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TOOLS AND TECHNIQUES

Detecting Corrosion to Prevent Cracks in MLCCs with AI

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Abstract The electronics industry faces a challenge posed by cracks in multilayer ceramic capacitors (MLCC), which can undermine device reliability and longevity. In this study, we investigate the multifaceted factors underpinning crack formation, unveiling their intimate connections with corrosion, contamination, and mold. We show that hygroscopic properties, humidity exposure, and ion migration, play a role as precursors triggering both the inception and escalation of cracks. The correlation between corrosion, contamination, and cracking mechanisms in MLCCs presents a unique opportunity, as the visibility of corrosion and contamination on the component's exterior offers a distinct advantage for detection, unlike the elusive nature of cracks which are often challenging to identify. We introduce a solution—an encompassing visual inspection methodology designed to detect corrosion evidence on electronic components. This approach employs advanced AI algorithms and pick-and-place machine cameras already in-place to examine all components during assembly. The algorithm detects corrosion indicators, effectively neutralizing the detrimental effects of corrosion and mitigating its potential role in crack formation. Our work includes the presentation of the AI model, which showcases exceptional accuracy in identifying corrosion-associated concerns. This innovative tool is directly confronting a major root cause of cracks. This novel solution marks a substantial stride toward fortifying product reliability and extending the operational lifespan of electronic devices.

Keywords Cracks · Electronic components · MLCC · Corrosion · Contamination · Mold · Reliability · Hygroscopic properties · Humidity exposure · AI algorithms · Visual inspection

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Introduction

Multilayer ceramic capacitors (MLCCs) stand as vital components in the realm of electronics, serving a pivotal role in electronic devices and circuits. The adoption of electric vehicles and sustainable energy solutions has amplified the demand for MLCCs, particularly in the automotive and green tech industries, both of which confront harsh operating environments and stringent performance standards.

As the automotive landscape rapidly transitions toward electric mobility and sustainable practices, modern electric vehicles, exemplified by electric cars, encompass an astounding number of over 10,000 MLCCs per vehicle. This exponential increase in MLCC usage underscores their fundamental role in modern electronic assemblies. Moreover, the escalating proliferation of electronic devices across industries signifies the escalating reliance on MLCCs, making it crucial to address potential issues that could impede their functionality and overall reliability.

A significant concern that has come to the forefront is the presence of cracks within these ceramic capacitors [1]. Cracks within MLCCs can be characterized as structural discontinuities or fissures that compromise the integrity of the component (see examples in Fig. 1) [1]. These seemingly innocuous cracks, however, can wield substantial consequences, propagating from a localized issue to adversely affecting the entire electronic system. The ramifications extend from diminished performance and compromised lifespan of the MLCC itself to broader

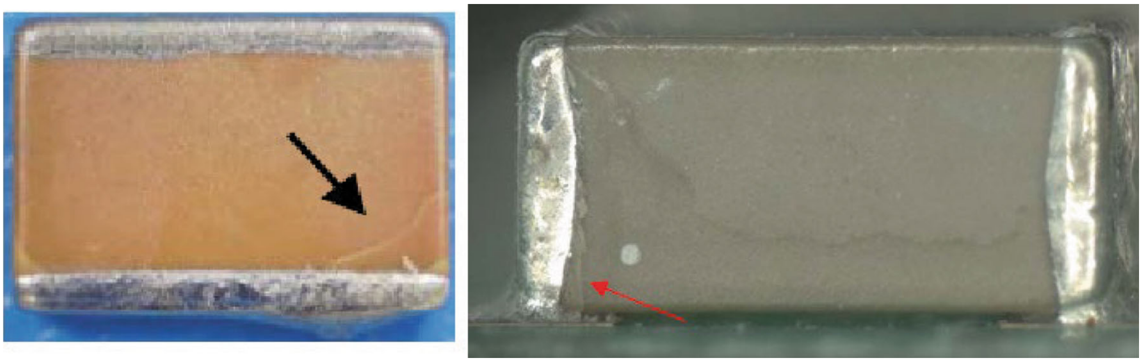

Fig. 1 Two examples of external cracks in MLCC's [1]. In both cases, the cracks originate from the terminations

repercussions on the circuit board and the entire electronic assembly [2].

