A Comprehensive Taxonomy of PCB Defects

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***Abstract*—Printed circuit boards (PCBs) contain complex, minuscule elements, that when defective, can be challenging to detect. The cause of PCB defects can be divided into malicious and non-malicious actions, although both can produce detrimental effects to a board. Malicious attacks on a board can be the result of intellectual property infiltration, secure data acquisition, counterfeiting, and denial of service. Non-malicious causes can result in unpredictable behavior or dangerous/unreliable operation. The lack of literature on various types of PCB defects hinders applications involving defect detection and classification. The taxonomy proposed in this paper provides structured defect classes, defect image examples, various causes, and subsequent effects in order to create a comprehensive reference for hardware security and assurance purposes.[1]**

***Index Terms*—printed circuit board, counterfeit, trojan, hardware trust and assurance**

I. Introduction

Printed circuit boards (PCBs) designs are employed in virtually all electronic devices, and have wide range of complexities. In order to produce boards with a lower cost and time to manufacture, designs are often outsourced for production, leaving risks to supply chain processes. A lax manufacturer can cut costs by producing boards with lower quality materials or processes. PCB security attacks such as counterfeiting, hardware Trojan insertion, and alteration can also occur during manufacturing, transit, installation, or after distribution of the product. One alleged instance was “The Big Hack”, where a microchip was implanted into server motherboards that infiltrated thirty U.S. companies. The implants could serve as a backdoor to alter operating instructions, move data, edit information, and inject malicious code to the host device [1].

Detection of hardware threats will be an everlasting need for outsourced products. To adequately inspect a device that is potentially tampered, a full range of possible defects should be examined. There is a need for an extensive collection of PCB defects in order to properly begin detecting any harmful alteration to the product. While there are defects to a PCB that are implemented with malicious intent, it is also important to take into account the possibility of defects from manufacturing or assembly processes, device conditions, or mishandling. This paper primarily focuses on collecting and defining all types of PCB defects, while also noting possible effects to the board. Intent is not implied during analysis of the collection, but all possible sources of a defect should be considered during inspection.

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II. Defect Taxonomy and Descriptions

The collection of defects, which is shown in Fig. 1, is organized according to the feature impacted on the PCB. Each primary class is further divided into subclasses that generalize the appearance, cause, or impact of the defect on the PCB. For larger subclasses, groups of defects with similarities have been created in order to assist in analyzing and comparing the defects. Each feature, class, and subclass are discussed in the subsections below.

A. Trace

A trace is a conducting path that electrically connects one or more points on a PCB layer, and is the first PCB feature that we consider. The *trace* defect category is broken down into four subclasses: defects that are additive to the area of the conductor, subtractive to the area of the conductor, damaging to the conductor, and designed with error.

1) Additive Trace Defects: Additive defects for traces include

a) *Spurs* (Fig. 2-7) are rigid projections of conductor along a linear trace, which can result in short circuits if in contact with other PCB elements.
b) *Short circuits* (Fig. 2-8) between traces occur when conductor connects two tracks that should not be connected for correct operation of the circuit.
c) *Spurious copper* (Fig. 2-11) is an isolated region of conductor appearing in a location not intended by design. This risks the possibility of electrical failure in connections or devices.

2) Subtractive Trace Defects: Subtractive defects are

a) *Open circuits* (Fig. 2-3) in traces occur when conductor between two points is discontinuous, which is a critical defect regarding the operation of a PCB.
b) *Mouse bites* (Fig. 2-5) are rigid depressions of conductor along a linear trace, which is the antithetical defect to spurs. Mouse bites are capable of causing unreliable electrical connections or open circuits when more extreme.

3) Damaging Trace Defects: Damaging defects include

a) *Pin holes* (Fig. 2-2) in conductors are the result of contamination or moisture escaping through the copper when heated and causes holes that deteriorate the reliability of the connection [2].
b) *Scratches* (Fig. 2-18) are the result of mishandling, and the physical impact on the conductor can cause open circuits on connections.

