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EVALUATING THE ROLE OF CONDUCTIVE EPOXY COMPOSITE LAYER IN MULTI-LAYER CERAMIC CAPACITORS UNDER ENVIRONMENTAL AND THERMAL STRESSES

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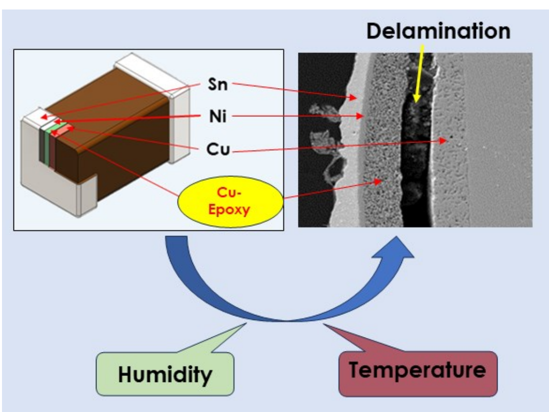
Graphical abstract



Abstract

Multi-Layer Ceramic Capacitors (MLCCs) are vital components in modern electronics, where reliability under harsh environmental and thermal conditions is essential. This study evaluates the role of conductive epoxy composite (Cu-Epoxy) layer in the MLCC during simulated reflow thermal cycling. Structural analysis revealed that the Cu-epoxy layer mitigates mechanical and thermal stresses in standard conditions, maintaining an intact interface. However, prolonged humidity exposure and thermal cycling led to delamination at the Cu-epoxy/Cu interface, compromising mechanical integrity and electrical performance. Elemental mapping confirmed alumina infiltration in delaminated area, providing evidence of structural degradation. These findings underscore the importance of optimizing reflow profiles and Cu-epoxy formulations to improve adhesion strength, moisture resistance, and thermal stability. This study offers actionable recommendations for enhancing MLCC reliability in surface mount assembly processes and demanding operating environments.

Keywords: Cu-Epoxy Layer, Delamination, Thermal Cycling, Humidity Preconditioning, Surface Mount Assembly (SMA)

Abstrak

Kapasitor Seramik Berbilang Lapisan (MLCC) merupakan komponen penting dalam elektronik moden, di mana kebolehpercayaan di bawah keadaan persekitaran dan haba yang ekstrem adalah sangat kritikal. Kajian ini menilai peranan lapisan komposit epoksi konduktif berasaskan kuprum (Cu-Epoxy) dalam MLCC semasa simulasi kitaran haba aliran semula. Analisis struktur menunjukkan bahawa lapisan Cu-Epoxy mampu mengurangkan tekanan mekanikal dan haba dalam keadaan standard, sekali gus mengekalkan antara muka yang utuh. Namun begitu, pendedahan berpanjangan kepada kelembapan dan kitaran haba menyebabkan pengelupasan berlaku pada antara muka Cu-Epoxy/Cu, yang menjejaskan integriti mekanikal dan prestasi elektrikal. Pemetaan unsur mengesahkan penembusan alumina di kawasan yang mengalami pengelupasan, memberikan bukti berlakunya degradasi struktur. Penemuan ini menekankan kepentingan mengoptimumkan profil alir semula dan formulasi Cu-Epoxy bagi meningkatkan kekuatan lekatan, rintangan kelembapan, dan kestabilan terma. Kajian ini menawarkan cadangan praktikal bagi meningkatkan kebolehpercayaan MLCC dalam proses pemasangan permukaan (SMA) dan persekitaran operasi yang mencabar.

Kata kunci: *Cu-Epoksi, Pengelupasan, Kitaran Haba, Pra-pengkondisian Kelembapan, Pemasangan Permukaan (SMA)*

1.0 INTRODUCTION

Multi-Layer Ceramic Capacitors (MLCCs) are passive components in various electronic devices, serving crucial roles in circuitry design due to their high capacitance density, reliability, and cost-effectiveness. One significant aspect influencing their performance and longevity is the integrity of the terminal electrode layers. Ensuring the robustness of these layers against environmental factors, such as thermal and mechanical stresses during assembly processes, is paramount to maintaining the functionality and reliability of electronic systems.

Extensive research has been conducted on the properties and behavior of MLCCs under different environmental conditions. Studies have investigated the effects of temperature variation and mechanical stresses [1,2,3] on the structural integrity and performance of MLCCs.

