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Preventing Corrosion-related Failures in Electronic Assembly: A Multi-case Study Analysis

E. Weiss

***Abstract*— Corrosion is a prevalent failure mode in electronic products. The initiation of failure often stems from pre-existing corrosion contamination on soldering terminations prior to assembly. This corrosion is further accelerated by environmental factors such as humidity, temperature, and acidity, ultimately leading to degradation of the board and failure during both post-assembly testing and the product's lifespan.**

This study presents a method for the real-time, early detection of corrosion contamination on electronic components during the mounting process using pick-and-place technology. The method utilizes the correlation between light reflectance from soldering terminations during placement photography and the degree of corrosion present. Corroded terminations possess a rougher surface and pitting spots which result in different light reflectance compared to pristine terminations. This difference can be detected through AI forensic analysis of component images. The study presents an AI model that correlates termination finish with corrosion content and progression, and evaluates its performance on large-scale data.

This study also presents a real-world case where corroded components were identified during the pick-and-place process, but later failed during in-circuit testing (ICT). The post-failure analysis, using scanning electron microscopy/energy-dispersive spectroscopy (SEM/EDS) and cross-section analysis, confirms the accuracy of the AI failure predictions on multiple components with corrosion, during large-scale production.

The proposed method has been implemented in multiple production lines, where it inspects all components without compromising throughput, and identifies contaminated components that are unsafe. The method has been tested on over 3.5 billion components, and has achieved an accuracy rate of over 99.5% in its predictions.

***Index Terms*— Artificial intelligence, Corrosion, Deep learning, Electronic assembly, Failure analysis, Intermetallic reactions, Non-destructive testing, Solderability, Surface reflectance, Thermal cycling.**

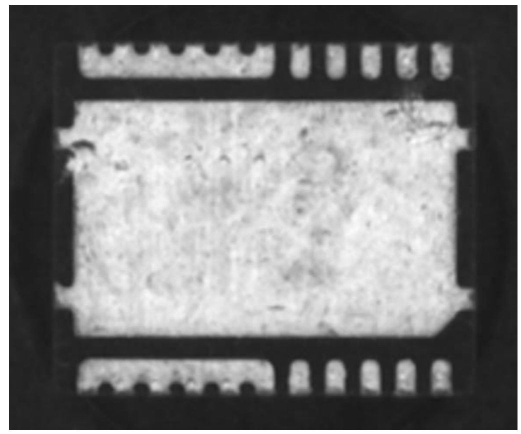

Fig. 1. VSON-12 Gate Drivers NexFET images captured by an ASM Siplace SX mounting machine and detected by Cybord.ai system with quality issues.

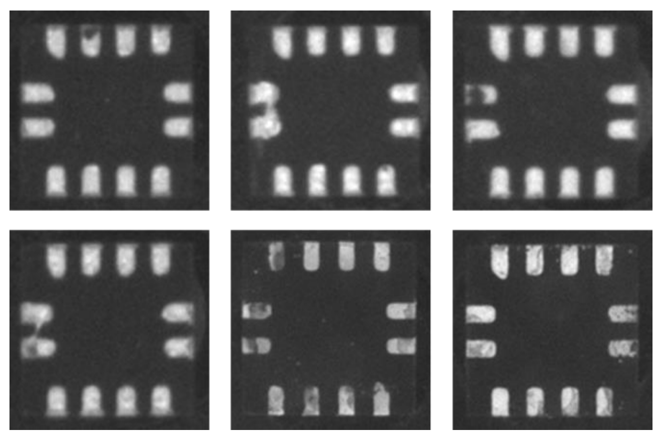

Fig. 2. QFN-12 Power switch images captured by an ASM Siplace SX mounting machine and detected by Cybord.ai system with quality issues: Terminal contamination, Corrosion, Shorts.

I. INTRODUCTION

Electronic components are the most expensive part of the Bill of Materials (BOM) and are also the most common cause of failures in electronic products. Nevertheless, traditional production methods don’t carry out systematic inspection, and seldom any tests are being made at all [1]. This is even though electronic components are the means of most of the failures in electronic products [2]. Unsafe components are more common today because of the electronic components shortage that has made the supply chain more complex and vulnerable to fraudulent falsifications [3]. As a result, components that were obtained from non-reliable sources, recycled components, components that were poorly stored, handled, or old components are more frequently used by the electronic industry. These components have a higher ratio of quality issues. The most dominant cause of the failure of aged components is corrosion propagation.

