AI Detection of Body Defects and Corrosion on Leads in Electronic Components, and a study of their Occurrence

2022 IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA) | 978-1-6654-9815-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/IPFA55383.2022.9915776

Eyal Weiss[1]
[1]Technology, Cybord Ltd, 126 Yigal Alon St., Tel-Aviv, Israel
Phone: (972)50-6292458, Email: eyal.w@cybord.ai

***Abstract*— A large-scale evaluation of the quality of electronic components at the time of the electronic board assembly is presented. Counterfeit components are often recycled or old component, therefore, the quality of components and the soldering leads is a good indicator of the component's authenticity. The quality of the components is evaluated based on their visual appearance by quantifying their visual defects and the corrosion evidence as they appear on the component and its soldering leads. The effect of body defects and corrosion in the soldering leads on the reliability of the component bond to the board is reviewed. A machine learning method to detect body defects and evidence of corrosion on soldering leads is presented. Over 11 million components images were inspected by the presented AI algorithm. It is shown that 290 components out of a million had body visual defects that cannot be seen by conventional AOI. In addition, over 1,100 out of million had visible corrosion evidence on their soldering leads. Corrosion on the soldering not only affects the production yield but is the most common cause for random statistical failures in the field resulting in products failure. The presented method allows inspection of all the components used in production thus reducing the risk of failures in the field caused by poor quality electronic components originating from counterfeit, and poor storage or handling conditions.**

Keywords—electronic components, machine-learning, ai, solderability, defects, big-data, AOI, SMT.

I. Introduction

Quality is not left for the chance in electronics manufacturing. At every stage along the production process parts and materials are tightly inspected and controlled before allowing them to proceed to the next check-point [1]. Nevertheless, the quality chain is as strong as its weakest link [2], [3].

Electronic components are the most expensive part of the Bill of Materials (BOM). Nevertheless, conventional production methods don't perform systematic inspection, and seldom any tests are being done at all [4]. This is despite the fact that electronic components are the vehicle of most of the failures in electronic products [5]. The unsafe components may be counterfeit, recycled, remarked, copies, cloned, etc. However, there may also be external defects, temperature, or moisture exposure affected during handling and transport [6]. Unsafe components are more common now because of the shortage of electronic components that have made the supply chain more elaborate, complex, and sensitive to fraudulent manipulations [7].

The conventional method to mitigate unsafe components is by procuring components from authorized distributors and thus to trusting the outgoing inspection of the components by the original components manufacturer (OCM). The underlying assumption is that the ratio of defective components after OCM outgoing inspections is negligible and the anti-counterfeiting detection techniques are optimal,

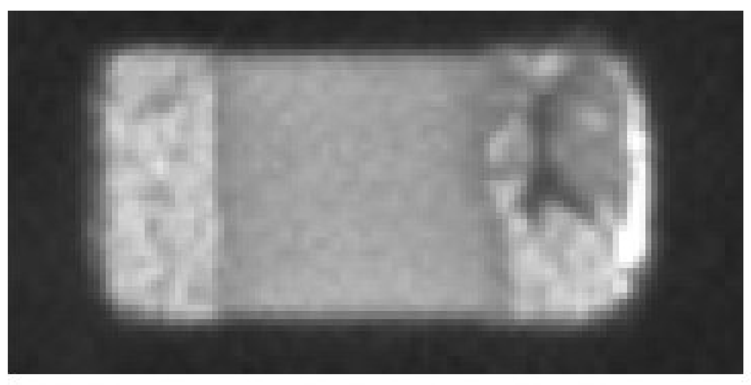


Fig. 1. CAP SMT 0.1µF 10% X7R 16V 0402 with a body visual defect.

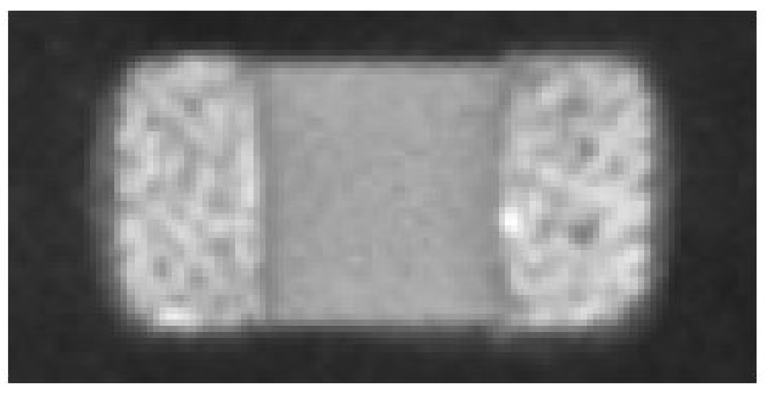


Fig. 2. CAP SMT 0.1µF 10% X7R 16V 0402 with a rough soldering leads issue.

thus does not require additional incoming inspection before the electronics assembly.

The electronics industry sees corrosion on soldering leads as a potential risk to the components solderability [8]. There are several conventional methods to assess the solderability of an electronic component [9]. In the defense industry, samples from a component batch that are suspected of poor solderability must be inspected according to MIL-STD-202, Method 208 [10]. Typically, samples of the tested components are selected and tested under specified conditions to gauge the solder wetting ability on the component leads and the strength of the bond. However, the effect of corrosion on soldering leads on the quality of the product is rarely considered. Although there are numerous evidence and research on the effects of corrosion on the bond strength and its reliability [11]–[14].

