PCB	Solder Paste	500 Cycles	1000 Cycles	1500 Cycles	2000 Cycles
Standard Insulating Layer	Standard Lead-free Solder Paste	0/20	18/20	20/20	20/20
Low Elastic Modulus Insulating Layer - A	High Reliability Lead-free Solder Paste	0/20	0/20	0/20	0/20
Low Elastic Modulus Insulating Layer - B	High Reliability Lead-free Solder Paste	0/20	0/20	0/20	0/20

The cross-sectional analysis results at 2000 cycles are shown in Table 16 for reference.

Table 16. Cross-sectional Analysis Results

Materials Used	Cathode	Chip Heatsink	Anode
Standard Aluminum-core PCB and Standard Lead-free Solder Paste			
Ratio of Solder Cracks[5]	100%	100%	100%
PCB B (Low Elastic Modulus Insulating Layer) and High Reliability Lead-free Solder Paste			
Ratio of Solder Cracks[5]	0%	0%	0%

6. Summary

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, solder cracks can occur, and this may cause the LED not to emit light.
As examples of measures to reduce solder cracks, this application note explains suitable combinations of the package materials of LEDs and PCBs, use of aluminum-core PCBs containing low modulus elasticity insulating layers, and use of high reliability lead-free solder pastes for reference purposes.

When designing the chosen application, the solder joint temperature and the environment where the chosen application is actually used must be sufficiently verified. If the solder joint temperature tends to be high, a suitable thermal design must be required to prevent excess stress on the solder joints. In addition, the lifetime required for the chosen application must be considered when measures to reduce solder cracks are taken.

In the final design stage, considering the PCB and the solder paste selected for the chosen application and the environment where the chosen application is actually used, ensure that there are no adverse effects on the solder joints and that the lifetime required by the chosen application is maintained.

The cross-sectional images in Figures 1 and 8 and Table 16 were taken by Qualtec Co., Ltd.

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[5] Ratio of Solder Crack (%) = The length of a solder crack / The length of the electrode of the solder joint × 100

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