

Flexure Robust Capacitors

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Abstract

Board-flexure-related cracking has long been an issue with multilayer ceramic capacitors (MLCC), especially when larger case sizes (ca. 0603 and larger) are used. Careful circuit board design is needed in order to keep MLCC from areas of high flexure stress such as edges, large connectors, etc. Additionally, careful handling of boards during chip population and subsequent SMT processes is necessary in order to avoid board-flexure-related cracking. This paper discusses various aspects of board flexure as well as guidelines useful in avoiding board flexure related cracking. Several MLCC products that either reduce the incidence of flexure cracking, or fail open when cracked in the classic board flexure crack mode, or eliminate flexure cracking altogether are discussed in detail with respect to design philosophy, board flexure test performance, and other device performance parameters, as well as suggested application. Use of various design philosophies has resulted in a broad flexure robust product line that offers an optimal solution for most applications.

Introduction

Multilayer ceramic capacitors have many features that are desirable to circuit designers. They have extremely low ESR, high capacitance-per-unit volume, and small size, resulting in ever increasing year over year growth that has shown no signs of slowing down. However, due to the inherent brittle structure of ceramic materials, MLCCs are vulnerable to excessive stress once soldered to a printed circuit board (PCB).^[1] This stress is often created by inadvertent board bending during routine handling, depanelization, “snap together” manufacturing steps, or the attachment of external devices (such as large connectors) after solder mounting is complete.

The stress applied to the circuit board can transfer directly to the capacitor via the solder joint, resulting in a signature crack commonly referred to as a board flex crack. See Figure 1. The board flex signature is well known and well documented^[2]. It always originates at the edge of the termination band near the substrate, and subsequently propagates through the body of the capacitor at a high angle (typically 60° to 65°). If the crack crosses electrodes of opposing polarity, the crack can create a short and lead to catastrophic failure. This failure mode is not always seen immediately after surface mount assembly; unfortunately, the failure may not be detected until the part is in the field.

Many papers have been written and studies conducted^[3,4] on educating board assemblers on the merits of careful handling and board assembly in order to minimize the chance of creating board flex cracks. However, failure due to board flex is still a leading root cause of failures in customer complaint failure analysis. As a result of continuous improvement by MLCC manufacturers, circuit designers can now utilize a two-pronged approach to minimize the deleterious effects of failures caused by flex stresses: a) continued education for board manufacturers to use best handling-practices and design rules, and b) various MLCC design choices providing a solution to mitigate the catastrophic effects of flex cracks when they do occur.

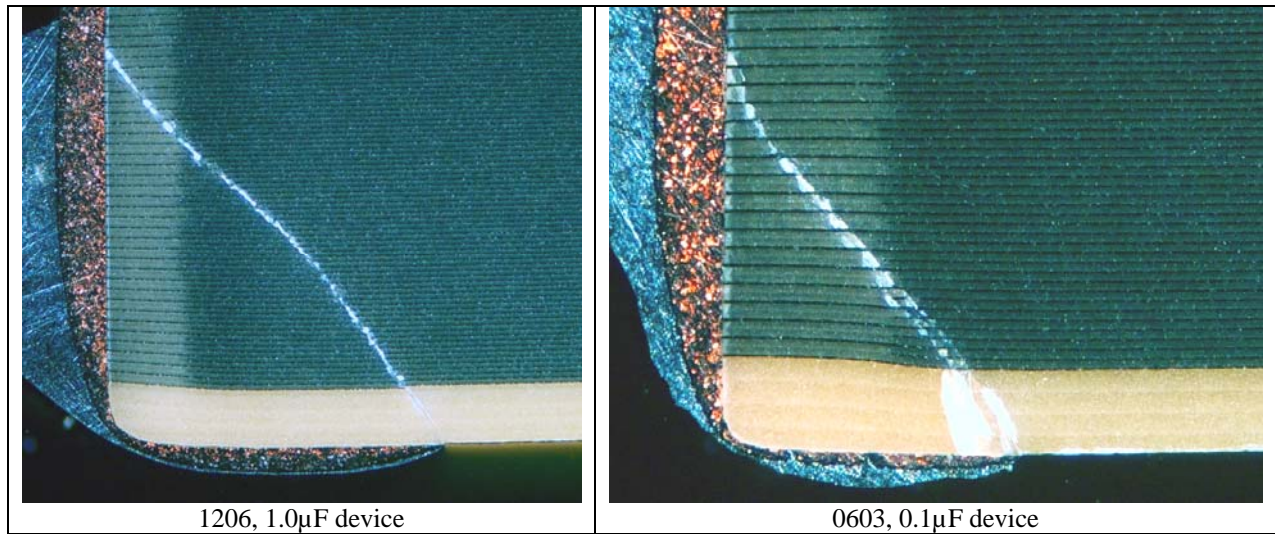


Figure 1: Examples of typical flex cracks.

The Flex Crack – Why it matters!

Figure 2 shows a drawing depicting a typical flex crack. The 60° angle of the crack, contained within the end termination, is a typical flex crack signature. The main concern is that the crack crosses opposing electrode layers, potentially leading to an electrical short.