Cracks within MLCCs encompass a spectrum of variations, with two primary categories: internal and external cracks. These variations can manifest during various stages of the component's life cycle. Some cracks originate during the manufacturing process, embedded within the ceramic structure itself. Others emerge during the intricate assembly procedures, as electronic components are placed on circuit boards. Additionally, certain cracks appear because of environmental stressors and mechanical wear, taking form during the operational lifespan of the electronic device.

In response to the escalating demand for reliable MLCCs, the electronics sector has proactively addressed the technical challenges associated with cracking. Manufacturers are continuously refining manufacturing processes to enhance the robustness and durability of MLCCs [2]. Modern manufacturing technologies have enabled tighter control over material properties, resulting in improved structural integrity and resistance to cracking. These quality control measures, combined with enhanced materials and design considerations, have substantially reduced the prevalence of manufacturing-related cracks in MLCCs [3–5].

Furthermore, advancements in assembly methodologies have played a role in minimizing cracking risks. The integration of sophisticated pick-and-place machines equipped with AI-powered cameras allows for precise and gentle handling of MLCCs during assembly onto printed circuit boards (PCBs). This minimizes mechanical stresses and potential damages that could lead to cracks. Additionally, manufacturers have developed innovative soldering techniques and solder materials that cater to the unique vulnerabilities of MLCCs, effectively mitigating the occurrence of cracks during and after the soldering process [1, 2]. Rigorous testing, including temperature cycling and mechanical shock tests, simulates real-world operational conditions and aids in identifying and rectifying potential cracking issues [1, 3, 4].

In this study, we illuminate a significant correlation between the presence of corrosion, contamination, and mold and the susceptibility of MLCCs to develop cracks [1–8] (Fig. 2). They can be used as mean of failure analysis [9–12] and prevention. These underlying factors, often underestimated, serve as key catalysts in the initiation and exacerbation of cracks, compromising the structural integrity and operational effectiveness of electronic systems. By delving into the interplay between these precursors and crack formation, our research provides a comprehensive framework for preemptive intervention.

Central to our solution is the introduction of a pioneering method for inspecting MLCCs during the assembly process [13–15]. Unlike conventional quality assurance practices that rely on sampling, the methodology ensures the examination of every individual component, thereby greatly mitigating the risk of flawed units entering the production line. Test cases for detection of body defects and corrosion are presented in [16, 17]. By proactively isolating and excluding MLCCs exhibiting signs of corrosion, contamination, or mold, we aim to disrupt the chain of events that culminate in crack propagation and potential failure. Eliminating components with corrosion, defects, and mold holds inherent value, not only by enhancing the manufacturing process but also by significantly bolstering the overall reliability, quality, and performance of electronic devices.

The implications of this work extend beyond technical realms, aligning with broader industry objectives of sustainability and enhanced resource utilization. Through the prevention of cracks in MLCCs, we contribute to a reduction in electronic waste, prolonging the operational lifespan of devices and reducing premature replacements. Moreover, this approach is congruent with contemporary industry trends, particularly within sectors such as electric vehicles and renewable energy systems, where robust electronic components are paramount.

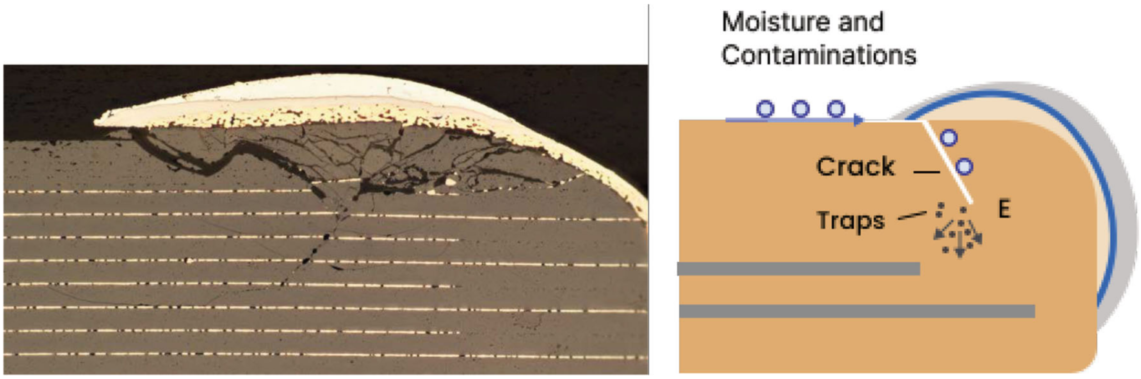

Fig. 2 A shallow crack under the termination of an MLCC (top) [1] and a schematic of the time-dependent dielectric breakdown mechanism of failure (bottom)