The electronics industry recognizes corrosion on soldering terminations as a potential risk to component solderability [4]. Various traditional methods are used to evaluate the solderability of electronic components [5]. In the defense industry, samples from batches of components suspected of poor solderability must be inspected in accordance with MIL-STD-202, Method 208 [6] and SAE 26262 used in the automotive industry. These methods typically involve testing a

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small sample of components under specified conditions to assess the ability of the component terminations to wet solder and the strength of the bond. However, this approach is based on the assumption that a small sample represents the entire batch, which is not always the case as demonstrated in [7]. Despite this, the impact of corrosion on soldering terminations on product quality is often overlooked, despite the numerous studies and evidence on the effect of corrosion on bond strength and reliability [8]-[11].

In this study, we propose a method for detecting defective soldering terminations on components during assembly [2], [12], [13]. The method allows for early detection of components with corrosion and contamination in the soldering terminations during production, enabling their avoidance. Furthermore, we present evidence of the method's effectiveness by showing how failures caused by corrosion on components during assembly are correlated to field failure analysis cases.

The inspection was carried out using data processed by Cybord.ai electronic component authentication and qualification software [14]. The software interfaces with the pick-and-place (PNP) machines during production and collects images of the components [15]. These images are then processed using a deep learning algorithm that searches for visual defects in the components and flags any suspected components [12], [16]. Additionally, another network is utilized to evaluate the texture of the soldering terminations and estimate their solderability [13].

The method was applied to real assembled components. We present examples of electronic components VSON-12 Gate Drivers NexFET in 12-VSON-CLIP package (see Fig. 1), and QFN-12 Power switch (see Fig. 2) with corrosion that was detected by the presented method. The failure analysis of these components was performed using X-ray analysis, scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) microscopy, and visible light microscopy. The analysis demonstrates a clear correlation between the AI-detected corrosion and the corrosion and failure mode identified in the failure analysis. The AI method was then calibrated to detect potential failures that may result in future failures.

II. Corrosion's Impact on Electronic Product Reliability

Corrosion is the most prevalent failure mode in electronic products. Studies on the reliability of electronics impacted by corrosion demonstrate that various factors, such as materials used in the print circuit board assembly (PCBA), dc or ac bias applied, contamination of the PCBA surface by ions, high humidity, dust residues, pollutants comprising ions, etc. can cause significant reliability issues due to corrosion [8]-[11]. Some electronic system failures are caused by corrosion resulting from the formation of a water layer on the surface of the PCBA in areas with high humidity and temperature variations [17], [18]. These failure modes begin with untainted soldering procedures that later take place under conditions favorable to corrosion development. Corrosion that is already present in the soldering terminations before the soldering process has a far more devastating effect as it becomes a breeding ground for the corrosion epidemic.

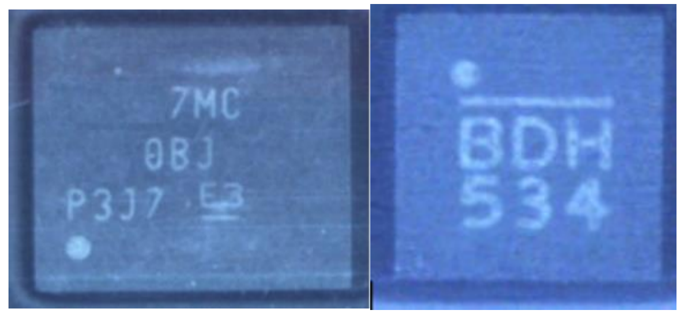


Fig. 3. VSON-12 (left), and QFN-12 (right) images were taken from the top side by an authentication system (an image of similar components from a different production batch).