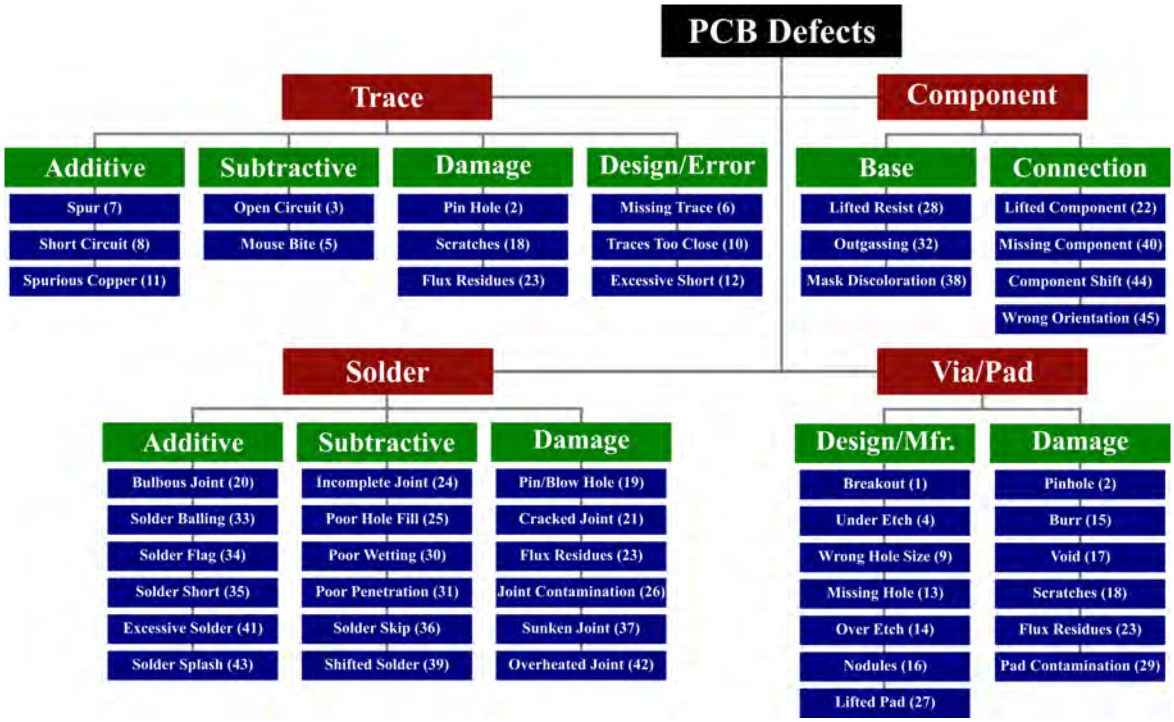

Fig. 1. Printed Circuit Board Defect Taxonomy

c) *Flux residues* (Fig. 2-23) on the board can be the result of poor processing conditions [2]. Flux left on a PCB is capable of reacting with moisture to cause current leakage [3].

4) Design or Error Trace Defects: Trace defects caused by design or error include

a) *Missing traces* (Fig. 2-6) occur when two points are not connected on the PCB due to lack of conducting path. This can occur due to errors in PCB manufacturing or design.