In the ensuing sections, we delve into the intricacies of crack formation within MLCCs, examining the diverse mechanisms and manifestations involved. We elucidate the role played by corrosion, contamination, and mold in the initiation and propagation of cracks, affording a comprehensive comprehension of their complex interdependencies. Through a combination of theoretical analysis and empirical validation, we endeavor to establish the efficacy of our approach, substantiating its potential to revolutionize electronic component quality assurance practices.

Cracks in MLCC

Cracks in multilayer ceramic capacitors (MLCCs) can manifest through various mechanisms and at different stages of their lifecycle. Understanding the types of cracks and the underlying factors that contribute to their formation is crucial for enhancing their reliability. Cracks in MLCCs can be broadly categorized into two main types: internal cracks and external cracks.

Internal Cracks

Internal cracks refer to fractures within the dielectric layers or between the layers and electrodes of an MLCC. These cracks can result from manufacturing defects, thermal stresses, and material inhomogeneities. For instance, rapid cooling during firing processes can lead to firing cracks that propagate perpendicular to the plane of the terminals [4, 5, 18]. Insufficient binding strength and foreign materials can result in knit-line cracks that extend parallel to the electrodes. Moreover, delamination between layers, although rare in modern MLCCs, were more prevalent in early ceramic capacitors due to various factors such as trapped air, surface contamination, and solvent binder outgassing. These internal cracks weaken the structural integrity of the MLCC and can initiate failures during subsequent assembly, testing, or application stages [1].

External Crack

External cracks encompass fractures on the external surfaces of MLCCs and are often linked to stresses encountered during handling, assembly, or operation [2]. During assembly, pick-and-place machines can apply excessive stresses, leading to thermal shock cracks, which are caused by abrupt temperature changes during soldering processes [1, 19, 20]. These thermal shock cracks can be large and visible, affecting the integrity of the capacitor. Additionally, stresses arising from differences in coefficients of thermal expansion (CTE) between the ceramic material and the substrate can cause tensile stresses and cracking, especially in cases where MLCCs are soldered onto alumina boards.

Degradation of Capacitors in the Presence of Moisture

The degradation of capacitors in the presence of moisture is a complex phenomenon driven by electrochemical processes and material interactions. These processes are influenced by factors such as humidity, voltage, contamination, corrosion, and the materials used in the capacitor construction. The primary mechanisms responsible for degradation include anodic dissolution, ion migration, and the subsequent formation of precipitates and deposits [1, 7, 21].

Anodic dissolution is a fundamental process wherein metal ions are released from the anode electrode due to the presence of moisture, contamination, mold, corrosion, and an applied electric field [7, 21]. This process can be described by Faraday's law of electrolysis, which relates the quantity of material dissolved to the quantity of charge passed:

$$m = \frac{Q}{ZF}, \qquad \text{(Eq 1)}$$

where: m is the mass of metal dissolved, Q is the total charge passed, Z is the valency of the metal ion, and F is Faraday's constant.

The released metal ions from anodic dissolution migrate through the moisture-absorbed layer on the surface of the capacitor. The migration is influenced by the electric field E, the ion mobility μ, and the diffusion coefficient D of the ions. Fick's first law of diffusion describes the rate of ion migration:

$$J = -D \cdot \frac{\mathrm{d}C}{\mathrm{d}x}, \qquad \text{(Eq 2)}$$

where J is the ion flux, D is the diffusion coefficient, C is the concentration gradient of ions, and x is the distance.