Contaminations on the surface of the PCBA, residues left from the manufacturing process, as well as corrosion previously present on the soldering terminations before assembly, all have an impact on the reliability of the device. Electrochemical migration (ECM) is also a contributing factor to device malfunction [8], [19]. A key factor in this is the flux agents used in the soldering process and the residue, which contains ionic activators that are hygroscopic. These hygroscopic residues on the PCBA decrease the relative humidity, leading to moisture adsorption at lower relative humidity levels [20], [21]. These residues absorb moisture from the atmosphere until they deliquesce and dissolve in the condensed water film, producing an electrolyte solution with a higher conductivity level [22]. This can lead to reduced surface insulation resistance, increased leak current, and ultimately corrosion contamination such as ECM [23], [24].

The issues outlined above do not usually impact solderability as during the reflow process, there is only a small amount of corrosion present, thus the effect on bond strength during production is minimal. However, these phenomena greatly impact the reliability of the product during its lifespan and may also affect the results of post-assembly inspection as the corrosion continues to spread.

III. A Parallel Filter-based Network Architecture for Corrosion Detection in Electronic Components during Assembly

The algorithm interfaces with pick-and-place (PNP) machines during production and collects images of all the components [14]. These images are then processed using a deep learning algorithm that authenticates the components, searches for visual defects, and flags any suspected components [12], [16]. Additionally, another network is utilized to assess the texture of the soldering terminations, and estimate the presence of corrosion and the terminations' solderability [13]. Detecting corrosion in electronic components is an image classification problem, where images are classified as normal or defective (in some cases, the defective ones can be further classified into finer levels like minor, moderate, or major) [25].

In this work, we propose a new network architecture specifically designed to address the issue of corrosion contamination [26]. Unlike the serial architecture commonly used in popular image classification models, which employs multiple layers of small filters (often of size 3x3) that are connected in series, our approach utilizes a set of filters with different window sizes that are concatenated in parallel. Each filter is designed to detect a specific type of defective region in the component images and generates a feature that indicates the likelihood that the image contains such defects. The overall feature is the concatenation of all features produced by the set of filters. This feature is then fed into a dense layer which produces the final defects score [26]. This parallel architecture results in an efficient detection engine that can process up to 3,000 images per second on a Tesla T4 GPU, while also requiring fewer samples of images to train (a few hundred samples are sufficient). Additionally, this architecture is inspired by the template matching method commonly used in traditional computer vision for object detection when there is limited data. In this architecture, the defective templates represented by the filters are learned from the training images, rather than being manually chosen as in traditional template matching methods. The size of the filters should be approximately the same as the size of the defective spots in the components. Since there are a variety of defects with different sizes, different filter types with corresponding sizes are used. For large defect spots, the filter sizes can be large, resulting in slow processing, therefore, the filters are downscaled. The method was trained on a dataset of over 1 billion inspected components.

IV. Detection of Defects and Corrosion Issues by Deep Neural Networks

The task of detecting defects in electronic components is a challenging image classification problem, where images are classified as normal or defective, and sometimes into finer levels like minor, moderate, or major. However, using popular ImageNet models to solve this problem proved to be inefficient due to two main reasons. Firstly, there is a lack of abundant training data, given that the ratio of defective items in electronic components is very small, and collecting enough items to build a good training dataset is difficult. Secondly, some defective items may be very similar to the normal ones, which causes popular CNN models to poorly recognize the defects, especially when the defects are just small dots inside the components.

To address these challenges, we presented a new network architecture [26] that is tailored to handle defects (Fig. 4). Instead of using the serial architecture used in popular image classification models, we propose using a set of filters with different window sizes that are concatenated in parallel. Each filter is designed to detect a type of defective region in the component images and generate a feature that indicates the likelihood of the image containing such defects.

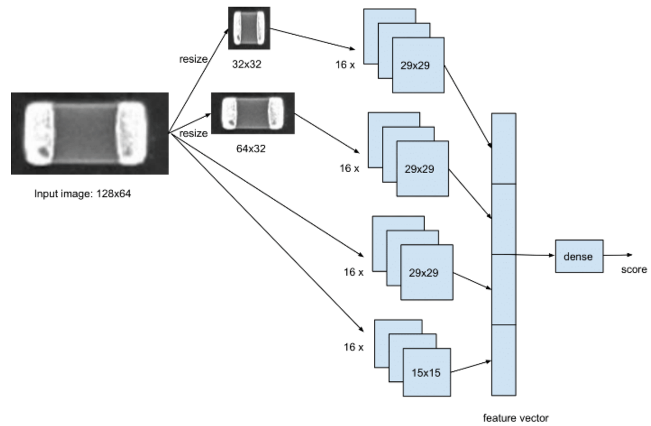


Fig. 4. Neural network architecture [26].