MLCCs with soft terminations have garnered significant interest in recent years due to their ability to mitigate mechanical stresses during assembly processes and enhance reliability in various electronic applications [4,5,6]. One approach to improve the performance of these soft terminations involves the incorporation of conductive epoxy layers at the terminal electrode interface (Figure 1). For example, Lee and Yoon [7] reported the addition of Ag-epoxy layers to reduce termination cracking caused by thermal and mechanical stresses. While the epoxy layer acts as a mechanical buffer, mitigating stress-induced damage, researchers such as Vargas *et al*. [8] and Lin and Chan [9] highlighted the susceptibility of Ag-based terminations to silver dendrite formation in humid environments, which can compromise electrical reliability. Donnelly and Randall [10] further emphasized that under extreme humidity and applied fields, electromigration of Ag/Pd electrodes leads to degradation, reducing MLCC longevity.

Despite these studies, limited attention has been given to the behavior of Cu-epoxy soft terminations, particularly under combined extreme humidity and thermal cycling conditions. Cu-epoxy is a conductive polymer composite consisting of epoxy resin with dispersed copper that ensures electrical integrity is maintained during and after external forces are applied to the component [4,7,11,12]. While Cu-epoxy systems offer improved mechanical flexibility and reduced cost compared to Ag-based systems, their susceptibility to moisture absorption, thermal expansion mismatches, and subsequent interface delamination has not been comprehensively explored. Bridging this gap is crucial for understanding failure mechanisms and optimizing terminal electrode designs to enhance MLCC performance in harsh environments.

Understanding how the Cu-epoxy soft termination layer influences the susceptibility of MLCCs to moisture absorption and thermal stresses during assembly processes is critical for optimizing assembly parameters, particularly during reflow processes, and for improving their reliability in practical applications.

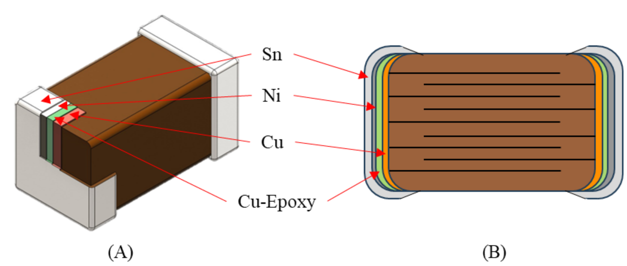


Figure 1 Schematic diagram of (a) soft termination MLCC with Cu-Epoxy and (b) cross-sectional view of soft termination MLCC

This study presents one of the first systematic investigations into the effect of Cu-epoxy composite layers on the reliability of MLCCs subjected to combined high-humidity preconditioning and thermal cycling during surface mount assembly (SMA) processes. By simulating accelerated aging conditions and performing comprehensive structural analysis using non-destructive X-ray imaging, FESEM, EDX, and FIB techniques, the study aims to reveal the evolution of interfacial degradation at the Cu-epoxy/Cu interface. The findings provide critical insights into the dual role of moisture and thermal stresses in initiating and propagating delamination, highlighting both the benefits and limitations of Cu-epoxy as an alternative soft termination material. These results contribute valuable guidance for optimizing material formulations and process controls to improve MLCC reliability in harsh electronic packaging environments. While this study focuses on 0402, the observed failure mechanisms at the Cu-epoxy interface are expected to be relevant to other MLCC sizes using similar materials and surface mount processes.

2.0 METHODOLOGY

2.1 Material and Experimental Method

In this study, the 0402-sized MLCC (1.0 × 0.5 mm) was selected due to its widespread use in compact, high-density applications such as solid-state drives (SSDs) and mobile devices, where mechanical and thermal reliability are critical. The terminal electrode of the MLCC incorporates an epoxy composite layer filled with copper particles (Cu-epoxy), which serves as a soft termination material designed to absorb mechanical stress and enhance solder joint reliability during surface mount assembly. The Cu-epoxy material was chosen for its cost-effectiveness and growing industrial relevance as an alternative to Ag-based terminations. This MLCC is rated as Moisture Sensitivity Level 1 (MSL 1) according to the Joint Electron Device Engineering Council (JEDEC) standard, indicating that it can be exposed to ambient room conditions for an unlimited duration without requiring dry storage.

In order to investigate the effect of moisture absorption and the reflow temperature, first, 50 unit of MLCC samples were subjected to the controlled temperature and humidity at 85 °C and 85 % RH for 168 h in controlled chamber (Amade Tech Environmental Chamber AT-C1001). This condition was simulated to expose the MLCC at higher humidity to observe the potential latent defect at the terminal electrode layers during reflow process.