As metal ions migrate, they can encounter counter ions and chemical species in the environment, leading to chemical reactions and the formation of precipitates and deposits. The specific reactions depend on the materials involved [1]. For example, the following reaction illustrates the formation of nickel oxide from nickel ions:

$$\mathrm{Ni}^{2} + 2\mathrm{OH}^{-} \rightarrow \mathrm{NiO} + \mathrm{H_2O}, \qquad \text{(Eq 3)}$$

Similarly, silver ions can react with oxygen and moisture to form silver oxide:

$$4\mathrm{Ag}^{+} + \mathrm{O_2} + 2\mathrm{H_2O} \rightarrow 2\mathrm{Ag_2O} + 4\mathrm{H}^{+} \qquad \text{(Eq 4)}$$

The degradation of capacitors in the presence of moisture involves a complex interplay of anodic dissolution, ion migration, and the subsequent formation of precipitates and deposits. The intricate dependence on humidity, voltage, and material properties underscores the challenges in predicting and mitigating the degradation processes. In real-world scenarios, these interactions are influenced by a multitude of factors, with one of the most notable being the circular impact of humidity. This circular effect is particularly pronounced in the context of the creation of corrosion and mold, which subsequently intensifies the absorption of humidity due to their inherent hygroscopic properties [7, 16, 17, 22–26].

Role of Corrosion

Corrosion, a phenomenon involving the gradual degradation of materials due to chemical reactions with their environment, plays a significant role in the formation of cracks in MLCCs. Corrosion can weaken the material's mechanical properties and create pathways for crack initiation (Fig. 3). Corrosion-induced cracks can be particularly problematic in harsh environments, such as those encountered in automotive and aerospace applications, where temperature fluctuations, humidity, and contaminants are prevalent [16, 27–35].

Recent research indicates that corrosion can act as a precursor to crack formation in MLCCs [27, 29, 33, 34]. Corrosion-related changes in material properties can reduce its ability to withstand external stresses, making it more susceptible to cracking during subsequent handling or thermal cycles. Moreover, corrosion can introduce voids, impurities, or structural irregularities that serve as initiation sites for cracks (Fig. 3). Recognizing the connection between corrosion and crack formation is vital for developing effective strategies to mitigate the risk of failures in MLCCs.

Corrosion Contamination is Hygroscopic

The interrelation between corrosion and cracks in MLCCs holds significant implications for their reliability and performance within electronic systems. Corrosion, initiated by factors such as humidity, contaminants, and manufacturing residues, instigates a cascade of events that can ultimately lead to the manifestation of cracking phenomena (Fig. 3). Notably, corrosion possesses a hygroscopic propensity, facilitating the absorption of moisture from the surroundings [22].

This hygroscopic nature of corrosion is particularly crucial in the context of soldering terminations of MLCCs. As corrosion progresses, it forms a layer that contributes to an elevation in humidity at the terminations–body interface, creating a film [15, 22, 23, 26, 36]. This absorbed moisture enhances the influencing the behavior of cracks. It also accelerates the dendrite growth outside the MLCC on the surface of the PCB. The absorption of condensed water into microscopic cracks sets the stage for the emergence of dendrite growth (Fig. 4), a process characterized by the formation of conductive pathways bridging electrodes. Figure 4 (left) illustrates the failures mode in MLCCs with cracks caused by migration of ions that are anodically dissolved from terminations, and Fig. 4 (right) presents an example of a visible external crack originated by this mechanism [1, 31, 33, 34, 37].

Furthermore, the progression of cracks is intertwined with ion contamination [1, 16], stemming from various sources including water, corrosion, mold, and surface contaminants present on the MLCC. Ions present in the environment migrate toward areas of high stress concentration, such as the tips of emerging cracks. Under the influence of an applied electric field, these ions accumulate and form conductive paths, thereby intensifying the localized electric field. Therefore, electrochemical reactions take place, leading to the degradation of the material and an accelerated propagation of the crack. This ion-assisted