The overall feature is the concatenation of all the features produced by the set of filters. The feature is then fed to a dense layer that produces the final score of defects.

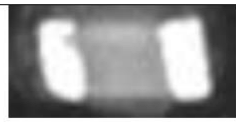
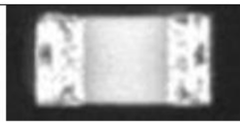
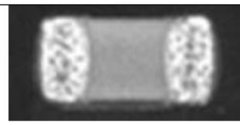
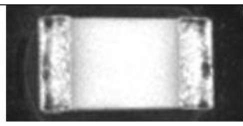
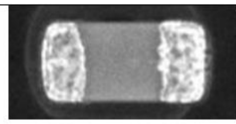
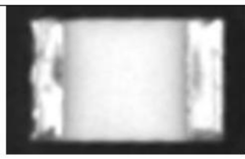
The parallel architecture offers a more efficient defects detection engine, capable of processing up to 3,000 images per second on a Tesla T4 GPU, while requiring much fewer image samples to train. Only a few hundred samples are needed to build a good model. The architecture is also inspired by the template matching method in traditional computer vision, which is used for object detection when there are few labelled data. In this architecture, the defective templates represented by the filters are learned from the training images instead of being manually chosen as in the traditional template matching method. The size of the filters should be approximately the same as the size of the defective spots in the components. As there are various defects with different sizes, there are different filter types with corresponding sizes. For large defect spots, the filter sizes can be large, but the processing will be slow. Therefore, the filters are downscaled to 2 or 4 times smaller and then applied to the corresponding 1/2x or 1/4x rescaled images. The input image size for MLCC and chip resistors is 128x64.

The performance of the proposed network architecture is presented in Table I, indicating that it outperforms the popular ImageNet models. Table II provides a summary of examples of visual defects detected on MLCC and Chip resistors using the method described in this paper [26]. The defects in the form of body defects and corrosion on terminations may not necessarily affect the component's functionality during outgoing tests, but they do significantly impact its reliability

TABLE I. MODELS PERFORMANCE. CAP = MLCC CAPACITORS, RES = CHIP RESISTOR, SLDR=SOLDERABILITY [26].

	CAP-defect	**CAP-defect**	**CAP-defect**	**CAP-defect**
Accuracy	0.953	0.930	0.943	0.917
Precision	0.945	0.945	0.954	0.867
Recall	0.961	0.912	0.932	0.984
F1	0.953	0.929	0.943	0.922

TABLE II. EXAMPLE IMAGES OF MLCC AND CHIP RESISTORS DEFECTS [26].

Chip size - Imperial	Chip Resistor	MLCC
0201		
0402		
0603		
0805		
1206		

during its lifespan. While the reflow process creates a strong bond that can withstand the stress of production tests, environmental stresses and thermal cycling can weaken the bond strength of contaminated components leading to random failures in the field. This could be a possible explanation for product returns even after passing outgoing tests at the manufacturing stage.

VI. Experimental Methodology

In order to demonstrate the effectiveness of the proposed method, we present two case studies of failure analysis for two different electronic components: VSON-12 Gate Drivers NexFET (with moisture sensitivity level (MSL) 2, hence it is sensitive to moisture and must be kept according to standards in vacuum during storage and handling) and QFN-12 Power switch (MSL 1). The method was implemented in a full-scale, high-volume SMT production line, using the presented authentication system, which inspects all components assembled on all PCBs in real-time using the ASM-SX vision system's mounting machine.