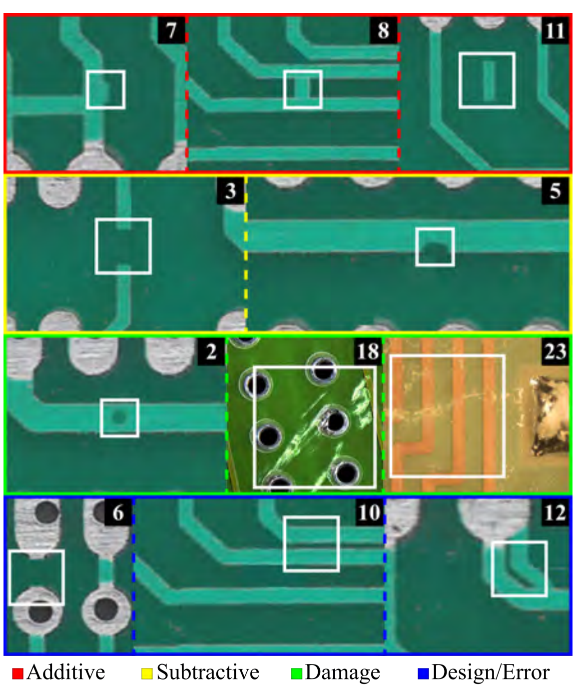

Fig. 2. Trace Defects: 2-3, 5-8, 10-12 [4]; 18 [5]; 23 [2]

b) *Traces too close together* (Fig. 2-10) can also be the result of poor manufacturing or design. When in operation, the trace placement can result in electrostatic discharge or a short circuit. For generic trace distance detection, copper weight must also be identified to properly measure standardized trace width and spacing dimensions [6].

c) *Excessive short circuits* (Fig. 2-12) have a similar cause as missing traces, but instead of two points being disconnected, they are unnecessarily connected twice.

B. Solder

Solder is a metal alloy used to create strong permanent bonds between PCB traces, PCB vias, and component pins. The *solder* defect category is classified as follows: defects that are additive to the volume of an ideal solder joint, defects that are subtractive to the volume of an ideal solder joint, and defects that are damaging to the solder joint area and components.

1) Additive Solder Defects: Additive defects for solder volume include

a) *Bulbous joints* (Fig. 3-20) are solder connections with a height greater than the connected component and a convex meniscus [2]. The implications of this joint can vary, as too much solder can create unnecessary connections, unreliable connections, and damage the material of the component.

b) *Solder balls* (Fig. 3-33) form as a result of resist failure or poor process conditions. Depending on the size, location and adhesion to the solder mask, the effect of the balling can range from being a visual defect to creating short circuits [2].

c) *Solder flags* (Fig. 3-34) are points or spikes on the ends of pins that occur as a result of inconsistent flux application or

Fig. 3. Solder Defects: 19-21, 23-26, 33-37 [2]; 39 [9]; 30-31, 41-43 [8]

poor solder drainage [2]. Depending on the length the flag, the defect can lead to short circuits, but at shorter lengths, they are only visual differences.

d) *Solder shorts* (Fig. 3-35) occur when two or more pins are electrically connected as a result of an incorrect solder connection or excess solder that wets nearby pins around a targeted joint. Short circuits created by soldering defects are a high priority and create critical conditions for the operation of the circuit, similar to the effect of short circuits created by trace defects.

e) *Excessive solder* (Fig. 3-41) on joints appears spherical on the connection as opposed to the ideal cone shape for pins. Causes of the defect include poor flux applications, poor process parameters, solder pollution, or poor board layout [7]. The spherical shape extending outside the targeted area can be indicative of heating damage, contamination, or unreliable connections in the area around the joint.

f) *Solder splash* (Fig. 3-43) refers to unnecessary solder speckled at random positions on the PCB. The splashing occurs due to insufficient flux agent, surface pollution, or unstable temperatures while soldering and can cause short circuits between any component or connection affected on the board [8].