In this work, we present a method to detect defective components, and the occurrence of defects and corrosion on soldering leads during assembly [5], [15], [16]. We focus on passive components as they are most commonly used and often taken for granted. The occurrence research was performed only on resistors and capacitors as they are a common large group and therefore, easier to demonstrate the occurrence without going into the details of the different component package case types and their unique properties. In addition, passive components have short shelf life of typically 24 months, compared to other soldering leads. This is because the corrosion and intermetallic process in their leads takes place faster and have a more dramatic effect on their bond reliability than ordinary IC leads. and have However, the method is practiced on all types of components and termination. Nevertheless, they can be the weakest link as they are rarely tested or examined.

The inspection was performed on data processed by Cybord.ai electronic component authentication and qualification software [17]. The software is interfacing with the pick-and-place (PNP) machines during production and collects the images of the components [18]. The images are then processed using a deep network algorithm that is looking for visual defects in the components flagging every suspected component [15], [19]. In addition, another network is used to evaluate the texture of the soldering leads and estimate their solderability [16]. An example of a body visual defect is presented in Fig. 1, and a component with corrosion on the leads appears in Fig. 2.

In this work, we present the apparent state of the electronic components as they are assembled onto circuit boards. After they have passed through the supply chain and in the critical time of placement. We show that the ratio of components with external visual body defects or corrosion on the soldering leads is significant. On average a production line places ~2,000 components per day that have a higher probability to later fail in the field than of pristine components. This calls for tighter production process control and automatic inspection of all electronic components before assembly.

A. The effect of corrosion on quality

Corrosion is the most dominant failure mode in electronic products. Many published work on reliability of electronics caused by corrosion show that the print circuit board assembly (PCBA) materials, *dc* or *ac* bias applied, contamination by ionic on the PCBA surface, high-level humidity, dust residues, pollutants comprising ions, etc. can cause serious corrosion reliability issues [11]–[14]. Some cases of failures in electronic systems are due to corrosion driven by the formation of a water sheet on the surface of the PCBA where high level of humidity and temperature variations took place [20], [21]. These failure modes start off with untainted soldering procedure that are later arranged in conditions that are in favor of corrosion growth. Corrosion that is already present in the soldering leads before the soldering process has a far more devastating effect because they become a propagation seed of the corrosion eruption.

Contaminations on the surface of the PCBA and residues left from the manufacturing process, as well as corrosion already present on the soldering leads prior to assembly influence the reliability of the device. Electrochemical migration (ECM) also has an influence on the functionality of devices [11], [22]. A major contributing factor to this is the flux agents used in the soldering process, and the residue contains ionic activators that are hygroscopic. Hygroscopic residues on the PCBA decreases the critical relative humidity and results in moisture adsorption at the lower relative humidity levels [23], [24]. These residues absorb moisture from the atmosphere until it deliquescence and dissolves in the condensed water film, and produces an electrolyte solution with a higher conductivity level [25]. Consequently, the electrolyte layer sandwiched between the conductors may have a reduced surface insulation resistance, elevated leak current, and finally corrosion contamination like ECM [26], [27].

A common practice to mitigate soldering leads with corrosion is to use aggressive flux that attacks the corrosion layer and by that remove some of it from the leads surface to the top of the solder as residues. However, the increased amount of residues contribute to the accelerated corrosion by growing a hygroscopic residue on the PCBA. Other failures related to these residues include increased corrosion and contact resistance [8]. It may also affect the radio frequency of a Bluetooth antenna or other RF coils [26], [27] as well as other circuits operating at high frequencies and data rates, such as high-speed switches and GPU's.