Although the presented method provided real-time alerts, during the test period, the system only reported on deviations after assembly, and no actions were taken in real-time. A retrospective analysis was performed only after analyzing the post-assembly test results. The post-assembly test conducted, In Circuit Test (ICT) is a basic electrical test performed on the PCB. The test consists of resistance, capacitance, and basic electrical signals to find shorts, disconnections, or other faults. This test provides the first level of quality assurance and gives preliminary insight into whether or not there is a problem. In this case, a high failure rate was reported on two different part numbers, in two separate production lines. The involved reels were isolated and a retrospective analysis was performed.

The reels suspected of containing defective components were inspected using the reel-to-reel authentication system to ensure authenticity before being used in the production line. The pre-production tests reported that the reel was authentic. The reels were then used in the production process. Images of the electronic components were obtained by harvesting them from the pick-and-place machines [16]. The PNP machine picks up the components and takes their picture using a monochrome camera with a resolution of 17µm. The component's bottom side is shown in the field of view against a dark background, with the possibility of the pick-up nozzle being visible in some cases. All component images are then extracted and processed by the algorithm for defects and corrosion detection. This test found a large ratio of components originating from these reels to be contaminated with corrosion. In production, the alerts are used to detect faulty reels and components, and they are blocked. In the next section, we present the post-process analysis of the failures and compare the predictions and alerts of the presented algorithm.

VII. Results

A. *Case Study 1: Analysis of VSON-12 Package Failure*

In this section, we present a failure case of VSON-12 Gate Drivers NexFET electronic components, which are sensitive to moisture with a Moisture Sensitivity Level (MSL) of 2. The failure is attributed to multiple factors, including exposure to humidity during storage and handling, resulting in the growth of corrosion on the exposed metallic parts of the component surface. Additionally, the presence of corrosion on the soldering terminations acts as a failure mode in itself, as it propagates over time and affects the package case. Furthermore, the corrosion also affects the soldering terminations' wettability, resulting in a partial bond. Fig. 5(A) shows an image of the component taken by the SMT mounting camera during placement, which illustrates the visible evidence of corrosion, and Fig. 5(B) presents an image of a failed component after removal from the board. The top side of the image in Fig. 5(B) shows residues of the wetted area, while the bottom side of the component appears to not contain paste, only a rough surface finish consistent with corrosion.

To further understand the condition of the inner parts of the component, a Scanning Acoustic Tomography (SAT) analysis was performed. SAT is a non-destructive method for evaluating the structural integrity of materials by measuring the speed and energy of an ultrasonic wave as it travels through a material of a certain thickness. The analysis included a C-scan inspection with a horizontally x-sectioned 2D image after focus and a detailed T-scan (as seen in Fig. 6). The results of the SAT analysis revealed delamination, which

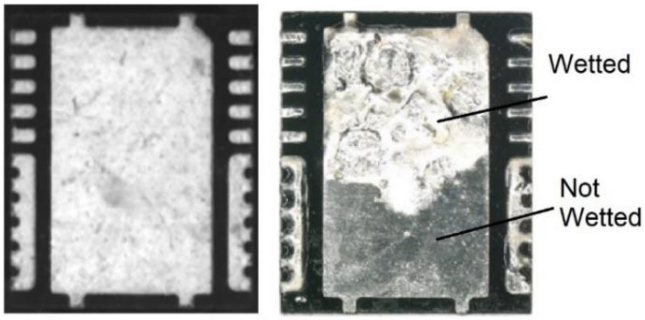


Fig. 5. VSON-12 (A) Image of a component taken by the SMT mounting camera during placement, evidence of corrosion visible, and (B) image of a failed component after removal from the board. In (B) the solder paste residue is visible on the top side, whereas on the bottom side, no evidence of wetting.

is presented in red in the image.

The results of the SAT analysis shown in Fig. 6 clearly indicate that there is a degradation in the internal structure of the component, specifically in the chip's internal metallization. This degradation is likely caused by the corrosion present on the terminations as seen in Fig. 8. The poor wettability of the metallic pad, as evidenced by the lack of paste on the bottom side of the component in Fig. 8, also contributed to the failure. This lack of proper wettability resulted in poor heat removal capability from the component to the board via the thermal pad. In summary, the root cause of the failure is the corrosion which affected both the wettability and propagated into the package case, causing internal delamination.