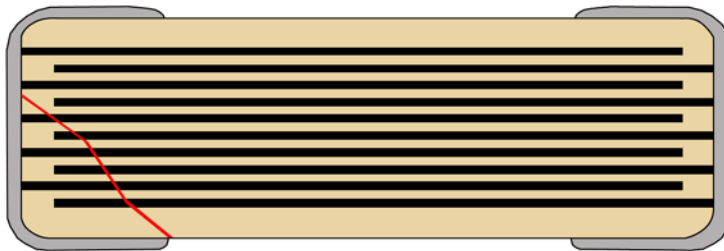


Figure 2: Drawing of a Typical Flex Crack

Cracking is a major failure mode for MLCCs, and the flex crack is the main type of crack seen through failure analysis. Once the crack is initiated after solder mounting, there is no guarantee that it will be detected prior to final assembly – thus board assemblers may not be aware they have a problem with flex cracks until the end customer experiences a failure in the field. This “latent failure effect” is due to the inherent nature of cracking in MLCC’s – simply having a crack does not necessarily result in failure. Other environmental conditions are necessary to allow the crack to become catastrophic. Typically high temperatures can cause ionic penetration (aided by moisture) resulting in electrical failure.^[5]

For purposes of this paper, all flex board tests were conducted using the test setup shown in Figure 3. All parts were manually mounted onto test boards using Sn63/Pb37 solder paste in an IR reflow oven. The volume of solder paste was controlled by periodically measuring the weight of 10 solder dots on a slide. The test board was placed in a 3-point bend fixture, and the center pin was continuously displaced at 1 mm/sec to apply flexure to the backside of the test board. This caused the mounted parts to be placed in tension. The outer posts rotate, minimizing any friction and pinning of the board during the test. The capacitance was measured during the flexure of each test board to monitor cracking. A constant displacement was applied until the either the

capacitance of the part deviated by more than a limit or the total displacement reached 10 mm. The limit for change in capacitance was adjusted depending on the purpose of the test.

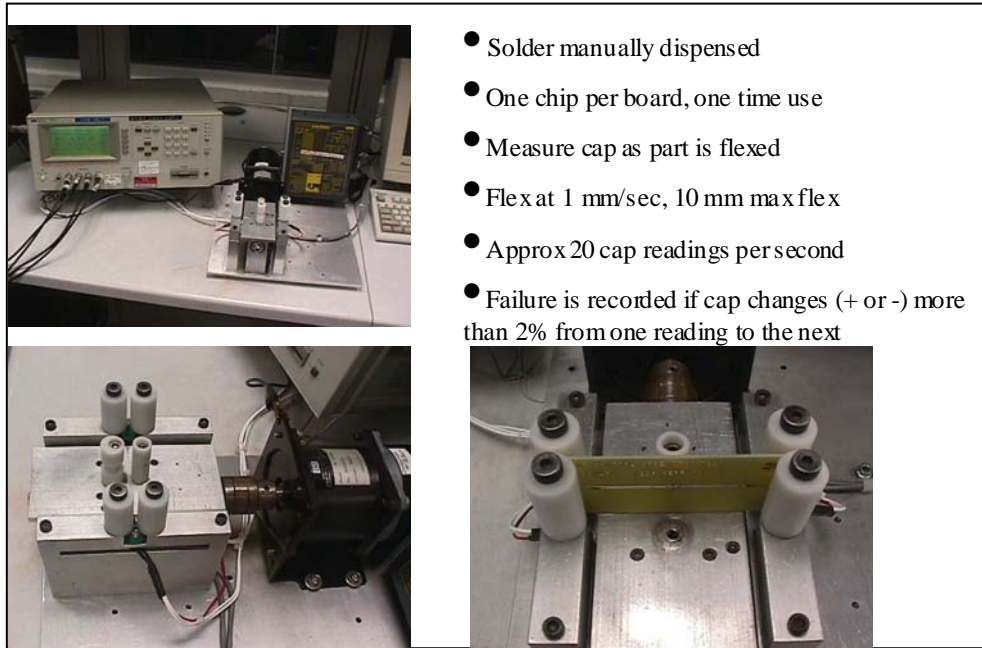


Figure 3: Flex test setup.

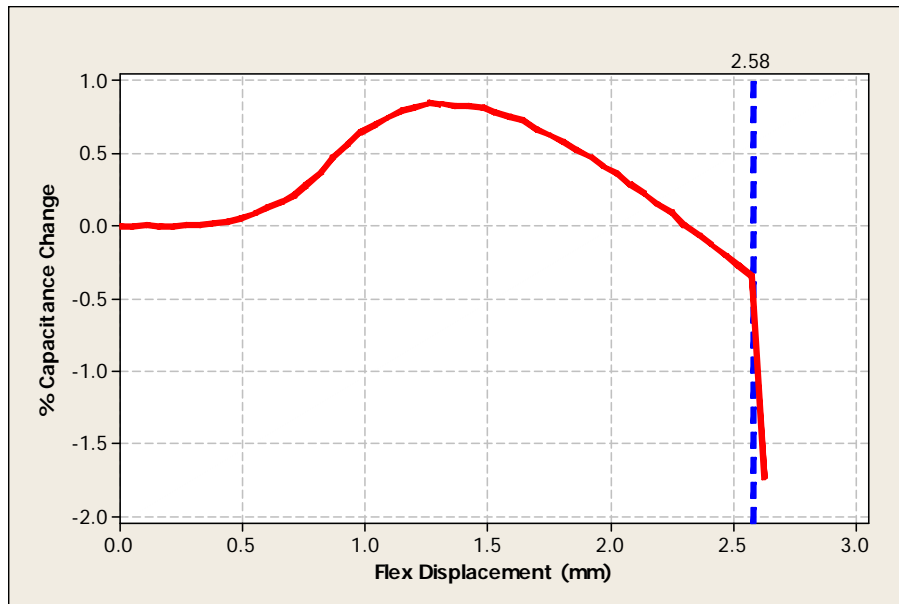


Figure 4: Typical capacitance behavior during flex testing.

Figure 4 illustrates capacitance monitoring in order to detect the initiation of cracking. Typically a limit of 2% was selected for percent capacitance change; however, 0.2% was often used to obtain better resolution for catching the initiation of the crack. The example is for an 0805, $0.01\mu\text{F}$ device with a detection limit of 0.2%.