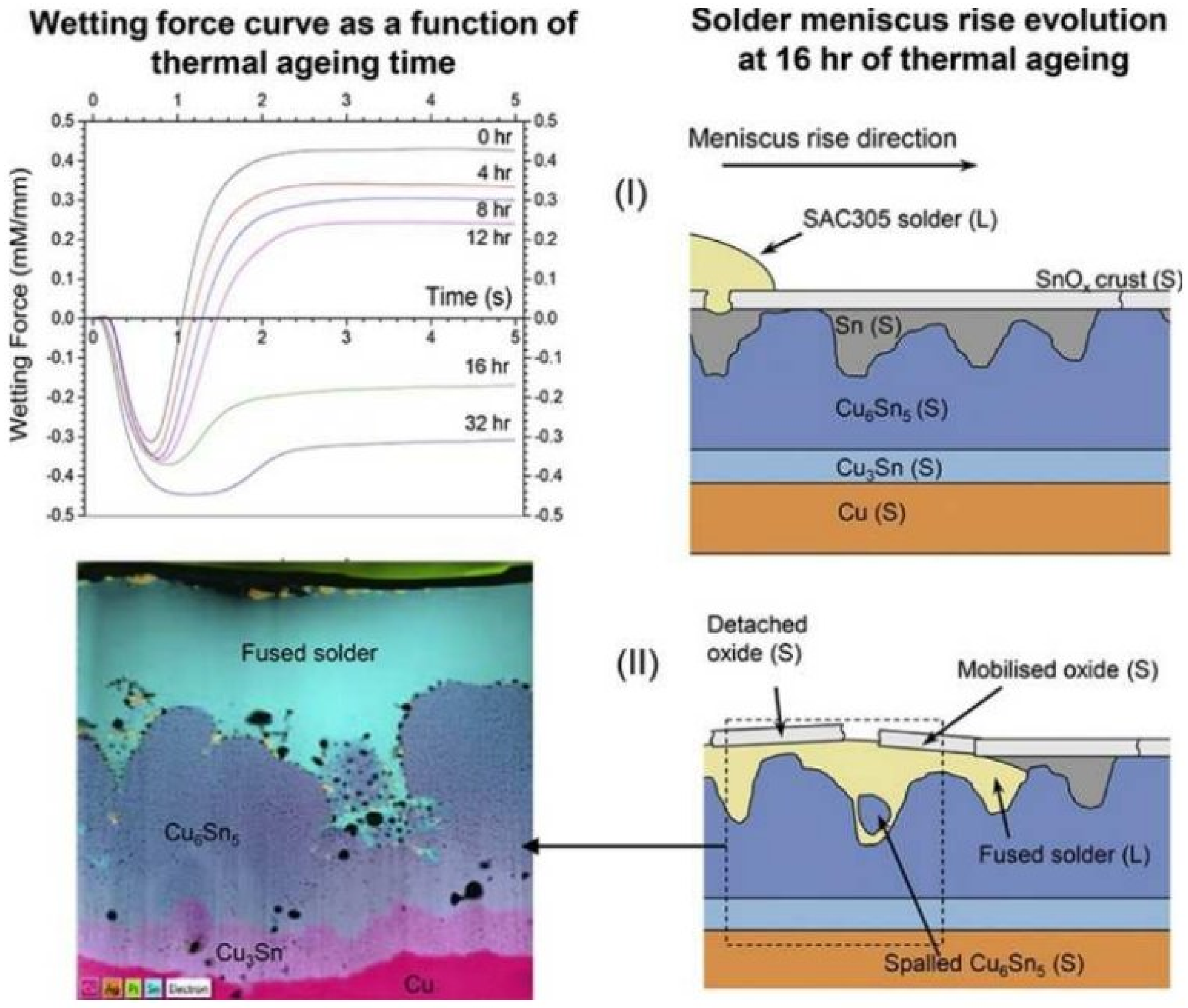


Fig. 3. Cross-sectional schematic diagram showing the evolution of meniscus rise front of the 2.5 µm thick Sn on Cu sample after thermally ageing at 155°C for 16 hr. [6].

Failures due to corrosion of electronic devices are not only limited to ECM but also other failures such as solder joints [28]. These contaminations may originate from the manufacturing process, contamination of the soldering leads, and from the field environment. A high level of Chloride contamination along with high level of humidity may cause corrosion on positively biased bond pads.

Classical chemical, electrochemical, and galvanic corrosion processes, induced or assisted by ionic contamination, particularly in the presence of adsorbed moisture, have often been found to cause degradation of electronic equipment and devices in a wide variety of ways. Often even small amounts of corrosion, on the order of nanograms or less, can cause complete failure.

Clearly, corrosion-induced failures must be essentially eliminated to achieve sufficient reliability. Knowledge of the characteristics of the environment in which equipment must operate is an obvious prerequisite to understanding the effects of the environment on performance.

The interfacial Cu-Sn IMC growth is governed by diffusion controlled, parabolic kinetics [6]. By 16 hr of aging at 150C the metal/oxide boundaries had only seen limited exposing of IMCs (see Fig. 3). The Sn oxides formed on the exposed Cu_6Sn_5 IMC surface did not demonstrate any significant difference compared to that on Sn metal in terms of crystal structure and composition. These indicate an insignificant role of the IMC surface oxide in the solder wettability loss. Based on the wetting balance analysis, the onset of solder wettability loss at 16 hr was found by [6] to coincide with a complete coverage of patch-like oxide morphology, together with significant consumption of Sn metal due to interfacial IMC growth.

These reported issues rarely affect solderability. This is because during the reflow process there is only a little amount of corrosion in place and therefore the effect on bond strength during production is small. However, the described phenomena affect the reliability of the product during its life cycle as the corrosion propagates.

B. Corrosion behavior of solder alloys

Reliability data has been reported by several researchers [29]–[31], and the long-term reliability data for lead-free solders [29]. There are several studies on corrosion of SAC lead-free solders upon exposure to NaCl and there is some information on the corrosion under high-humidity and high temperature. Researchers [26]–[33] report that the intermetallic compounds in solders accelerated the corrosion of tin through galvanic corrosion. Thus, it could be concluded that presence of intermetallic compounds accelerates the corrosion process. This can also form the initiating sites for cracks.

The thermal oxidation of Sn thin films on Cu at 155° is obeying a direct logarithmic rate law, the oxidation exhibits heterogeneous inward thickening at discrete surface locations (formation of ‘patches’, see Fig. 3), accompanied by lateral expanding and outward growth into platelet-like structure [6]. The oxidation products are identified mainly as nanocrystalline tetragonal SnO_2 , an oxide with high oxygen deficiency and pronounced voiding/cracking propensity.

Evidence of intermetallic interaction within the soldering lead before assembly can be examined by the increase surface roughness of the soldering leads that can be detected by the change in their emissivity as presented in [16]. The intermetallic interaction causes discontinuities in the morphology of the leads that are a source of cracks [6].

A Precondition of corrosion on soldering leads before reflowing indicates that the soldering lead aging has already been accelerated and that in addition to the surface layer of corrosion there is also a developing intermetallic process within the soldering lead bulk. The contaminated bulk is prone to further degradation after reflowing and during the bond life cycle while having little effect of the solderability.

The corrosion occurrence in soldering leads is a statistical phenomenon that affect quality in an order of parts-per-million. In order to evaluate the occurrence of aged soldering leads that already exhibit external surface of corrosion and rough surface a large-scale research is required.