2.2 Reflow Process

The samples were subjected to the reflow process which simulate the surface mount assembly (SMA) process. The reflow temperature profile was set according to the IPC-7801 Reflow Oven Process Control Standard to follow industrial practice for Solid State Drive (SSD) assembly. The temperature profile in BTU Pyramax 150N z12 convection reflow oven was controlled within the pre-determine range as shown in Table 1. All temperature dataset were analyzed by KIC 2000 ver.3 software to obtain the process window index (PWI).

Table 1 Temperature profile range for reflow oven process

Parameters	Low limit	High limit	Units
Maximum Rising Slope	0.0	3.0	ºC/s
Maximum Falling Slope	-3.0	-0.0	ºC/s
Soaking time (150 – 200 ºC)	50	70	s
Time Above Liquidus (217 ºC)	50	70	s
Peak Temperature	235	255	ºC

The PWI is widely accepted statistic used to qualify the robustness of a thermal process and the goodness of the thermal profile fits for the predefined process limits in the electronics assembly industry. It is a quantifiable, reproducible, statistical measure of how well a profile performs relative to critical process limits [13]. The PWI was calculated using the formula that includes all statistics for all thermocouples given in Eqn. 1.

$$PWI = 100 \times MAX_{N,M}^{ij-1} \left\{ \left| \frac{(x_{[ij]} - y_{[ij]})}{(R_{[ij]}/2)} \right| \right\} \quad \text{Eqn. 1}$$

where, N stands for the number of thermocouples, i = 1 to N, M represents the number of statistics per thermocouple, j = 1 to M, x is the i,jth statistic's value, y is the average of the i,jth statistic's high and low limit, and R is the i,jth statistic's high limit minus the low limit.

While the control samples were freshly taken from the packaging (tape and reel) and subjected to the analysis after reflow process without exposing to the humidity condition.

2.3 Characterizations

The samples were inspected with YXLON 3D X-ray (non-destructive analysis) model Y-Cheetah to observe the internal defect at the terminal electrode. The samples that were suspected having the signature of defects from 3D X-ray were then cold mounted using epoxy and hardener with the ratio of 1:6.25. After curing at room temperature for 12 h, the samples were ground using silicon carbide grinding paper with the grit size of 180, 240, 400, 600 and 1200 accordingly. The micro cloth and alumina suspension (1.0 and 0.3 µm) were used as final polishing for the samples. The surface of polished cross-sectioned was observed through Keyence VHX-7000 Digital Microscope.

The Hitachi SU-8030 Field Emission Scanning Electron Microscope (FESEM) was used to evaluate the occurrence of the defect such as delamination at the Cu-Epoxy layer. The FESEM was equipped with the Horiba X-Max 80 energy dispersive X-ray analysis (EDX) and it was able to detect all elements from Boron to Uranium (B-U) with detection limit of 1% and above. The elemental analysis was acquired through area scan mode.

Dual Beam analysis (FIB-SEM) was performed on Helios Nanolab 650 from FEI and the elemental analysis was captured on X-MaxN 150 from Oxford. The platinum was coated prior to the analysis.