Solutions for Flex Crack Issues Through MLCC Design

There are several options available for reducing the impact of flex cracks. Table 1 summarizes the capability of these solutions. Increased design complexity provides better protection against flex crack issues. Many of these solutions simply remove the deleterious effects caused by flex cracks even though the parts are still cracked. One solution uses a clip-on lead frame as a means to fully eliminate the cracks altogether. A final solution uses vertical electrodes to address not only the adverse effects of low IR, but also the loss of capacitance as a result of flex cracks.

Solution	Type	Moves Out Point of Failure During Board Flex	Eliminates Catastrophic Failure Mode	Eliminates Flex Cracks	Reduces Risk of Cap Loss due to Flex
Flexible Termination	MLCC	X			
Fail Open	MLCC		X		
Floating Electrode	MLCC		X		
Clip-On Leadframe	MLCC			X	
Vertical Electrode	MLCC				X

Table 1. Solutions Summary

Solution 1: Fail Open Design (Open mode)

The first proposal for flex crack mitigation is the Open Mode capacitor. Through enhanced electrode and dielectric design, the end margins are widened, causing the active area to be “squeezed” into the middle of the chip, greatly increasing the margin area where flex cracks occur and creating a safe zone.

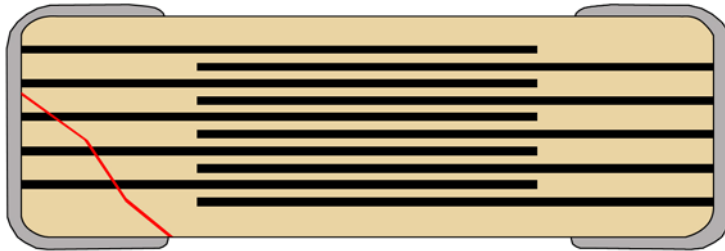


Figure 5: Open mode design.

The open mode does not prevent the occurrence of the flex crack, but rather mitigates the effect, as the crack does not cross electrodes of opposing polarity. This design has been very popular in the industry due to its simple but effective design. Unfortunately, the open mode solution cannot be utilized for products having high capacitance. Shown in the capacitance equation below, capacitance is directly proportional to the surface area of the electrodes (commonly referred to as “overlap area”).

$$C = K \left[\frac{A}{t} \right] = K \left[\frac{w \times l}{t} \right] (n - 1)$$

By greatly decreasing the active area (overlap) of the device, the maximum capacitance is limited for the open mode design. Thus, the open mode design is best suited for products requiring only mid-capacitance values, typically less than 1.0µF depending on case size.

Figure 6 shows the crack behavior for an open mode design leads to a “fail open” as compared to a “short” shown for the standard design. Typically the flex displacement behavior using the open mode is similar to that for standard parts (Fig. 7A).

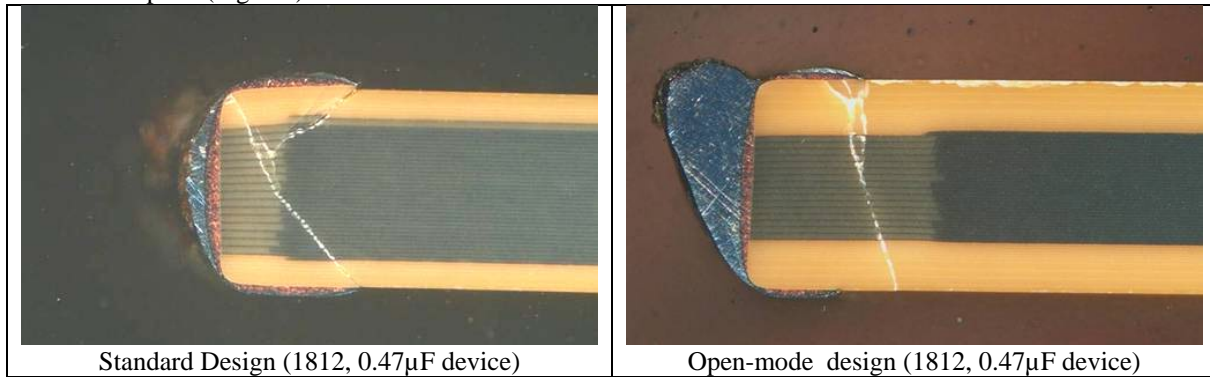


Figure 6: Comparison of the flex behavior of a standard electrode design to an open mode design.

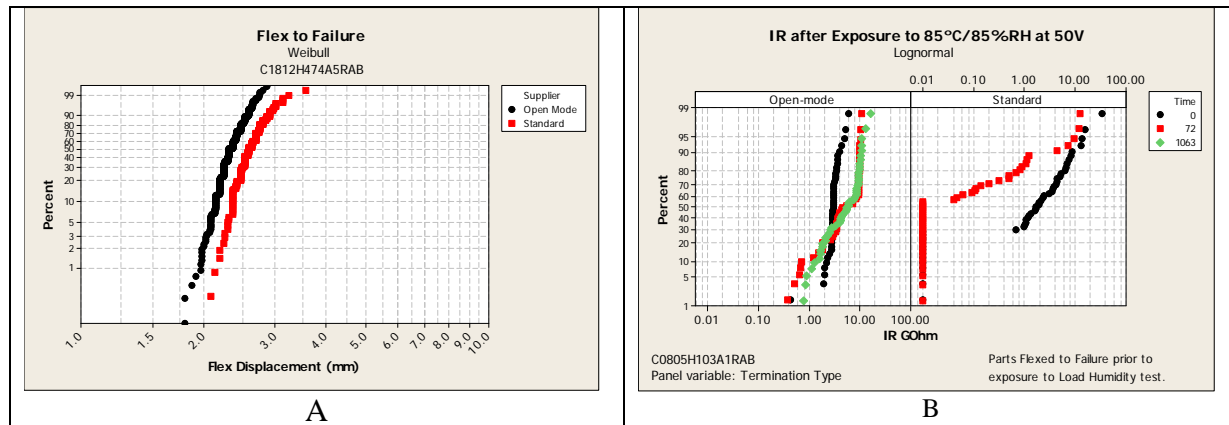


Figure 7: Plot A shows the flex to failure behavior for the open mode design. Plot B shows the enhanced IR performance for the open mode design when precracked parts are exposed to load humidity.