II. State of the Art

The conventional method to mitigate the quality of electronic components in the electronic manufacturing industry is to purchase electronic components from authorized distributors. The underlying assumption is that the quality of the components is tightly controlled by the manufacturer and consumption within 18-36 months assures their quality and solderability.

The production site performs solderability destructive testing on a few samples on suspicious cases [10]. However, the tests are subjective, prone to human errors, and are performed on a very small sample of the assembled components.

Visual body defects inspection on electronic components are not performed as a part of the production. The automatic optical inspection (AOI) process may detect some types of defects on the available top side of the components. For example, bent leads [34]. However, AOI machines cannot see the bottom side of the components as they are using top-view images and is not capable of detecting corrosion on soldering leads because the leads are covered with paste or with solder at the time of the inspection. As a result, the industry takes as granted reworks within the production site or after failure at the testing stage. In addition, failure in the field, returns of products, and occasional recalls. On average over 5% of the circuit boards are reworked as a part of the production and 0.5-3.5% of the products returned due to failure in the field [5]. A sizeable part of these physical failures is due to the electronic components.

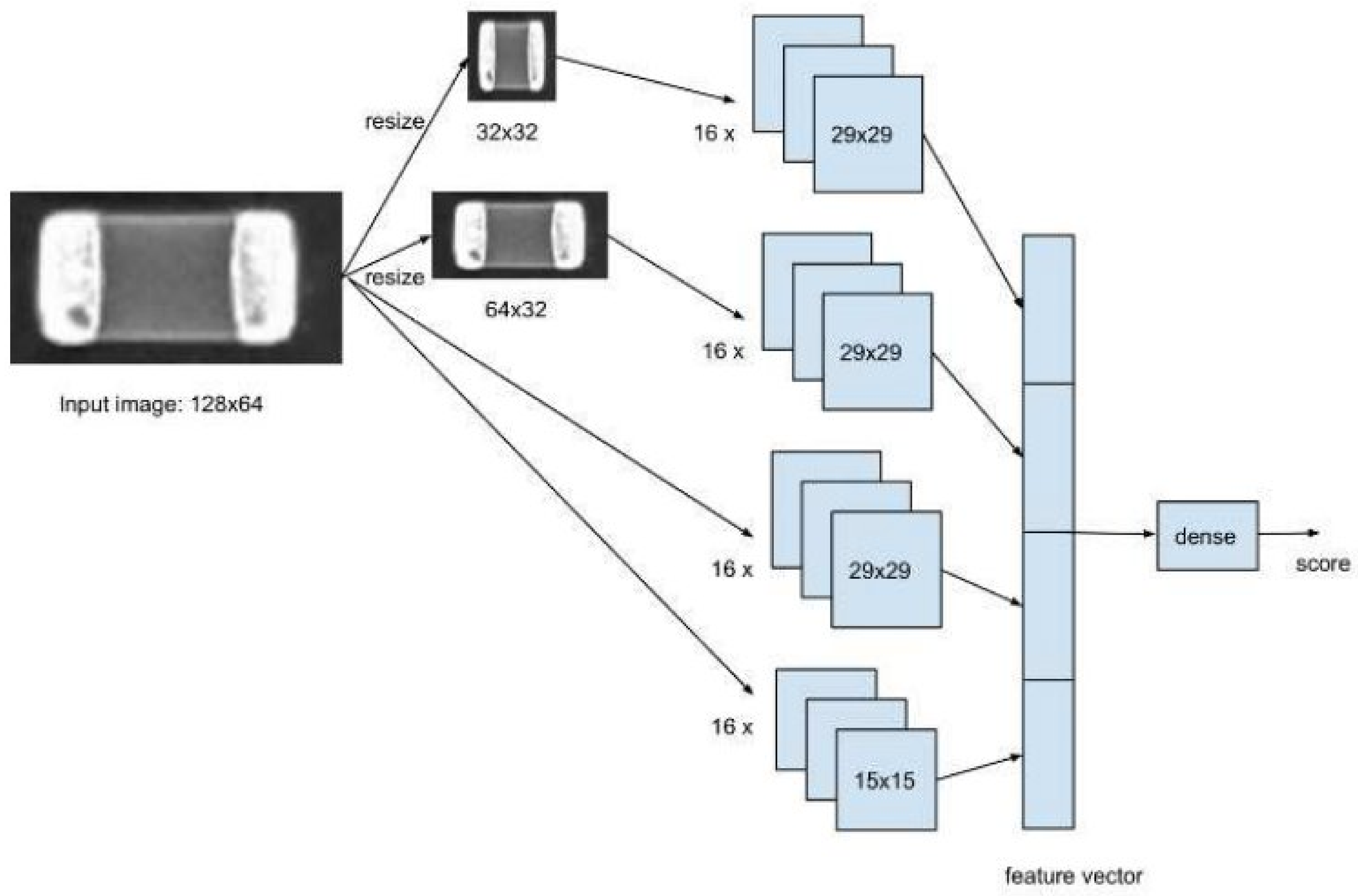


Fig. 4. Neural network architecture.

The status quo of not inspecting electronic components is challenged. We present an ai method that allows inspection of all the assembled components before placement. We also present large-scale research of the external conditions of the passive electronic components previous their assembly at the production floor.