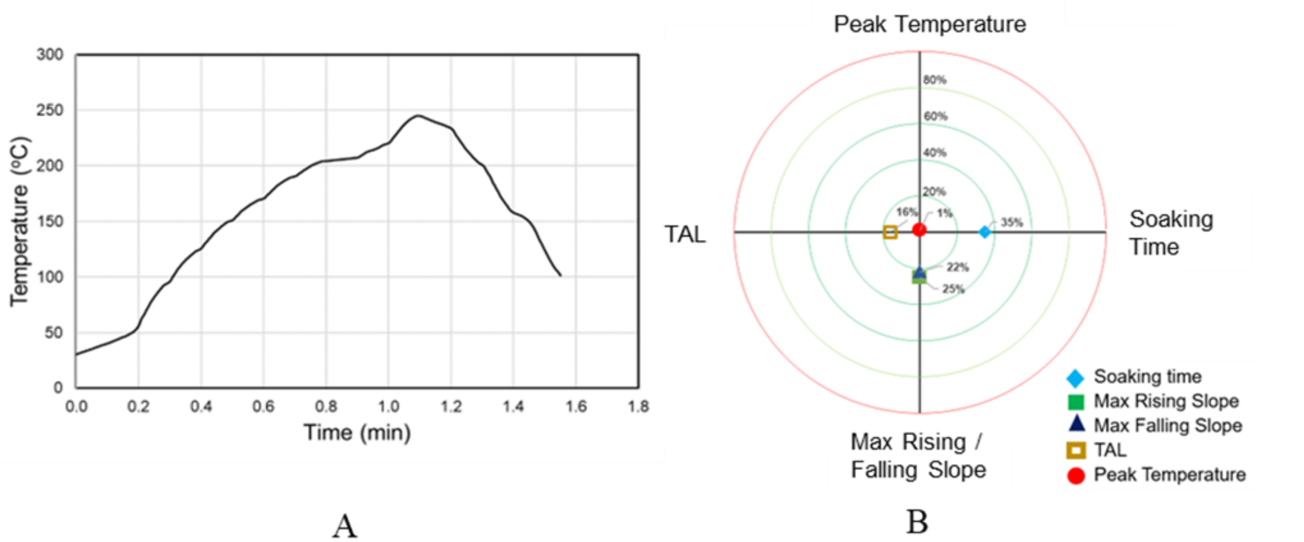


Figure 2 (a) Temperature profile taken during the reflow process for MLCC and (b) Bullseye representative of the PWI for reflow process parameters

3.0 RESULTS AND DISCUSSION

3.1 Reflow Temperature Profile: Establishing Process Control for Reliability

The reflow profile was set according to the industrial practice to simulate the real condition during assembly process. The temperature profile and the PWI values for various parameters during the reflow process were calculated and are visualized in Figure 2.

The results indicate varied adherence to optimal conditions across different parameters such as maximum rising and falling slope, soaking time, peak temperature and time above liquidus. The lower percentage value of PWI indicating the closer to the target value and better performance of the reflow process parameters.

Maximum rising slope recorded a PWI of 25%, indicating a moderately controlled heating rate within the desired range of 0.0 to 3.0 °C/s, with an actual average of 1.87 °C/s (Table 2). This suggests a controlled and gradual temperature increase, which is critical for minimizing thermal shock to the MLCCs. While the maximum falling slope showed a PWI of 22%, reflecting a controlled cooling rate, aligning closely with the target of -1.5 °C/s, observed at -1.84 °C/s. Controlled cooling rates are essential to avoid crack formation due to thermal stress. For the soaking time (150 – 200 °C), it had a PWI of 35%, with an actual soaking time of 56.5 s, which is within the expected range. This duration is crucial for allowing all parts of the MLCC to reach a uniform temperature before entering the peak phase, thus ensuring uniform solder reflow and minimizing thermal gradients. The time above liquidus (217 °C) had achieved a PWI of 16%, with the samples spending about 58.4 s above the liquidus temperature, slightly above the ideal range. This prolonged exposure could affect the integrity of the solder joints and the MLCC terminal coatings. Furthermore, the peak temperature exhibited a PWI of 1%, with a peak temperature of 245 °C, nearly at the centre of the desired range (235 - 255 °C). This precise control over the peak temperature is crucial for effective soldering without overheating the components.

Table 2 Process Window Index (PWI) obtained from the actual temperature profile

Parameters	Range limit (low - high)	Actual	PWI (%)
Maximum Rising Slope (target 1.5 °C/s)	0.0 - 3.0 °C/s	1.87 °C/s	25
Maximum Falling Slope (target -1.5 °C/s)	-3.0 - 0.0 °C/s	-1.84 °C/s	22
Soaking time (150 – 200 °C)	50 - 70 s	56.5 s	35
Time Above Liquidus (217 °C)	50 - 70 s	58.4 s	16
Peak Temperature	235 - 255 °C	245 °C	1

The PWI results provide a comprehensive insight into the thermal profile adherence during the reflow soldering process of the MLCCs. Literature highlights that precise control over the reflow temperature profile is critical for ensuring the reliability and performance of MLCCs [1]. The control over Maximum Rising and Falling Slopes is particularly significant, as rapid temperature changes are known to induce thermal stresses, leading to crack formation in ceramic capacitors [3].

The optimal soaking time and peak temperature control, as observed in the study, are aligned with industry best practices which dictate that these parameters ensure minimal thermal stress and optimal solder joint formation [14]. However, the slightly extended Time Above Liquidus observed in this study could potentially lead to degradation of terminal electrode materials, especially in the context of Cu-Epoxy layers, which might be sensitive to prolonged high temperatures [7].