The correlation between the light reflectance from the soldering terminations during their placement photography and the extent of the corrosion, as well as the rough surface texture caused by corrosion, were detected by the AI detection algorithm, as seen in the image captured by the pick-and-place vision system during the mounting process (Fig. 5(A) and Fig. 1). This correlation was later verified through cross-referencing with the failed units identified in post-assembly tests, where the algorithm had also predicted contamination by corrosion.

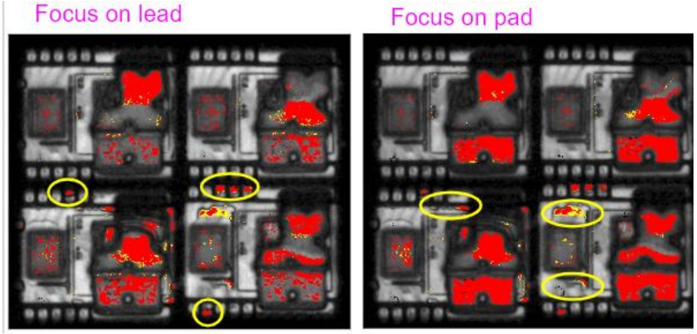


Fig. 6. VSON-12 Scanning Acoustic Tomography image. The red color indicates delamination. The internal delamination appears on the inner part of the soldering terminations.

B. Case Study 2: Analysis of QFN-12 Package Failure

The QFN-12 component, despite being MSL-1 and not being sensitive to humidity, was found to have severe corrosion and mold contamination during assembly. The component was 6 years old at the time and the contamination affected the performance of the board. The presented algorithm was able to detect the contamination during the SMT process and flag the component as contaminated. These flagged components were found to have failed in post-assembly tests, with failure modes including shorts, poor solderability, and opens. Approximately 6-11% of the components from this batch were found to have suffered from electrical failures as a result of the corrosion.

X-ray example analysis of the component did not reveal mounting issues except for a short. The short is also visible on the bottom-side image of the component taken before mounting. Shorts are easily detected automatically by the AI algorithm as there is a strong contrast between the light soldering terminations and the dark component body. The X-ray shows a metallic short between the pads after the mounting on the PCB. It is impossible to say if the short was already in place before mounting or only created during the mounting. By examining the bottom view image of the component before it was mounted on the PCB it becomes apparent that the short was there even before the assembly (Fig. 8-left).

In addition to the X-ray, more analysis was made as the X-ray could not explain the massive failure rate. The failed boards were analyzed by SED-SEM microscopy. The analysis revealed contamination on the soldering terminations as is visible in Fig. 10 where QFN-12 SED SEM analysis example of a soldering pad with a black spot taken by the SMT pick-and-place machine during mounting (left image), compared to a microscopy image taken by the SEM-SED (right image). The black marks are visible on both the pre-assembly Cybord.ai detection (Fig. 9-left) and the SEM-SED post-failure analysis (Fig. 9-right).

The SED analysis reveals that the contamination contains Oxygen, Silicon, and Carbon whereas clean termination doesn't contain any of these materials. Mold contains Silicon (Si), Carbon(C), and Oxygen(O), and oxidation (corrosion) contains Oxygen. From the microscopy images, it is apparent that the black marks are from mold and corrosion. Both are created by exposure to humidity under environmental stress,

Fig. 7. QFN-12 solder bond with the PCB cross-section. A crack is visible between the termination and the paste.

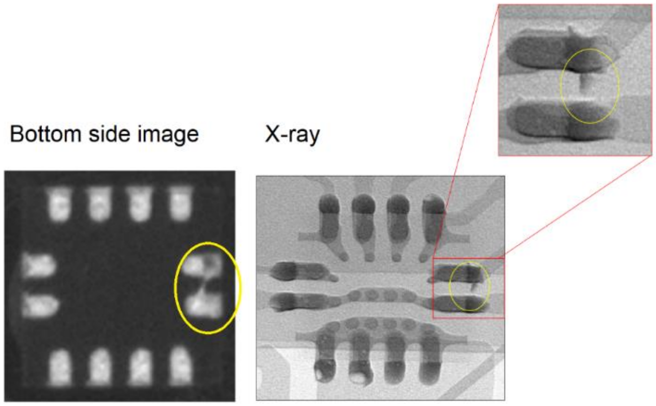


Fig. 8. QFN-12 Short is visible on the bottom view image taken by the SMT pick-and-place machine during mounting (left image), later to be also detected by the X-ray post-failure analysis. (Right image).