2) Subtractive Solder Defects: Subtractive defects for solder volume include

a) *Incomplete joints* (Fig. 3-24) occur when the board has a poor hole-lead-ratio, causing the joint filling to have gaps. [2] Therefore, the connection between component, pin, and solder is not reliable and can cause unpredictable behavior.

b) *Poor hole fills* (Fig. 3-25) are present when the solder does not fully fill the plated through hole. When there is a fluxing or heating problem in the processes, the solder can congregate at the top of the joint instead of filling the hole [2]. While the connection is still intact for this defect, the strength of the connection is not as reliable as one with a deeper connection.

c) *Poor wetting* (Fig. 3-30) occurs when heat is not applied to both the pin and the pad, causing the solder to insufficiently connect the two. Poor wetting directly results in a low strength joint with unpredictable connection behavior [8].

d) *Poor penetration* (Fig. 3-31) is often referred to as a solder starved joint that does not have enough solder, has insufficient flux, or has a short soldering time. Therefore, the solder does not make a strong connection between the pin and the through hole, which makes cracking a possibility [8].

e) *Solder skips* (Fig. 3-36) occur when a component does not receive solder on the surface of a joint where a connection should have been made in the soldering process. Incorrect height or resist thickness can be causes of the defect during assembly [2].

f) *Shifted solder* (Fig. 3-39) can occur during the reflow solder stage or when components are not placed in the exact correct position [9]. A shifted solder connection on a component can result in improper connections due to the misalignment of the component and board.

3) Damaging Solder Defects: Damaging defects to solder joints include

a) *Pin and blow holes* (Fig. 3-19) are created in the same manner as the pin hole defect that occurs in traces. Outgassing occurs during soldering and escapes through the solder when heated, leaving behind the hole when cooled. A blow hole is the terminology for a pin hole that is large. While the connection may still be functional, there is a reliability risk to the operation of the circuit if tests are not performed [2].

b) *Cracked joints* (Fig. 3-21) occur due to expansion and contraction of lead in the joint or from poor board design and handling. A brittle electrical connection between components can make the circuit defective [2].

c) *Flux residues* (Fig. 3-23) can appear on solder connections and will have the same effects as described in the damaging trace defects section.

d) *Joint contamination* (Fig. 3-26) is the result of improper temperature conditions that can cause nearby materials to melt into the solder joint. Melting of a component can cause the solder joint to perform in an unpredictable manner and may negatively affect the component's performance [2].

e) *Sunken joints* (Fig. 3-37) occur from outgassing, a poor hole-lead-ratio, obstructing contamination, or poor fluxing. The solder drops through the hole for the various reason, and solder does not flow on the top side of the board. A sunken joint can cause a poor connection to the pin, and the cause of the defect may be indicative of a more serious problem in the board [2].
f) *Overheated joints* (Fig. 3-42) are the result of a high soldering temperature. The intense heat can likely cause a poor connection and damage any component in the area of the joint [8].

C. Via and Pad

Vias are plated through-holes that connect signals between traces on different layers of a PCB. Pads are contacts used to connect components with a via and are the points to which components are soldered. The *via and pad* defect category is classified as follows: defects that are the result of design or manufacturing processes and defects that are damaging to the via or pad.

1) Design or Manufacturing Via/Pad Defects: Defects due to design or manufacturing processes include

a) *Breakouts* (Fig. 4-1) occur when the hole drilled for a pad is too close to the edge of a pad. Different classifications of products have tolerance allowances of how far a hole can be drilled from the center of a pad. Having a small hole size clearance or exceeding tolerances can cause a breakout, and the effect is that unreliable electrical connections with the via are made [10].
b) *Under etching* (Fig. 4-4) occurs when unwanted copper for a pad is not completely removed and leaves a larger than intended area for the connection. If not impeding on surrounding components, under etching can simply be a visual defect [11].
c) *Wrong hole sizes* (Fig. 4-9) are the result of improper drilling dimensions when manufacturing the board. A hole too large or small can cause insufficient spacing for an electrical connection.
d) *Missing holes* (Fig. 4-13) are locations on pads where a hole is intended to be drilled, but during creation of the board, no hole is made. Poor design or malfunction during manufacturing processes can cause holes to be missed, and this will result in unintended functionality of the board.
e) *Over etching* (Fig. 4-14) juxtaposes the under etch defect. Over etching is the result of poor protection of the copper by the resist, and the undercut resist may result in damage to trace and pad edges [11].
f) *Nodules* (Fig. 4-16) are protruding connections of the plate and its respective through hole. A blocked via can prevent correct electrical connections and cause unpredictable circuit behavior [5].
g) *Lifted pads* (Fig. 4-27) can occur from force on the board, or the adhesion of the copper foil can be decreased with increasing temperature. When solder pads become detached from the surface of a printed circuit board, the connection becomes unreliable and can result in circuit failure [2].