This analysis underscores the importance of precise control over reflow soldering parameters in maintaining the integrity and functionality of advanced electronic components such as MLCCs with modified terminal electrodes.

3.2 Detecting Latent Defects through 3D X-ray Analysis

All 50 conditioned MLCC samples tested in this study consistently exhibited similar defects, with delamination at the Cu-epoxy/Cu interface being the most prominent failure mode. The 3D X-ray images of the MLCC samples in Figure 3 reveal distinct differences between the control sample (Figure 3a and 3c) and the conditioned sample (Figure 3b and 3d) after subjected to reflow process. In the control MLCC sample, the terminal electrode and internal layers exhibit uniform density with no apparent defects such as delamination. However, in the conditioned sample, irregularities such as the signs of delamination was visible along the terminal electrode layers, particularly near the Cu-epoxy interface. The cross-sectional views highlight these internal defects, showing discontinuities in the material structure likely caused by stress during the thermal cycling and humidity exposure.

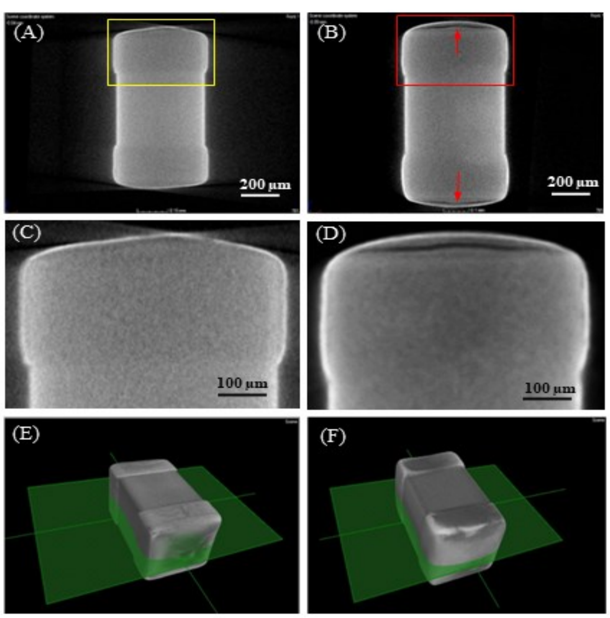


Figure 3 The 3D X-ray images of the MLCC for (a) control sample, (b) conditioned sample, (c) & (d) enlargement view at respective area, (e) & (f) the x-ray detection plane of respective components

The defects observed in the conditioned MLCC are attributed to the combined effects of prolonged moisture exposure (85 °C and 85% RH for 168 hours) and thermal stresses during the reflow process. Moisture absorption can cause swelling and stress concentration at the terminal electrode layers, weakening the bond between the layers [15,16,17]. During reflow process, the mismatch in thermal expansion coefficients (CTE) between the Cu-epoxy layer and adjacent materials likely exacerbates these stresses, leading to delamination formation. These defects compromise the mechanical stability and electrical conductivity of the MLCC.

The Cu-epoxy layer acts as a buffer, mitigating mechanical and thermal stresses during the reflow process [5]. Its polymeric nature provides flexibility, absorbing stresses that would otherwise lead to cracking or delamination in rigid materials. However, the conditioned samples indicate that prolonged moisture exposure weakens the Cu-epoxy interface, making it more susceptible to thermal stresses. The epoxy has the potential to adsorb the moisture in accordance with Fick's diffusion theory due to its hygroscopic nature [18]. The moisture ingression into Cu-Epoxy layer during the humidity precondition is related to the polar group of epoxy molecule. While the Cu-epoxy layer helps reduce defect propagation compared to MLCCs without such additional layer, optimizing its formulation for improved resistance to moisture absorption and thermal cycling could further enhance performance.

Based on the structural observations, moisture exposure appears to play a more dominant role in the initiation of interfacial degradation at the Cu-epoxy and Cu interface. The prolonged exposure to high humidity conditions (85 °C, 85% RH for 168 hours) enables significant moisture absorption into the epoxy matrix due to its polar molecular structure and hygroscopic nature. This results in interfacial swelling, reduced adhesion strength, and microstructural changes that predispose the interface to failure. On the other hand, thermal cycling during reflow acts as a secondary factor that exacerbates these pre-existing weaknesses. The mismatch in the coefficient of thermal expansion (CTE) between the Cu-epoxy and Cu layers introduces mechanical stresses, but these alone do not initiate delamination in the absence of prior moisture-induced softening. Therefore, it can be concluded that moisture acts as the primary driver of interfacial weakening, while thermal cycling accelerates the propagation of delamination once the interface integrity is compromised.