The chance for low IR as a result of a flex crack is greatly reduced using open mode design. Parts were exposed to load humidity tests to test the robustness of the open mode design after precracking the parts. Figure 7 shows the parts with standard design degraded in IR after only 72 hours exposure, whereas parts designed with open mode survived more than 1000 hours. This demonstrates the added protection an open mode design can provide for customers, especially in harsh environments such as automotive application.

Solution 2: Floating Electrode Design

In order to provide a cost-effective flex solution for lower capacitance values, the floating electrode design was introduced. Originally designed for manufacture of high-voltage devices, the floating electrode design (or Serial Cap) creates two separate capacitors in series within an individual case size. This design does not utilize a classic active area (Fig. 8). Instead, any flex crack in this design will be isolated to just one of the capacitive regions. Thus, a flex crack will not lead to the creation of a short circuit path (there is no direct path between electrodes of positive and negative polarity). However, as with the open mode design, significant active area has been sacrificed in order to provide a flex mitigation solution. The floating electrode design is only applicable for lower capacitance values (typically less than 0.1µF, depending on case size).

Figure 9 shows the floating electrode design leads to a “fail open” crack behavior, similar to the open mode design. Figure 10 shows the floating electrode design requires more flex displacement before fracture when compared to standard design; this is mainly due to the thickness of the device. In addition, precracked parts designed with floating electrodes, when exposed to load humidity, showed no degradation in IR after more than 1000 hours as compared to parts made with standard design, which failed in just 72 hours (Fig. 10).

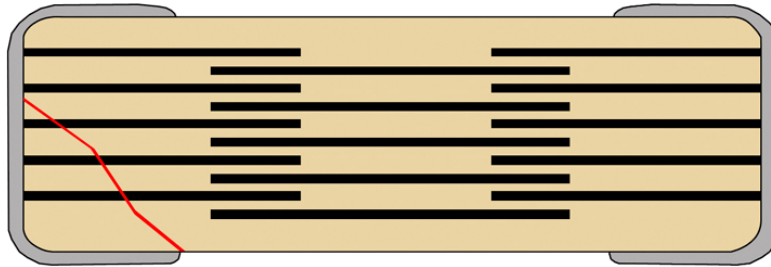


Figure 8: Floating electrode design.

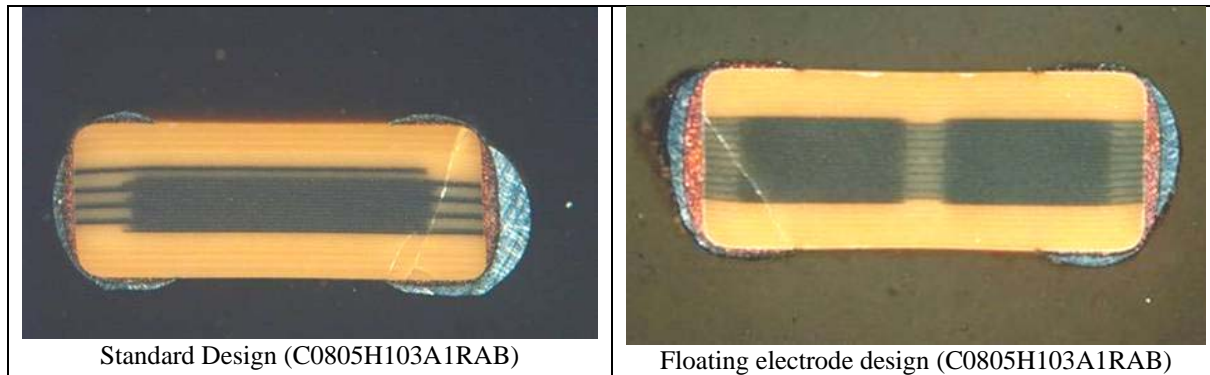


Figure 9: Comparison of the flex behavior of a standard electrode design to a floating electrode design.

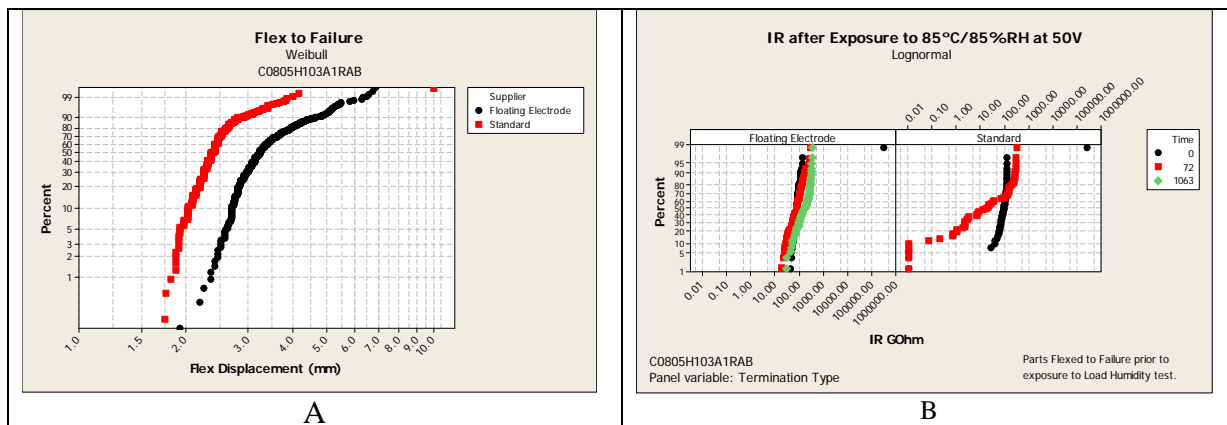


Figure 10: Plot A shows the flex to failure behavior for the floating electrode design. Plot B shows the enhanced IR performance for the floating electrode design when precracked parts are exposed to load humidity.