III. Apparatus

The images of the electronic components are obtained by harvesting them from the pick-and-place machines [19]. The PNP machine is picking up the components and then takes their picture using a monochrome camera with a resolution of 17-25 μm. All components’ images are extracted and processed by Cybord.ai defects and solderability detection algorithm. This work was performed on production lines where the AI system gave alerts to the operators where a reel with corrosion or excessive body defects was used. The operators were instructed to acknowledge the faults and specify if they would have removed the suspected components / reels from production. In production, the alerts are used during production and detected faulty reels and components are blocked. In order to obtain statistically significant conclusions a data set obtained at locations that utilize the state-of-the-art processes in electronic components procurement and handling is required.

Approximately 11 million MLCC capacitors and chip resistors images from 3 continents, and 19 production lines were collected. The production machines were Siplace S, and SX made by ASM with an image extraction software module [35].

IV. Detection of defects and corrosion

Detecting defects in electronic components is an image classification problem, in which images are classified as either normal or defective (in some cases, we may further classify the defective ones into finer levels like minor, moderate, or major) [36]. Originally, we try to use the popular ImageNet [37] models to solve this classification problem but the performance was poor.

Two reasons cause those popular models to not work well: The first challenge is that we do not have abundant training data like in other image classification problems. The ratio of defective items in electronic components is very small (often less than one defect per thousand components) so collecting enough items to build a good training dataset is difficult. With only a few hundred defective items collected from millions of components, most of the popular image classification models produce an overfitting result [38], with training accuracy reaching 100% while validation accuracy is much lower. In some cases, the validation accuracy is not better than a random guess. The second challenge is that some defective items are very similar to the normal ones. For example, the defects are sometimes just small dots inside the components. In those cases, most popular CNN models will poorly recognize the defects.

We present a new network architecture tuned to handle defects (see Fig. 4). Instead of using a serial architecture used in popular image classification models, in which multiple layers of small filters, often of size 3x3, are serially connected to each other, we use a set of filters with different window sizes which are concatenated in parallel. Each filter tries to detect a type of defective region in the components' images and generate a feature that indicates the possibility that the component images contain such kinds of defects. The overall feature is the concatenation of all features produced by the set of filters. This feature is then fed to a dense layer which produces the final score of defects (see Fig. 3). By using this parallel architecture, the defects detection engine is efficient (can process to 3,000 images per second on a Tesla T4 GPU), while requires fewer samples of images to train (a few hundred samples are enough). This architecture is also inspired by the template matching method in traditional computer vision, which is used for object detection when there is not much data. In this architecture, the defected templates represented by the filters are learned from the training images rather than by manually chosen like in the traditional template matching method. The size of the filters should be approximately the same as the size of the defected spots in the components, since there are a variety of defects with different size, there are different filter types with corresponding sizes. For large defect spots, the filter sizes can be large, and the processing will be slow, therefore, the filters are downscaled. See models performance in table I.

TABLE I. Models performance. CAP = MLCC Capacitors, RES = Chip Resistor, sldr=solderability.

	CAP-defect	CAP-sldr	RES-defect	RES-sldr
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

V. Results

6,259,712 MLCC and 4,745,216 chip resistors images from 19 production lines and of imperial dimensions of 0402, 0603, 0805, and 1206 were processed. Each component image was ranked by the algorithm according to the severity of the defect or the solderability. The threshold of a defect grade was calibrated based on feedback from SMT engineers on their severity. An example of a component with a visual defect is presented in Fig. 1, and of a component with corroded soldering lead in Fig. 2.

The defective components are presented in DPM in Table II. As seen the average number of DPM during placement for MLCC is 92 for body defects and 1,795 for leads corrosion defects. In the case of chip resistors, the body defect DPM is 200 and the leads corrosion defect is 541.

The results indicate a large ratio of defective components that are used in production. A sample board that contains a mix of 500 resistors and 500 MLLC is expected to have a DPM of 1314. Statistically, on average every board includes 1.3 components with body defects.