3.3 Understanding Structural Responses to Stress through Surface Morphology

The optical images and FESEM micrographs in Figure 4 illustrate clear differences in the surface morphology of the control and conditioned MLCC samples. The control sample (Figure 4a and 4c) exhibits a uniform, well-adhered interface between the Cu-epoxy and Cu layers. There is no evidence of delamination, indicating that the Cu-epoxy layer remains intact under normal conditions without exposure to environmental or thermal stresses.

In contrast, the conditioned sample (Figure 4b and 4d) reveals significant structural changes. Notable delamination is observed at the Cu-epoxy and Cu interface, with the presence of gap forming between these layers. These defects are attributed to the combined effects of preconditioning in a high-humidity environment (85 °C, 85% RH) and the thermal cycling experienced during the reflow process [17]. The repeated expansion and contraction due to mismatched CTE between the Cu-epoxy and Cu layers likely exacerbated the interface weakening, resulting in delamination.

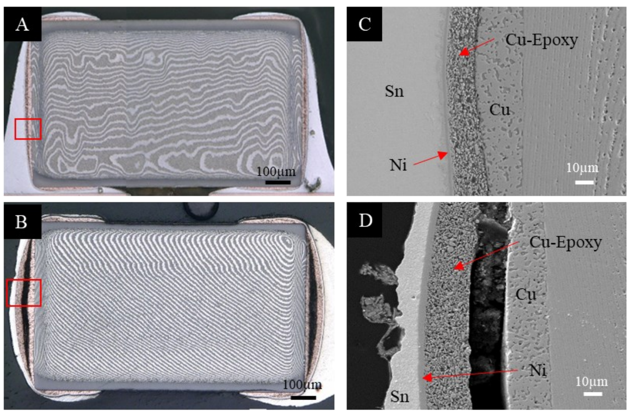


Figure 4 Optical images and FESEM micrograph of MLCC samples after reflow for (a and c) control sample and (b and d) conditioned sample

In contrast, the conditioned sample (Figure 4b and 4d) reveals significant structural changes. Notable delamination is observed at the Cu-epoxy and Cu interface, with the presence of gap forming between these layers. These defects are attributed to the combined effects of preconditioning in a high-humidity environment (85 °C, 85% RH) and the thermal cycling experienced during the reflow process [17]. The repeated expansion and contraction due to mismatched CTE between the Cu-epoxy and Cu layers likely exacerbated the interface weakening, resulting in delamination.

Figure 5 and 6 provide a detailed comparison of the structural and elemental characteristics of the control and conditioned MLCC samples. The control sample (Figure 5a) maintains a continuous and well-adhered Cu-epoxy interface, as evidenced by the FESEM micrograph.

In contrast, the conditioned sample (Figure 6a) displays visible delamination at the Cu-epoxy and Cu interface, indicating structural degradation caused by thermal and environmental stresses. The EDX aluminum element mapping (Figure 6b) highlights substantial alumina deposition within this crack, suggesting that the delamination formed during the reflow process and subsequently trapped alumina particles during polishing. The oxygen element mapping (Figure 6c) further corroborates this, with concentrated oxygen signals in the delaminated regions, indicative of alumina (Al_2O_3) deposition.

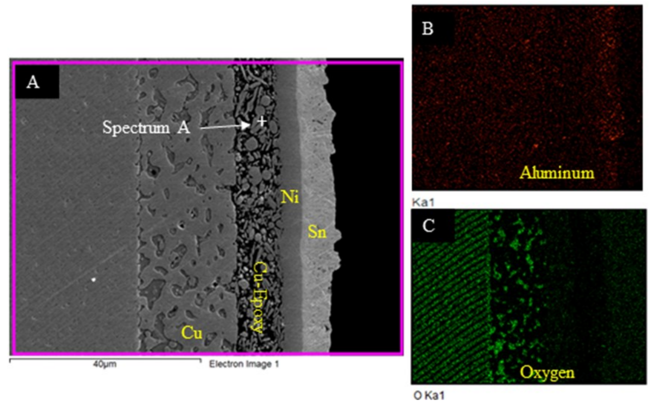


Figure 5 (a) FESEM micrograph and (b & c) EDX elemental mapping represent aluminum (red), and oxygen (green) elements for control MLCC

The EDX elemental mapping (Figure 5b and 5c) reveals minimal alumina residue, with aluminum and oxygen signals confined to the surface, indicating that alumina from the final polishing process did not infiltrate the interface. This reflects the absence of delamination or structural discontinuities in the control sample.