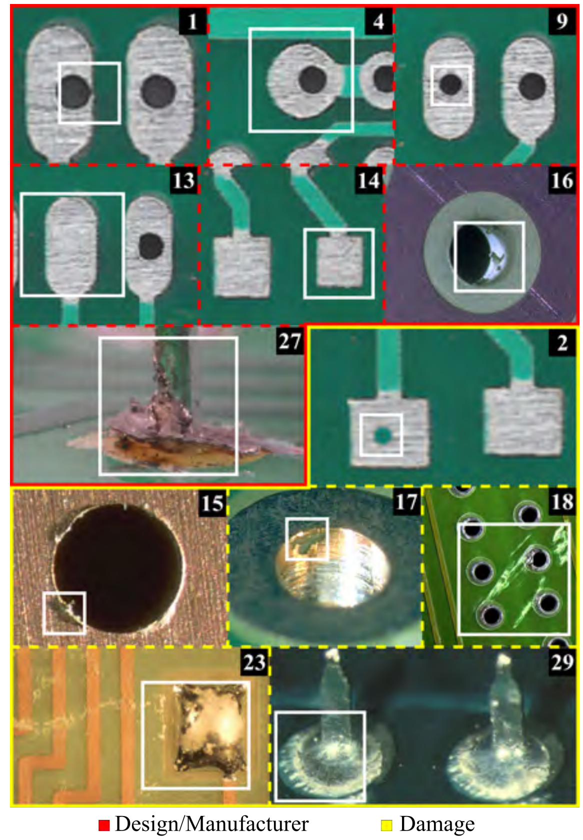

Fig. 4. Via/Pad Defects: 1-2, 4, 9, 13-14 [4]; 15-18 [5]; 23, 29 [2]; 27 [8]

2) Damaging Via and Pad Defects: Damaging defects to vias and pads include

a) *Pinholes* (Fig. 4-2) are caused by outgassing, which can create a hole in the pad to make the connection unreliable, similar to the effects of pinholes on traces and solder.
b) *Burrs* (Fig. 4-15) occur at the edges of drill holes and create a rim that can protrude the interior of the hole. The hole can then be too small for a desired connection, causing connection failure [5].
c) *Voids* (Fig. 4-17) are eroded openings of the conductor on the plating of a via. With discontinuous conduction, the flow of signals can be interrupted [5].
d) *Scratches* (Fig. 4-18) on pads are the result of mishandling the board, and similar to traces, this defect can cause open circuits and circuit malfunction [5].
e) *Flux residues* (Fig. 4-23) can also appear on pad connections and will have the same effects as described in the damaging trace defects section.
f) *Pad contamination* (Fig. 4-29) occurs when poor solder resist application causes a reduction in solder volume. Poor design rules of the resist aperture and annular ring cause the reduction. Less solder results in a less secure and reliable electrical connection to the pad [2].