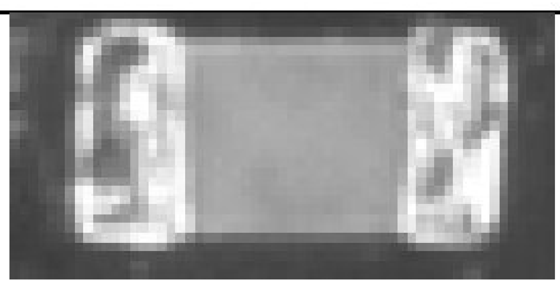
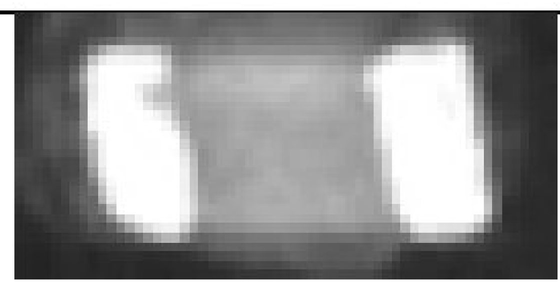
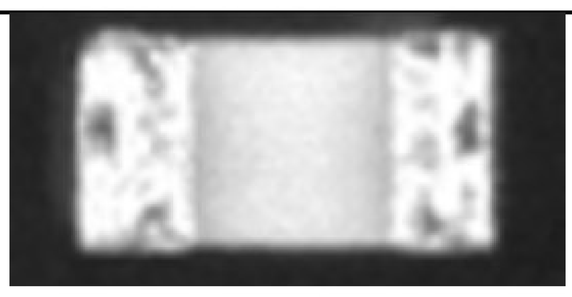
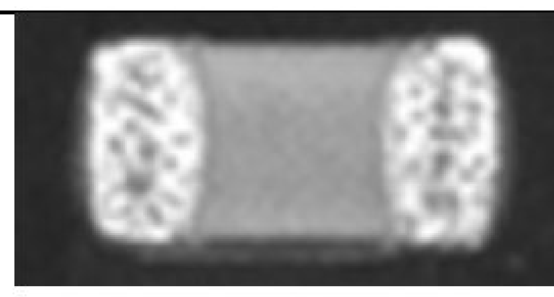
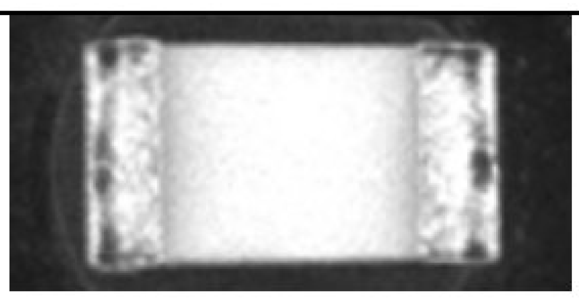
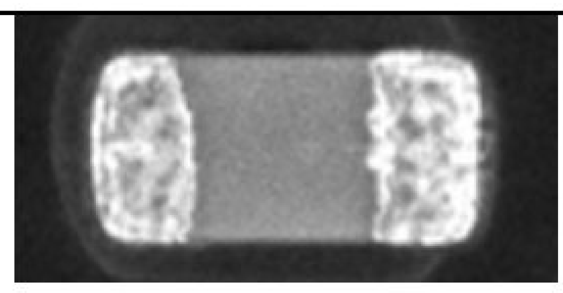
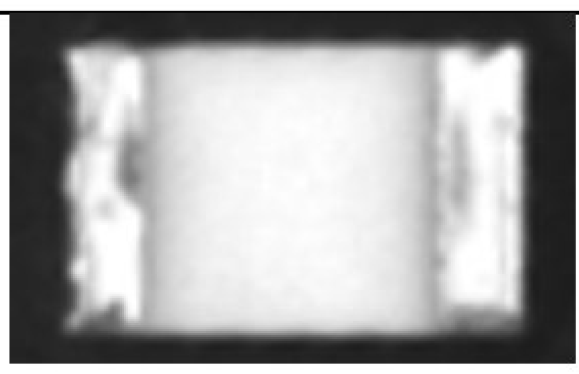
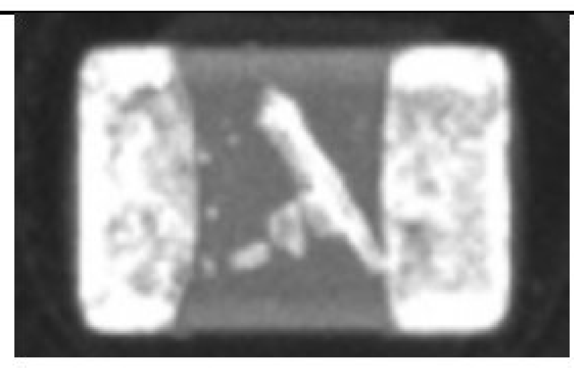
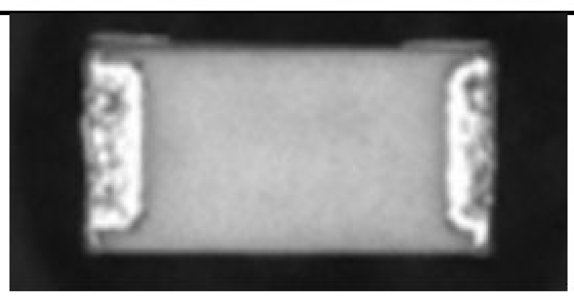
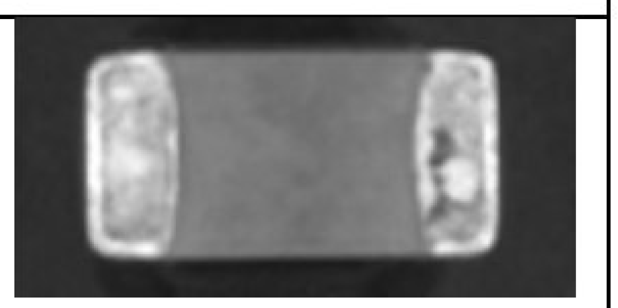
This suggests that MLCC is more prone to lead corrosion defects that may cause life-cycle reliability issues than chip resistors. This may be attributed to the fact that chip resistors are commonly terminated by sputtering whereas MLCC's termination is by dipping. Hence the lifecycle resilience of the metallic show presents lower sensitivity to the strain of the supply chain. The higher DPM rate for 0402 chip resistors compared to larger sizes may be explained by the fact that the 0402 termination is different from that of larger chip resistors. Table III presents some examples of visual defects on MLCC and Chip resistors.

Body defects and corrosion on leads rarely affect the component functionality on outgoing tests. However, the defect affects the reliability of the product during its life cycle. The reflow process in the production line creates a strong bond that can mechanically withstand the stress of the production tests. However, when exposed to environmental stresses, and thermal cycling, the contaminated bond strength weakens resulting in random statistical failures in the field. This phenomenon may explain product returns after passing the outgoing tests at the manufacturer.

TABLE II. Defects per Million (DPM) of body defect and leads corrosion defects affecting the bond reliability detected issues for different chip sizes.