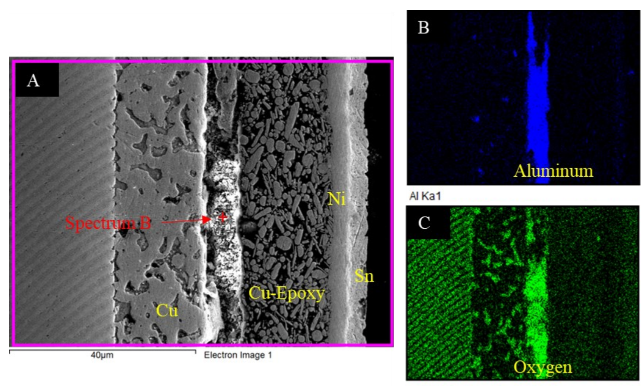


Figure 6 (a) FESEM micrograph and (b & c) EDX elemental mapping represent aluminum (blue), and oxygen (green) elements for conditioned MLCC

Table 3 quantitatively supports these observations, showing low oxygen content (6.5 wt%) and no significant aluminum accumulation in Spectrum A, further confirming the structural integrity of the Cu-epoxy interface in the control sample. Spectrum B reveal a marked increase in oxygen content (46.1 wt%) and aluminum (48.9 wt%), confirming the significant presence of polishing material in the delaminated surfaces. The minimal copper content (1.1 wt%) at Spectrum B indicates that the delamination disrupted the continuity of the Cu-epoxy interface, leaving it exposed to contamination.

Table 3 The quantitative analysis of the elements detected at localized area

Sample	Scanned Area	Element	Weight %	Atomic %
Control	Spectrum A	C	33.0	67.1
		O	6.5	9.8
		Cu	60.5	23.1
Conditioned	Spectrum B	C	3.9	6.4
		O	46.1	57.3
		Al	48.9	36.0
		Cu	1.1	0.3

The elemental and quantitative analysis emphasize the vulnerability of the Cu-epoxy interface to humidity preconditioning and thermal cycling. In the conditioned sample, the delamination observed are attributed to stress concentrations caused by the mismatch in thermal expansion coefficients between the Cu-epoxy and Cu layers during the reflow process. This aligns with findings by Fan *et al*. [19], which demonstrated that moisture preconditioning exacerbates interfacial weakening, leading to delamination during soldering reflow. The presence of alumina within these gap space provides further evidence that delamination occurred prior to polishing, confirming that the observed defects are process-induced rather than preparation-induced.

The accumulation of alumina and oxygen in the conditioned sample highlights the role of delamination as pathways for external contaminants. This empty space not only compromise the mechanical integrity of the Cu-epoxy interface but also create potential sites for electrical resistance increase and failure. The structural degradation observed in the conditioned sample emphasizes the need for optimized Cu-epoxy formulations with enhanced thermal stability and adhesion strength to mitigate delamination risks under harsh environmental and thermal conditions.

It is noteworthy from the SEM micrographs that delamination predominantly occurred at the Cu-epoxy–Cu interface, while the Cu-epoxy–Ni interface remained structurally intact in both the conditioned and unconditioned MLCC samples. This observation suggests a difference in interfacial stability between the two metal-epoxy pairings. One contributing factor is the inherent material properties of Cu and Ni. Copper is more prone to surface oxidation under ambient and humid conditions, which can introduce a weak interfacial oxide layer that hinders chemical bonding with the epoxy matrix. This reduced adhesion at the Cu–epoxy boundary may initiate mechanical separation, especially under moisture-assisted stress and thermal cycling. In contrast, nickel has significantly higher resistance to oxidation, and its chemically stable surface promotes stronger and more durable adhesion with the epoxy as shown in Figure 7.