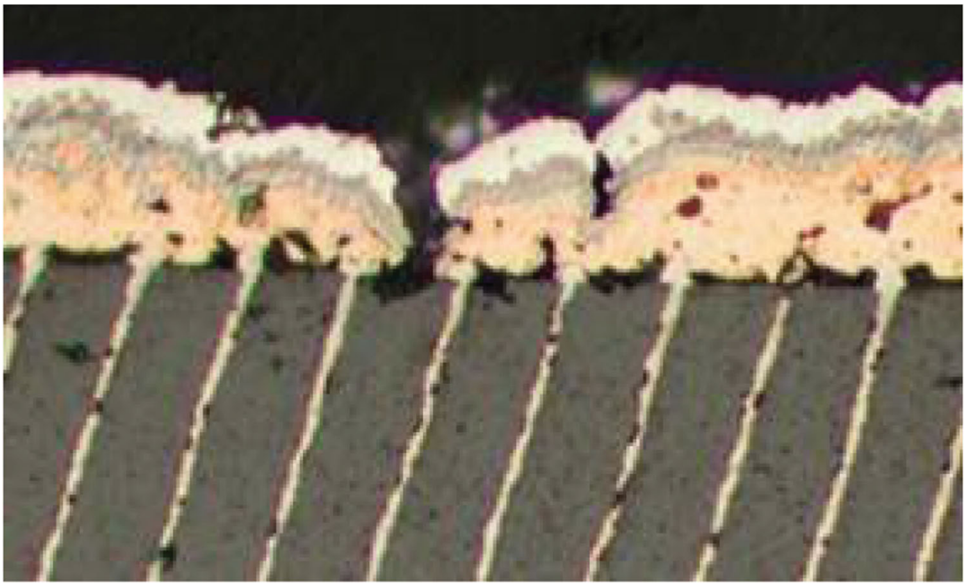

Fig. 3 Example of termination defects pinholes in capacitors [1]. The surface is perforated due to pitting resulting in exposure of the sensitive inner layers

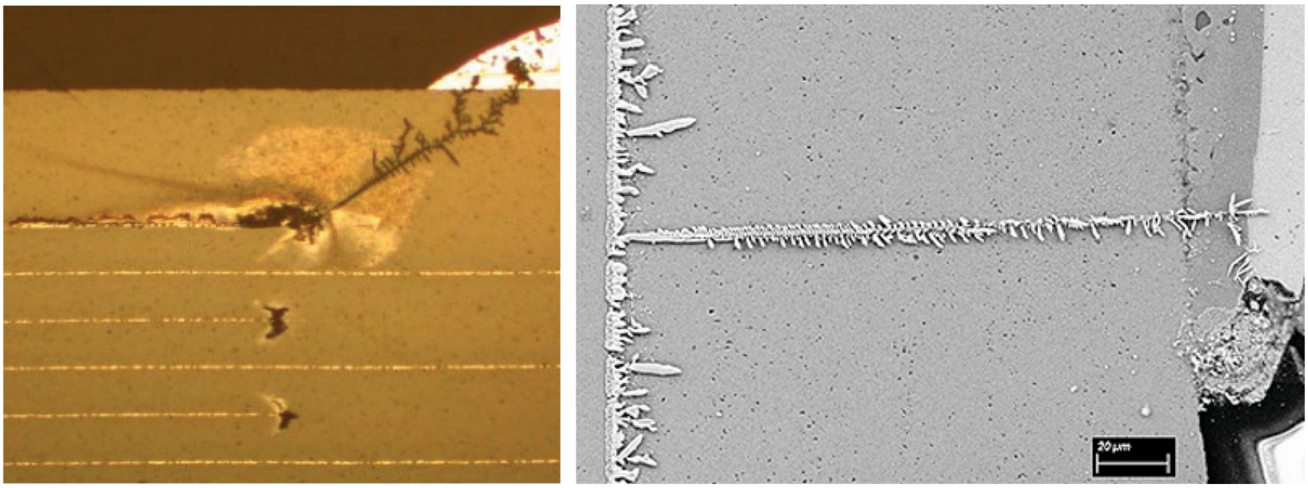

Fig. 4 An example of dendrites formed between the termination and the tip of the negatively biased electrode on the surface of a capacitor that was shorted after 3.6 min at 1.3 V and blown after shorting [1]

cracking mechanism is exacerbated by the hygroscopic nature of corrosion, as the absorbed moisture aids in the transportation of ions to crack sites (Fig. 5).

The interaction between corrosion, ion contamination, hygroscopic effects, dendrite formation, and crack development underscores the imperative nature of analysis and effective mitigation strategies. The correlation between corrosion, contamination, and cracking mechanisms in MLCCs presents a unique opportunity, as the visibility of corrosion and contamination on the component's exterior offers a distinct advantage for detection, unlike the elusive nature of cracks which are often challenging to identify.