Again, the load humidity test demonstrates the added protection a floating electrode design can provide for customers, especially in harsh environments. The floating electrode design decreases the occurrence of low IR more than an open mode design, through more complex design.

Solution 3: Flexible Termination Design

The most recent entry into the flex mitigation arena is the flexible termination solution (also commonly referred to as soft termination or flexible termination). The key characteristic of the flexible termination is that it can be applied to any surface mount capacitor, regardless of size, voltage, or capacitance value.

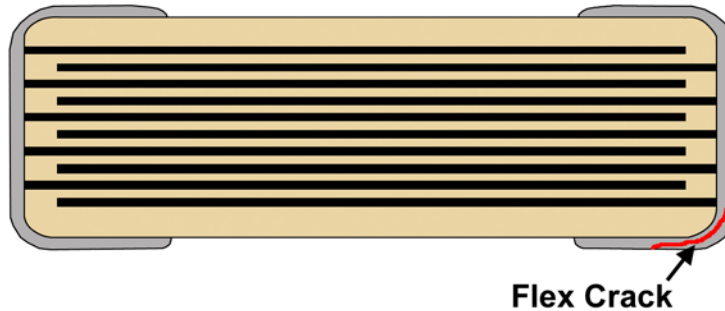


Figure 11: Flexible termination design.

More complex circuit designs require HICV (High Capacitance x Voltage), for which the flexible termination product is ideally suited. The application of a tear-away termination layer restricts all flex cracks within a safe zone away from the body of the MLCC (Fig. 11). Therefore, this design can be utilized for any MLCC product, regardless of capacitance, since there is no compromise in active area as required for open mode and floating electrode designs. The internal electrode design (see the capacitance equation) utilizes the widest possible active area, enabling the design of high capacitance products such as 22 μ F, 47 μ F, 100 μ F and beyond. Although the flexible termination can be applied to any MLCC, it is most cost-effective when applied to these HICV part types due to the increased cost of the more complicated termination design.

The flexible termination consists of a two part termination. The inner layer consists of a typical copper/glass material, covered by an outer layer of silver epoxy composition. Figure 12 shows the preferred “tear away” mode of failure caused by the crack propagating within the silver epoxy material. Figure 13 shows a closer look at the interface between the two termination layers. The flex crack prefers to propagate into the silver epoxy material to the interface, where it begins to track along the interface until the stress is relieved.

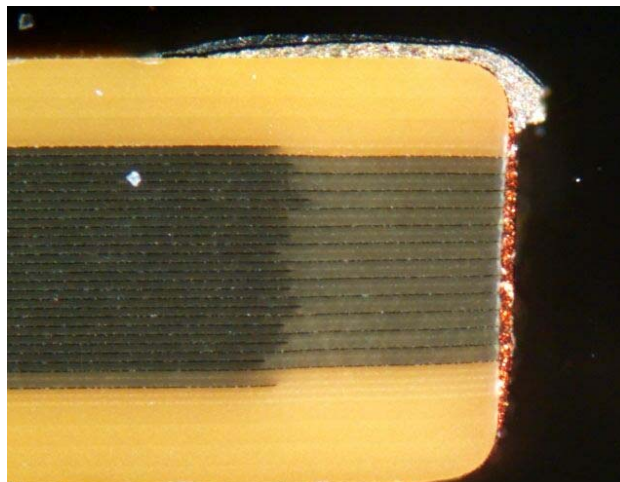


Figure 12: Typical failure mode for the flexible termination design.

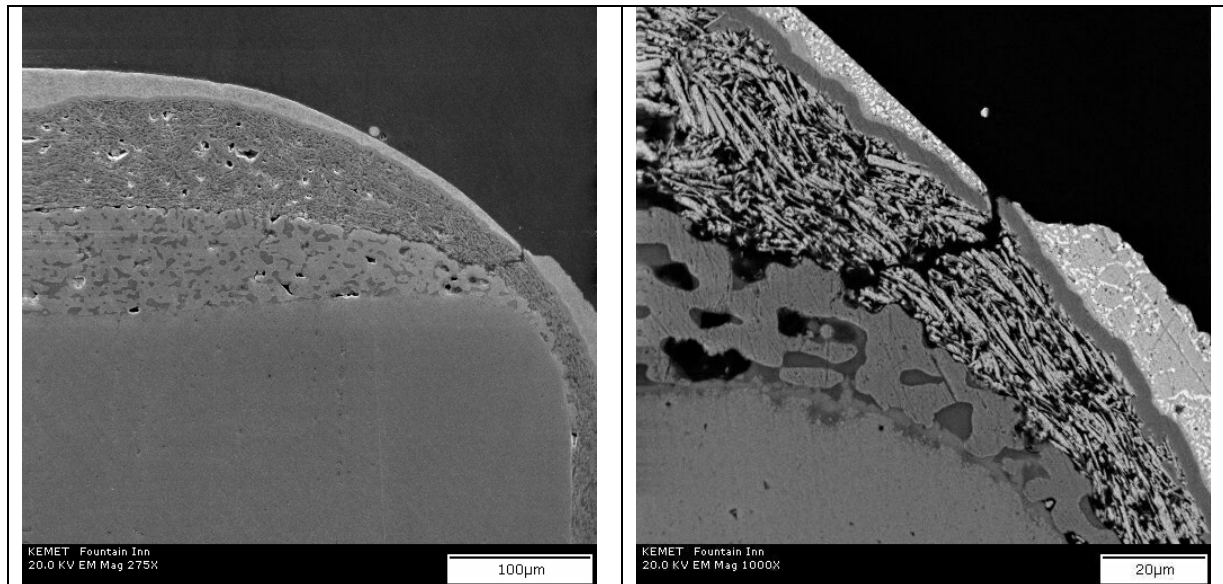


Figure 13: SEM micrographs show the preferred mode of crack propagation along the interface between the copper/glass and silver epoxy termination layers.