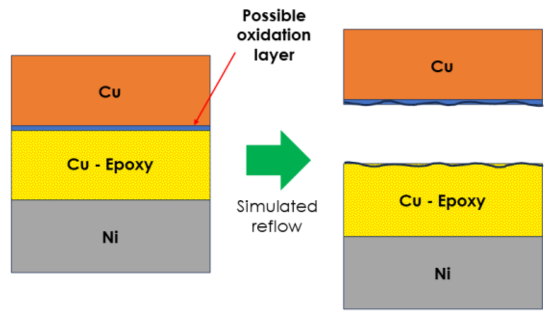


Figure 7 Schematic illustration on the Cu-Epoxy/Cu and Cu-Epoxy/Ni interface layers

These findings align with previous work by Akçay *et al*. [20], who demonstrated that electroless nickel-coated copper fillers enhanced interfacial and mechanical performance in epoxy composites due to improved surface compatibility and reduced oxidation effects. This explains why delamination was preferentially initiated at the Cu–epoxy interface, while the epoxy–Ni boundary remained unaffected, thereby highlighting the critical role of metal surface chemistry in interfacial reliability under environmental and process-induced stress.

3.4 Cross-sectional Analysis of Cu-Epoxy Layers

The Focused Ion Beam (FIB) cutting and FESEM images (Figure 8) reveal significant differences in the Cu-epoxy layers of the control and conditioned samples. For the control sample (Figure 8a and 8b), the Cu-epoxy layer demonstrates a continuous, well-adhered interface with the Cu layer. No visible cracks, or delamination are present, indicating the structural stability of the Cu-epoxy interface under standard conditions.

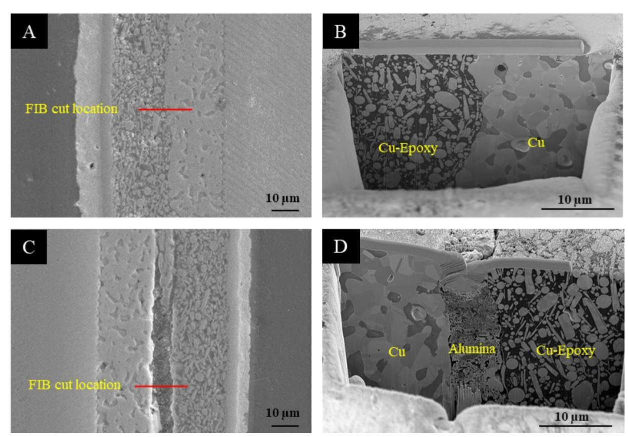


Figure 8 FESEM micrograph and FIB cutting image for (a, b) control sample and (c, d) conditioned sample

In contrast, the conditioned sample (Figure 8c and 8d) exhibits substantial delamination at the Cu-epoxy and Cu interface. The crack observed in Figure 8d indicate separation between these layers, which were further filled with alumina during the final polishing step. The alumina's presence within this crack confirms the occurrence of delamination during the reflow process, as the crack provided pathways for the polishing material to infiltrate. These findings highlight the structural degradation caused by environmental preconditioning (85°C, 85% RH) and thermal cycling during reflow.

The observed delamination in the conditioned sample can be attributed to thermal and mechanical stresses imposed during the reflow process. The thermal cycling results in repeated expansion and contraction, and the mismatch in the CTE between the Cu-epoxy layer and the Cu layer creates significant shear stress at the interface. These stresses likely initiate and propagate delamination, as evidenced by the gap space between the surfaces in Figure 8d. Additionally, the prolonged preconditioning at high humidity weakens the adhesion between the Cu-epoxy and Cu layers, making the interface more susceptible to mechanical stress-induced damage during reflow.

The structural changes in the conditioned sample significantly impact both the electrical and mechanical reliability of the MLCC. Delamination at the Cu-epoxy and Cu interface introduces discontinuities that compromise the mechanical integrity of the terminal electrode. This can lead to increased susceptibility to cracking or further delamination under operational conditions, especially in environments with thermal cycling. Electrically, the delamination reduces the effective conductive area, increasing resistance at the interface and potentially leading to intermittent electrical connections. These defects could manifest as performance degradation or failure in high-reliability applications.

4.0 CONCLUSION

This study demonstrates the critical role of the Cu-epoxy layer in enhancing MLCC reliability under standard conditions by acting as a mechanical buffer. However, under prolonged humidity and thermal cycling, delamination and crack formation at the Cu-epoxy/Cu interface were observed, compromising structural and electrical integrity. These failures are attributed to moisture ingress and thermal expansion mismatch. To improve MLCC performance, optimizing epoxy formulations for better adhesion and resistance is essential. Future work should include electrical tests (such as insulation resistance and breakdown voltage) to assess the impact of interface degradation under real operating conditions.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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