Solution

Detecting cracks during the assembly process is challenging due to their often-inconspicuous nature, thus making accurate risk assessment a formidable task. However, recent strides in technology, particularly in the domains of big data and artificial intelligence (AI), offer a promising avenue for addressing this issue.

The innovative solution proposed addresses the crucial concern of corrosion detection in electronic components, thereby enhancing their performance and reliability [14, 16]. This approach harnesses advanced AI algorithms in tandem with cameras that are already integrated into pick-and-place machines, capturing images of electronic

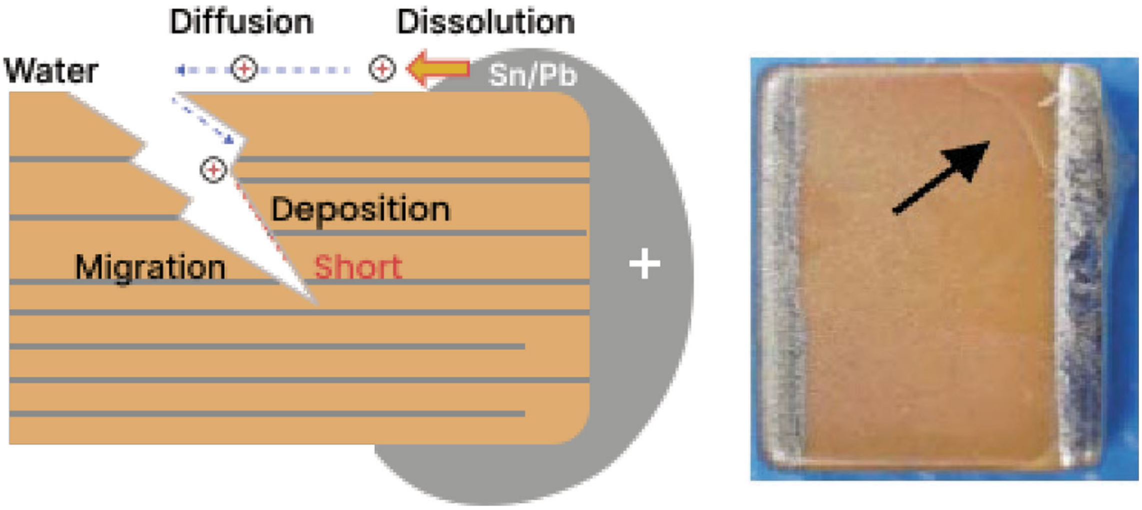

Fig. 5 Schematic of failures in MLCCs with cracks caused by migration of ions that are anodically dissolved from terminations [1]. The crack originates from the termination and ionic electrochemical interaction propagates it into the body of the MLCC

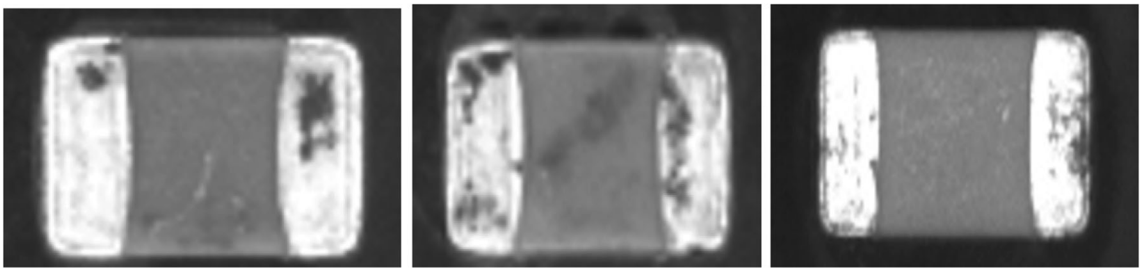

Fig. 6 Instances of contamination detected on MLCC soldering terminations using the proposed system. The corrosion is visible as stains

components during assembly. These images (Fig. 6) undergo scrutiny via AI algorithms, revealing subtle visual cues indicative of corrosion. These cues encompass a range of characteristics including discoloration, oxidation, and surface degradation. An intrinsic capability of this methodology is its ability to distinguish between routine surface irregularities and genuine instances of corrosion. This discriminatory analysis provides an evaluation of component quality, thus facilitating the early detection of potentially compromised units. Significantly, the impact of corrosion detection extends beyond immediate inspection; it plays a pivotal role in precluding the progression of cracks that may emanate from corrosive environments. By identifying and rectifying corrosion-prone components during initial production stages, the method not only preserves the integrity, longevity, and reliability of electronic products but also hampers the development of cracks due to corrosive influences. Figure 6 illustrates instances of contamination detected on MLCC soldering terminations by the system.