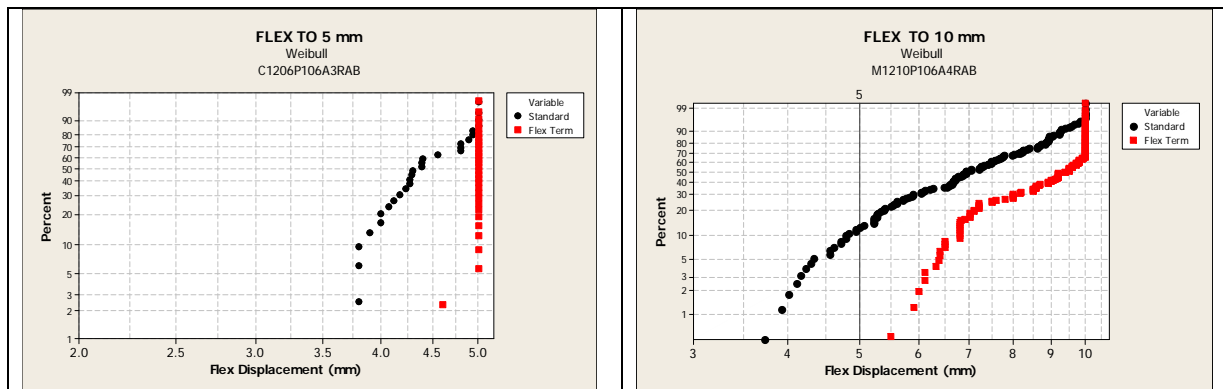


Figure 14: Comparison of the flex displacement performance for standard vs. flexible termination design at either a maximum of 5mm or 10mm. Note the enhanced performance of flexible termination designs.

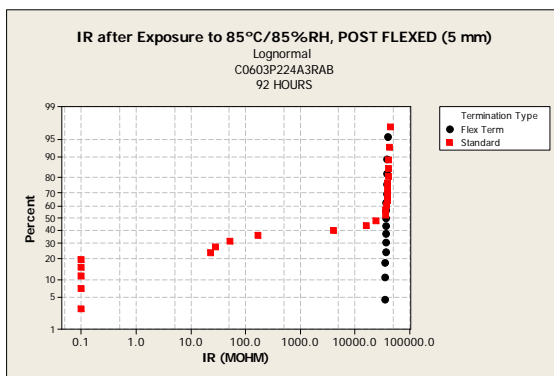


Figure 15: Comparison of IR for preflexed parts having either standard or flexible termination designs exposed to load humidity

When compared to standard parts, the flex displacement performance shows the flexible termination parts are more robust to cracking (Fig 14). This is due to the elastic behavior of the silver epoxy layer prior to crack initiation, allowing the MLCC to experience more board flex before cracking. In addition, preflexed parts with a flexible termination design do not exhibit degradation in IR when exposed to load humidity for 92 hours (Fig. 15), as opposed to parts with standard design which show a significant tail in IR. Since the cracks do not reach the body of the MLCC, the parts cannot fail due to a decrease in IR.

In summary, within the standard SMT chip design there are three (3) possible solutions for avoiding low IR issues caused by flex cracks. In relative terms, these solutions can be represented in the chart shown in Figure 16. The combination of solutions gives the designer different choices when selecting a solution for flex cracks.

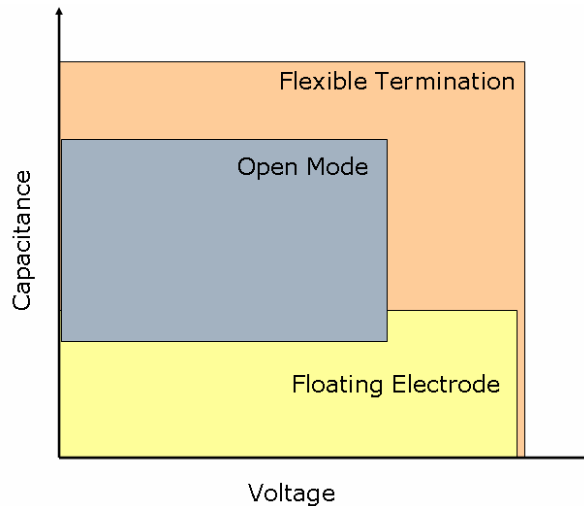


Figure 16: Schematic of the relative flex crack solutions as a function of capacitance and rated voltage.

Solution 4: Vertical Electrode Design

Industry data indicates as much as 50% of field failures caused by flex cracks are due to a loss of capacitance. Recent advances in manufacturing technique have allowed us to design MLCC's which will always have the internal electrodes perpendicular to the plane of the printed circuit board during surface mounting. By combining this vertical electrode technology with the benefits of an open mode or floating electrode design, we have added an additional measure of safety for preventing both loss due to IR and loss due to capacitance related to flex cracks. Figure 17 shows implementation of vertical electrodes in both an open mode and floating electrode design. Note the crack does not cause complete separation of electrode layers when using vertical electrodes, which would cause a loss of capacitance in standard horizontal orientation.