Chip size (Imperial)	MLCC (DPM)		Chip Resistors (DPM)	
	Body defect	Leads corrosion defects	Body defect	Leads corrosion defects
0402	59	3,395	412	2,055
0603	120	3,144	205	29
0805	255	275	135	72
1206	30	3,556	48	8
Average	*92*	*1,795*	*200*	*541*

TABLE III. EXAMPLE IMAGES OF MLCC AND CHIP RESISTORS DEFECTS.

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

VI. CONCLUSION

A large-scale evaluation of body defects and corrosion on soldering leads on electronic components prior to the time of the electronic board assembly is presented. The quality of the components is evaluated based on their visual appearance by quantifying their visual defects and the corrosion evidence as they appear on the component and its soldering leads.

A machine learning method to detect body defects and evidence of corrosion on soldering leads is presented. This method can be applied during the pick-and-place process to screen-test all mounted components in real-time.

Over 11 million passive components images were collected from worldwide production sites and inspected by the AI algorithm. The results indicate that a large portion of the electronic components arrives on the assembly floor with body defects and corrosion on the leads.

We have shown that 290 components out of a million have body visual defects that cannot be seen by conventional AOI. In addition, over 1,100 out of million have visible corrosion evidence on their soldering leads. Corrosion on the soldering not only affects the production yield but is the most common cause for random statistical failures in the field resulting in products failure. The conventional sampling technique for assessing solderability cannot statistically detect the 1,100-ppm rate of defects.

The quality and solderability of electronic components should not be left for a chance in electronics manufacturing. The presented method allows inspection of all the components used in production thus reducing the risk of failures caused by poor quality electronic components in the field and reducing the production reworks.

REFERENCES

[1] D. Powell, M. C. Magnanini, M. Colledani, and O. Myklebust, “Advancing zero defect manufacturing: A state-of-the-art perspective and future research directions,” *Comput. Ind.*, vol. 136, p. 103596, 2022, doi: 10.1016/j.compind.2021.103596.

[2] N. Das and W. Taylor, “Quantified fault tree techniques for calculating hardware fault metrics according to ISO 26262,” in *2016 IEEE Symposium on Product Compliance Engineering (ISPCE)*, 2016, pp. 1–8.

[3] IPC, “Calculation of In Process DPMO and Manufacturing Indices for Printed Board Assemblies DPMO and Assemblies,” 2000. [Online]. Available: http://www.ipc.org.

[4] P. Aryan, S. Sampath, and H. Sohn, “An overview of non-destructive testing methods for integrated circuit packaging inspection,” *Sensors (Switzerland)*, vol. 18, no. 7, 2018, doi: 10.3390/s18071981.

[5] E. Weiss, “Counterfeit mitigation by in-line deep visula inspection,”*SMTA*,2021. http://iconnect007.uberflip.com/i/1440051-smt007-jan2022/87?

[6] J. Wang, G. Chen, F. Sun, Z. Zhou, Z.-Q. Liu, and C. Liu, “Combined effects of surface oxidation and interfacial intermetallic compound growth on solderability degradation of electrodeposited tin thin films on copper substrate due to isothermal ageing,” *Corros. Sci.*, vol. 139, pp. 383–394, 2018.

[7] A. Spieske and H. Birkel, “Improving supply chain resilience through industry 4.0: a systematic literature review under the impressions of the COVID-19 pandemic,” *Comput. Ind. Eng.*, vol. 158, p. 107452, 2021.

[8] “EIA/IPC/JEDEC J-STD-002D.” [Online]. Available: www.ipc.org.

[9] J. R. Villalobos-cano and W. C. Johnson, “Advanced manufacturing Technologu A Solderability Inspection System,” no. February 1991, pp. 144–149, 1992.

[10] S. E. Harpe *et al.*, “METHOD 208, SOLDERABILITY,” *MIL-STD*, no. 2, 2015, doi: 10.5897/ERR2015.

[11] V. Verdingovas, M. S. Jellesen, and R. Ambat, “Relative effect of solder flux chemistry on the humidity related failures in electronics,” *Solder. Surf. Mt. Technol.*, vol. 27, no. 4, pp. 146–156, Sep. 2015, doi: 10.1108/SSMT-11-2014-0022.

[12] E. H. Wong, S. W. Koh, K. H. Lee, and R. Rajoo, “Comprehensive treatment of moisture induced failure - Recent advances,” *IEEE Trans. Electron. Packag. Manuf.*, vol. 25, no. 3, pp. 223–230, Jul. 2002, doi: 10.1109/TEPM.2002.804613.

[13] H. Conseil, M. S. Jellesen, V. Verdingovas, and R. Ambat, “Decomposition studies of no-clean solder flux systems in connection with corrosion reliability of electronics,” in *European Corrosion Congress (Eurocorr), Estoril*, 2013, pp. 1–5.

[14] K. Piotrowska, V. Verdingovas, M. S. Jellesen, and R. Ambat, “General rights Contamination, potential bias and humidity effects on electrical performance and corrosion reliability of electronic devices Contamination, potential bias and humidity effects on electrical performance and corrosion reliability of electronic devices.”

[15] E. Weiss and Z. Efrat, “SYSTEM AND METHOD FOR NONDESTRUCTIVE ASSESSING OF SOLDERABILITY OF ELECTRONIC COMPONENTS,” P-603537-PC, 2021.

[16] E. Weiss, “Electronic component solderability assessment algorithm by deep external visual inspection,” in *2020 IEEE Physical Assurance and Inspection of Electronics (PAINE)*, 2020, pp. 1–6.