The capability to discern corrosion externally through AI-driven image analysis provides manufacturers with invaluable insights into potential vulnerabilities within their components. Early detection of corrosion not only forestalls future cracking complications but also ensures the production of electronic devices with exceptional reliability.

AI Corrosion Detection Method

In this section, we describe a method for detecting corrosion in MLCC's during the assembly process. The proposed approach involves a network architecture tailored to identify and classify corrosion-related defects with high efficiency and accuracy. Leveraging deep learning techniques, this method effectively addresses the challenges posed by limited data availability and the complex nature of corrosion-related defects. The method is described in [14–17].

The foundation of the corrosion detection method is a parallel filter-based network architecture, designed to interface seamlessly with pick-and-place (PNP) machines during the production of electronic components. This network architecture is devised to process images of components captured during assembly, enabling the identification of defects and potential corrosion-related issues. A distinguishing feature of this method is the incorporation of multiple filter sizes that are concatenated in parallel, as opposed to the traditional serial architecture used in popular image classification models.

The algorithmic process initiates by analyzing the captured component images through the utilization of the parallel filter-based network. Each filter within this architecture is engineered to recognize specific types of defective regions within the component images, generating distinctive features indicative of the likelihood of defects [14, 17]. Through the aggregation of features derived from all filters, an overall feature representation is formed, which is subsequently fed into a dense layer. This dense layer ultimately computes the final score of detected defects, providing a comprehensive assessment of the component's condition. In practice, every component placed on all the boards is analyzed and its quality score is calculated.

One of the primary advantages of the proposed parallel architecture is its exceptional efficiency. The system can process a substantial volume of images at an impressive rate, achieving up to 3000 images per second on a Tesla T4 GPU. Furthermore, this method requires fewer training samples compared to conventional image classification approaches. A mere few hundred samples are sufficient to construct a robust and accurate model. The architecture's efficiency stems from its inspiration drawn from the traditional template matching method, particularly beneficial when dealing with limited labeled data.

Given the diversity of defect sizes, the proposed method adapts by employing filters of varying sizes. This adaptability ensures that the network is equipped to identify defects of different scales accurately. Larger defect spots necessitate larger filters, albeit potentially causing slower processing times. To mitigate this, larger filters are downscaled to maintain efficiency, yielding highly accurate results.

Conclusion

The electronics industry faces a persistent challenge that threatens the reliability and longevity of its products—cracks in MLCC. These faults have the potential to wreak havoc by compromising both the structural integrity and functionality of devices. In this work, we investigate the factors contributing to crack formation, unraveling their connection with corrosion, contamination, and mold. Through exploration of mechanisms including hygroscopic properties, humidity exposure, and ion migration, we unveil their roles as precursors to the initiation and acceleration of cracks. The interconnection between corrosion, contamination, and cracking mechanisms in MLCCs also brings about an advantageous prospect. Unlike the elusive nature of cracks that are hard to detect, the visibility of corrosion and contamination on the component's exterior provides a clear opportunity for identification.

We present an innovative solution—a comprehensive visual inspection method for the detection of corrosion evidence on electronic components. By harnessing AI algorithms and the cameras already integrated within the pick-and-place machines, this technique evaluates all electronic components throughout the assembly process. The algorithm is designed to discern corrosion indicators, effectively mitigating the potential for cracks.

The presented approach holds significant promise as a pioneering tool aimed at tackling this challenge head-on. By directly addressing the root causes of crack formation and propagation, our methodology has the potential to revolutionize electronic component manufacturing. This innovative solution marks a pivotal step toward ensuring enhanced product reliability, extending the operational lifetimes of electronic devices.

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