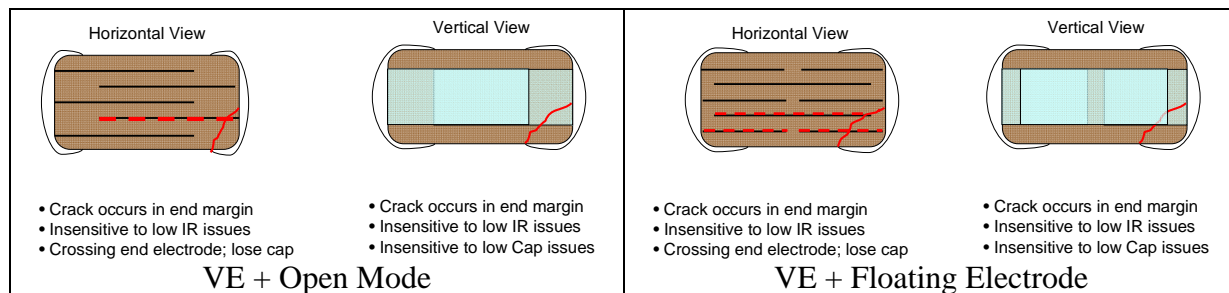


Figure 17: Description of the how vertical electrodes eliminated loss of capacitance caused by flex cracks when designed with either open mode or floating electrode designs.

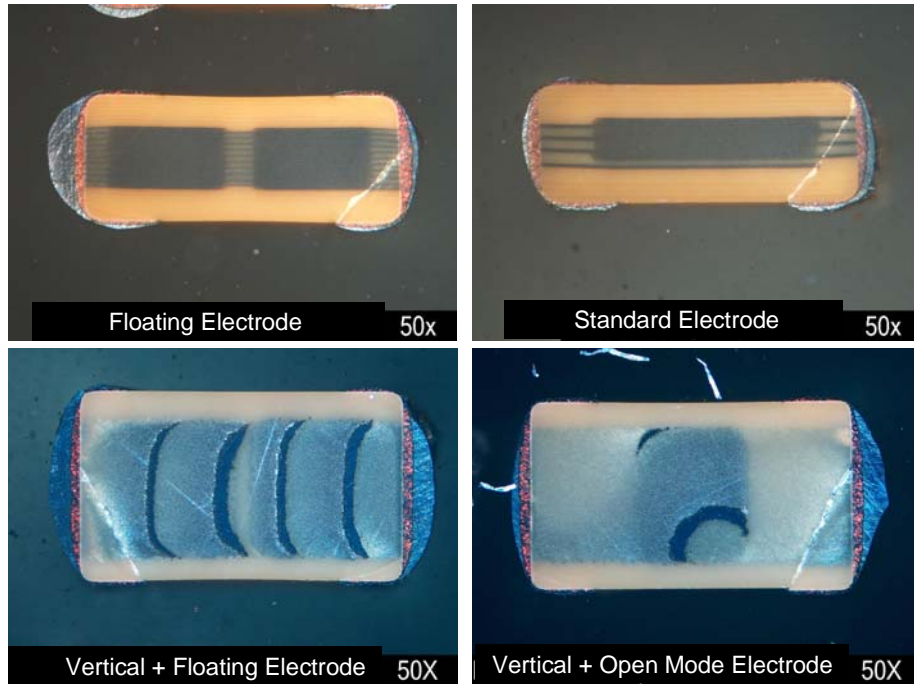


Figure 18: Micrograph shows the crack only partially traverses across the active layers; result is no loss of capacitance. Standard horizontal orientation allows the crack to separate active layers leading to loss of capacitance.

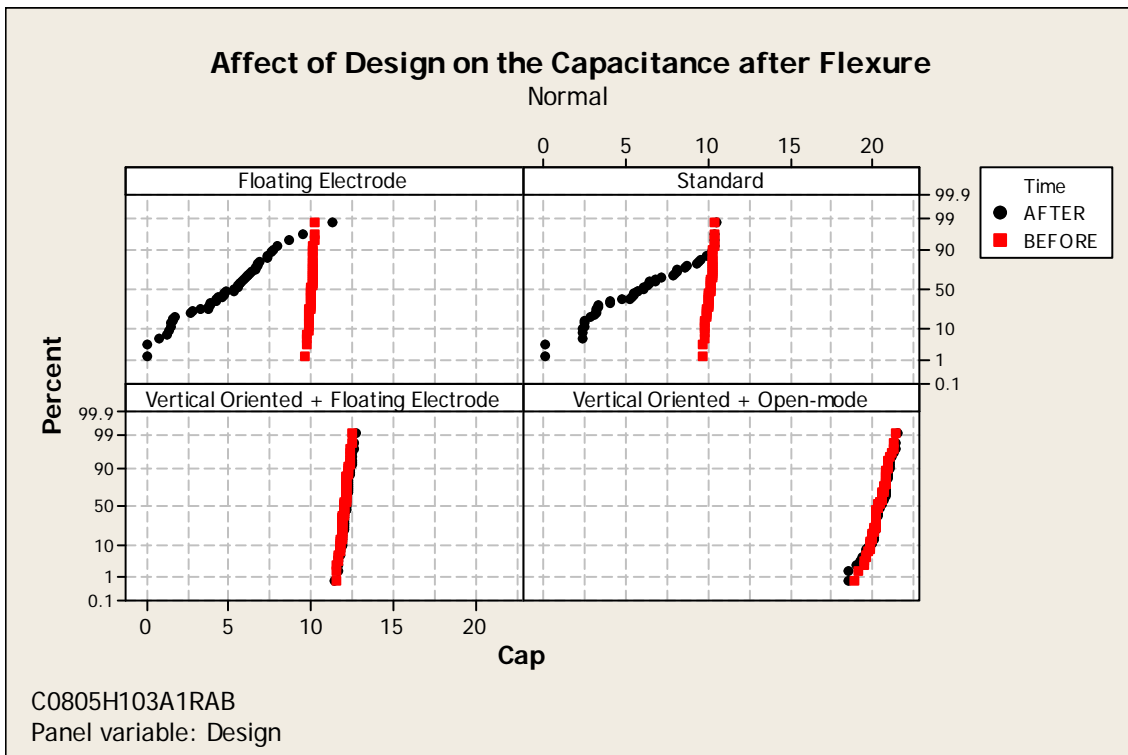


Figure 19: Compare the loss of capacitance for standard versus vertically oriented parts after flexure.