[17] E. Weiss, “Electronic Component Analytics and Traceability.” www.cybord.ai.

[18] E. Weiss and Z. Efrat, “TRACING COMPONENTS OF ELECTRONIC ASSEMBLY,” P-603538-PC, 2021.

[19] and G. G. E. Weiss Dr, E. Zeev, “System and method for detection of counterfeit and cyber electronic components,” WO2020202154A1, 2019.

[20] R. Ambat, H. Conseil-Gudla, and V. Verdingovas, “Corrosion in electronics,” in *Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry*, Elsevier, 2018, pp. 134–144.

[21] R. Hienonen and R. Lahtinen, *Corrosion and climatic effects in electronics*. VTT Technical Research Centre of Finland, 2000.

[22] M. S. Jellesen, D. Minzari, U. Rathinavelu, P. Møller, and R. Ambat, “Corrosion failure due to flux residues in an electronic add-on device,” *Eng. Fail. Anal.*, vol. 17, no. 6, pp. 1263–1272, Sep. 2010, doi: 10.1016/j.engfailanal.2010.02.010.

[23] K. Piotrowska, R. Ud Din, F. B. Grumsen, M. S. Jellesen, and R.

Ambat, “Parametric Study of Solder Flux Hygroscopicity: Impact of Weak Organic Acids on Water Layer Formation and Corrosion of Electronics,” *J. Electron. Mater.*, vol. 47, no. 7, pp. 4190–4207, Jul. 2018, doi: 10.1007/s11664-018-6311-9.

[24] V. Verdingovas, M. S. Jellesen, and R. Ambat, “Solder Flux Residues and Humidity-Related Failures in Electronics: Relative Effects of Weak Organic Acids Used in No-Clean Flux Systems,” *J. Electron. Mater.*, vol. 44, no. 4, pp. 1116–1127, Apr. 2015, doi: 10.1007/s11664-014-3609-0.

[25] K. Piotrowska, V. Verdingovas, and R. Ambat, “Humidity-related failures in electronics: effect of binary mixtures of weak organic acid activators,” *J. Mater. Sci. Mater. Electron.*, vol. 29, no. 20, pp. 17834–17852, Oct. 2018, doi: 10.1007/s10854-018-9896-0.

[26] X. He, M. H. Azarian, and M. G. Pecht, “Evaluation of electrochemical migration on printed circuit boards with lead-free and tin-lead solder,” *J. Electron. Mater.*, vol. 40, no. 9, pp. 1921–1936, Sep. 2011, doi: 10.1007/s11664-011-1672-3.

[27] J. D. Sinclair, “Corrosion of Electronics The Role of Ionic Substances.”

[28] M. Ohring and L. Kasprzak, “Chapter 9-degradation of contacts and package interconnections,” *Reliab. Fail. Electron. Mater. Devices (M. Ohring, ed.)*, pp. 475–537, 1998.

[29] J. Bang, D. Y. Yu, Y. H. Ko, J. H. Son, H. Nishikawa, and C. W. Lee, “Intermetallic compound growth between Sn-Cu-Cr lead-free solder and Cu substrate,” *Microelectron. Reliab.*, vol. 99, pp. 62–73, Aug. 2019, doi: 10.1016/j.microrel.2019.05.019.

[30] S. Zhang *et al.*, “Wettability and interfacial morphology of Sn–3.0Ag–0.5Cu solder on electroless nickel plated ZnS transparent ceramic,” *J. Mater. Sci. Mater. Electron.*, vol. 30, no. 19, pp. 17972–17985, Oct. 2019, doi: 10.1007/s10854-019-02151-w.

[31] C. W. See, M. Z. Yahaya, H. Haliman, and A. A. Mohamad, “Corrosion Behavior of Corroded Sn–3.0Ag–0.5Cu Solder Alloy,” *Procedia Chem.*, vol. 19, pp. 847–854, 2016, doi: 10.1016/j.proche.2016.03.112.

[32] D. Geiger and D. Shangguan, “Investigation of the effect of solder flux residues on RF signal integrity using real circuits,” *Solder. Surf. Mt. Technol.*, vol. 17, no. 4, pp. 27–32, 2005, doi: 10.1108/09540910510630403.

[33] M. DUFFY *et al.*, “RF characterisation of no-clean solder flux residues,” in *SPIE proceedings series*, 2001, pp. 138–143.

[34] J. R. Villalobos-Cano, R. Parra-Loera, and W. C. Johnson, “A solderability inspection system,” *Int. J. Adv. Manuf. Technol.*, vol. 7, no. 3, pp. 144–149, 1992.

[35] “ASM Software Tool to Enable Cybord Integration to Test Component Analytics and Counterfeit Detection in Production,” *Whats New in Electronics*, 2021.

[36] A. Alloqmani, Y. B. Abushark, and A. I. Khan, “Deep Learning based Anomaly Detection in Images: Insights, Challenges and Recommendations,” *Int. J. Adv. Comput. Sci. Appl.*, vol. 12, no. 4, pp. 205–215, 2021, doi: 10.14569/IJACSA.2021.0120428.

[37] H.-J. Yoo, “Deep convolution neural networks in computer vision: a review,” *IEIE Trans. Smart Process. Comput.*, vol. 4, no. 1, pp. 35–43, 2015.

[38] M. M. Bejani and M. Ghatee, “A systematic review on overfitting control in shallow and deep neural networks,” *Artif. Intell. Rev.*, vol. 54, no. 8, pp. 6391–6438, 2021.