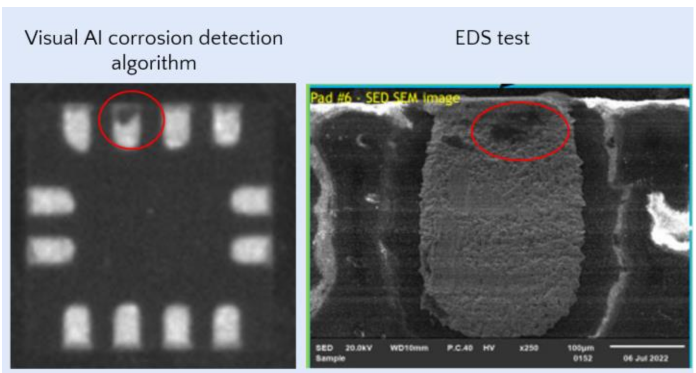


Fig. 9. QFN-12 SED SEM analysis example of a soldering pad with a black spot taken by the SMT pick-and-place machine during mounting (left image), compared to a microscopy image taken by the SEM-SED (right image).

and both degrade the bond reliability and solderability (see Fig. 10).

Further microscope inspection of components that did not go through production is presented in Fig. 11. It shows the QFN-12 SED microscope images. (A, C): Rough surface finish caused by corrosion and evidence of old and corrosion at the edges of the terminations. (B): zoom on mold at the edges of the soldering terminations. As depicted, the surface finish, the corrosion marks, and the mold are also visible during the assembly by the SMT pick-and-place vision system.

IIX. Discussion

The results section demonstrates that the surface finish quality of the soldering terminations can be evaluated through imaging. Soldering terminations and balls, made of chemically unstable materials, are prone to aging faster than other components. The surface of the terminations develops an oxidation layer and intermetallic reactions occur over time, both of which negatively impact solderability. This degradation is visually apparent, as the oxidation layer and altered metallic morphology have distinct characteristics and reflectivity compared to that of a new termination.

The changes in the surface texture and color of the soldering terminations can affect the way light is reflected from the surface, as observed in [27]. This change in reflectance is similar to the difference between a clear and a tarnished mirror. The alteration in texture is a result of the morphological changes that occur during aging, as previously simulated and reported in [3]. These changes involve the gradual shift of metallic alloys and the formation of a brittle corrosion layer, which ultimately terminations to breaks in the surface finish.

Our method utilizes machine learning to classify the level of corrosion on the terminations by analyzing the way light is reflected of the component's soldering terminations, as compared to terminations with corrosion. Additionally, the apparent age of the component can be estimated by analyzing the gradual degradation of the termination's reflectance.

Artificial intelligence techniques can be used to detect the degradation of soldering terminations in electronic components, which can lead to corrosion. By training a model using multiple images of terminations, the neural network can detect the corrosion level and estimate the solderability of the terminations. It is important to note that the age of the component does not necessarily reflect the quality of the termination, as storage and handling conditions can accelerate aging and degrade the termination's condition. The AI-based analysis can detect variations in the condition of terminations, including both good and poor conditions.

Each image in the input dataset is labelled with a score from 0 to 10 indicating the level of corrosion. The model comprises of a Convolution Neural Network, which is used to extract features from input images, connecting with a regression layer whose output represents the predicted corrosion scores of the input images. By comparing the predictions of the algorithm with failure analysis results from a full-scale production line, we can simulate real-life conditions.