This theoretical improvement has been validated through experimentation. Figure 18 shows that flex cracks in vertically oriented parts do not completely dissect the internal electrodes, and thus do not lead to a loss of capacitance. In addition, extreme flexure to 10mm displacement indicates no loss of capacitance for either option 1 (vertical electrode + open mode design) or option 2 (vertical electrode + floating electrode design) (Fig. 19). Thus, both low IR and loss of capacitance can be minimized through the sophisticated design and preferential orientation of MLCC's.

Beyond Flex Mitigation: Complete Elimination of Flex Cracks

If a circuit design is deemed critical, sometimes simply mitigating board flex cracks is not enough. Rather, a designer may seek to completely eliminate the possibility for the creation of flex cracks. We have developed a unique design which mimics the established stand-off lead configuration. This technology delivers a solution that adds an effective measure for eliminating the creation of board flex cracks within the MLCC.

Solution 5: Clip-On Leadframe Design

The Clip-On Leadframe (COLF) ^[6] uses a unique lead-attach to mechanically decouple the MLCC from the PCB. Figure 20 shows L-shaped leads are attached to the MLCC to isolate the part from the substrate. A layer of solder resist (green) is applied to prevent solder from wicking to the bottom of the MLCC. The leads are attached only near the upper half of the terminations. This design eliminates transmission of board stress to the ceramic body of the MLCC.

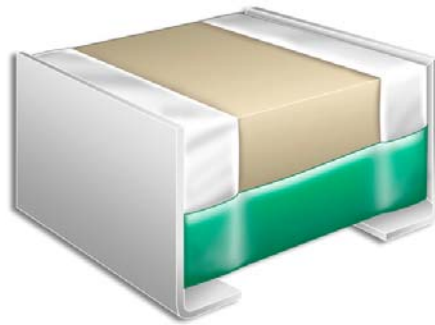


Figure 20: Clip on lead frame (COLF) design for MLCC.

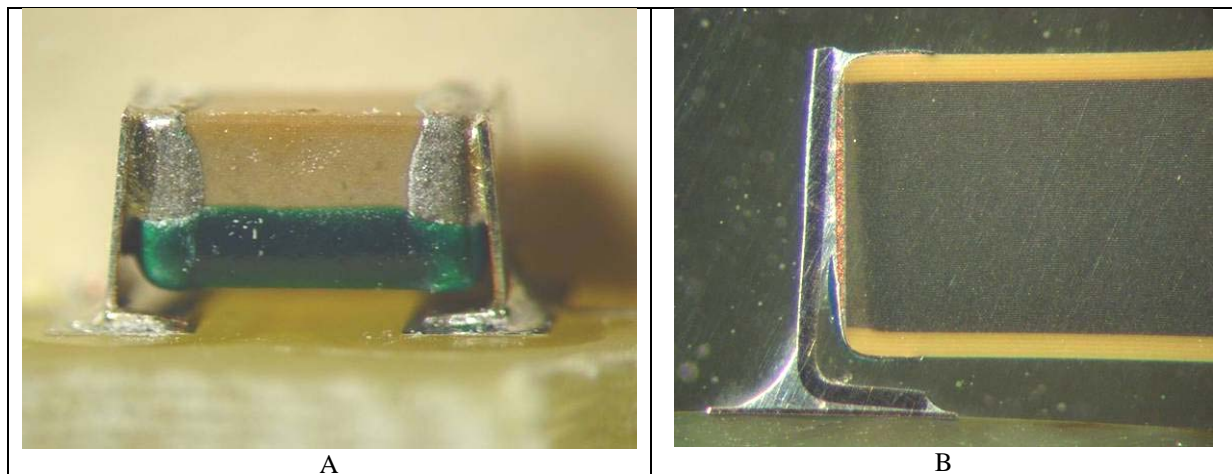


Figure 21: Picture A shows a COLF MLCC attached to an FR4 board. Micrograph B shows the cross section of a COLF MLCC after flexure to 10 mm.

Our testing has shown truly remarkable flex performance with this design – even when the FR4 board is bent to 10mm flex! Figure 21 shows a cross-section of the COLF. The leadframe has absorbed the stress after flexure to 10mm, preventing transmission of the stress to the MLCC. Thus, the COLF design is truly the ultimate design for eliminating the initiation of flex cracks altogether. The COLF design should be especially appealing for applications such as energy exploration drilling, aerospace, and military equipment, where failures due to board flex cannot be tolerated.

Summary

The circuit designer now has several options available when seeking to eliminate flex crack “headaches”. When laying out new circuit board designs, care should be taken upfront to ensure optimal layout to prevent many board flex issues. The first three solutions of open mode, floating electrode and flexible termination provide options for essentially all devices within desired CV values, but in a standard MLCC footprint. The addition of a vertical electrode option, although also in a standard MLCC footprint, uses unique manufacturing techniques to give the circuit designer a method to eliminate flex crack failures due to loss of capacitance and low IR. Finally, the clip-on leadframe solution allows for the elimination of flex cracks altogether.

By utilizing smart board layout design, and by choosing the correct Flex Mitigation capacitor design, failures due to flex (both related to IR loss and Cap loss) can essentially be eliminated.

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