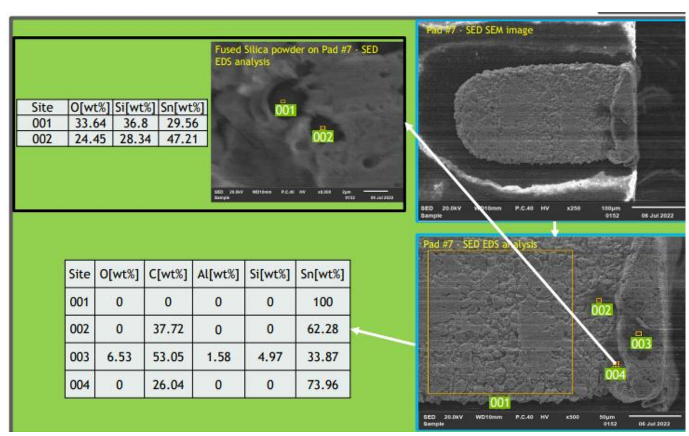


Fig. 10. QFN-12 SED SEM analysis example of a soldering pad with the black spot analyzed. The black spots contain Silicon (Si), Carbon (C), and Oxygen (O), which indicate the presence of mold and oxidation. Both are the result of exposure to humidity and environmental stress.

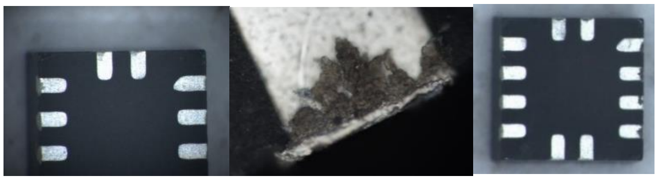


Fig. 11. QFN-12 SED microscope images. (A, C): Rough surface finish caused by corrosion and evidence of old and corrosion at the edges of the terminations. (B): zoom on mold at the edges of the soldering terminations.

The results show that the method can effectively detect and prevent failures caused by corrosion contamination of soldering terminations. It is important to note that while this method can detect issues at the production site, it is also essential to set a threshold that will prevent failure in the field after exposure to environmental stressors. This threshold can be calibrated to detect both solderability issues that fail in the production site and corrosion contamination that will fail later in the field.

IX. Conclusion

In this paper, we have presented a non-destructive method for assessing the condition of the soldering terminations of electronic components through deep visual inspection. This method allows real-time assessment of all assembled components during the SMT mounting process. By analyzing the surface reflectance of the terminations, the method is able to detect and classify the level of corrosion contamination and its correlation to reliability failures caused by corrosion and intermetallic reactions on the surface of the terminations. Our multi-tier classification network, trained on a dataset of over 1 billion inspected components, is able to classify terminations into good and poor corrosion levels based on their apparent age and contamination. The proposed method has the potential to be used in production lines to prevent failures caused by deteriorated soldering terminations due to corrosion contamination.

The proposed method for non-destructive assessment of electronic components' soldering terminations using deep visual inspection was successfully deployed and evaluated in a full-scale, state-of-the-art production facility. The method's ability to predict failures and failure modes on over 30,000 components with accuracy exceeding 99.5% was demonstrated through cross-checking with failure analysis results on over 2.5 billion components. The failure analysis revealed evidence of corrosion that had penetrated the inner package of the component in one case, and corrosion and mold deteriorating the wettability and thus, solderability in another case.

The proposed method's predictions were in line with the analysis report, and its implementation can help avoid the placement of components with solderability and corrosion issues, ensuring that only qualified components are used in production, thus avoiding failures, recalls, and reworks in the field.

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Eyal Weiss is a multidisciplinary technology expert, with a background in machine learning, plasma physics, optical assemblies, laser technology, and electromagnetics. He is a recipient of multiple awards, including the prestigious "Israel security prize" twice. He has 17 years of experience leading research at Soreq Research Center (SRC) and has designed and built several manufacturing production lines utilizing advanced technology and AI. He holds a B.Sc in Mechanical Engineering, M.Sc. in Plasma Physics from the Technion-Israel Institute of Technology, and a Ph.D. in Electronic and Computer Engineering from the Ben-Gurion University of the Negev. He is the founder and CTO of Cybord, which develops electronic component qualification and authentication technologies. Dr. Weiss is a member of the Israel Innovation Authority, Euramet, SAE, and IPC committees and has published over 25 peer-review articles, 4 patents, and a book.