D. Component

Components on a PCB include chips, resistors, capacitors, etc.. The *component* defect category is classified as follows: defects that affect the base of the printed circuit board and

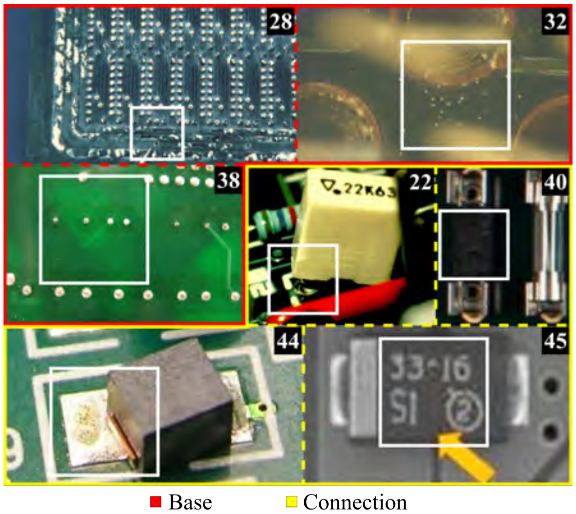

Fig. 5. Component Defects: 22, 28, 32, 38 [2]; 40 [12]; 44 [13]; 45 [14]

defects that affect the connections, such as surface mount component orientation or position.

1) Base Defects: Defects affecting the base of a PCB include

a) *Lifted resist* (Fig. 5-28) occurs when the solder mask is raised due to incorrect board specifications. Tin or lead should not be used under the resist, as these materials are prone to expanding. With the lifting, the board can lose adhesion to the solder mask [2].

b) *Outgassing* (Fig. 5-23) occurs when moisture in the board is turned to vapor and escapes when heated. This process can cause holes to appear, reducing the reliability of the board [2].

c) *Mask discoloration* (Fig. 5-38) can be caused by different flux being used, higher temperatures, resist type, board batches mixing, or changing circuit board suppliers. Discoloration is often only an appearance difference, but origination of the change should be identified [2].

2) Component Connection Defects: Defects that alter the placement of component connections include

a) *Lifted components* (Fig. 5-22) can be the result of thermal demands on the component leads, incorrect lead length, flexing of the board, or incorrect component insertion. A lifted component's pins may not all be connected, and those that are connected can have a weak joint. Component operation will therefore be unreliable [2].

b) *Missing components* (Fig. 5-40) occur when there is no component located on the board in a region where one was intended. Error in the manufacturing processes can cause a missing component, or damage to a board can break a component off. Having an incomplete board will result in incorrect operation of the circuit [12].

c) *Component shift* (Fig. 5-44) occurs when there is a mismatch in component and pad geometry, bent leads, or poor solder placement. Depending on the severity of the shift, the component can have unreliable or missing connections to the board [13].

d) *Wrong orientation* (Fig. 5-45) of a component occurs when there are assembly errors during the alignment phase of the manufacturing process. This defect can cause poor solder joints, short or open circuits, or make the device have reverse polarity, causing critical negative effects to the operation of the board [15].

III. Automated Defect Detection

PCB defect detection is a critical measure to secure the electronic manufacturing and distribution processes. The task is currently being tackled by various corporations, and research is further developing for hardware trust and assurance.

A. Defect Detection by Commercial Entities

ScanCAD International Inc. is a corporation providing services such as reverse engineering, quality analysis, failure analysis, and IP services to customers around the world [16]. ScanCAD's advanced scanning and software technologies are capable of producing PCB fabrication data, netlists, bill of materials, and schematics from different input sets. Input data is collected by using a flatbed scanner, flying probe tester, scanning electron microscope (SEM), computerized tomography (CT) scan, x-ray, PCB, or CAD data. For PCB comparisons, CT x-ray and flatbed scan data is overlapped with golden sample CAD data in order to confirm that the board in question has not been altered internally [17]. ScanCAD generates a proof of theft report for its customers that identifies physical and dimensional similarities, manufacturing specifications and materials, circuitry implementation, bill of materials comparison, netlist or schematic, functionality, and firmware, if applicable [18]. ScanCAD provides destructive and non-destructive options for inspection. Some defects in our proposed PCB defect taxonomy could possibly be detected with methods similar to those used by ScanCAD International Inc., but there are also defects that are not comparison based, where a golden sample may not apply for the detection process.

Integrated Sensor Technologies also provides reverse engineering services that can produce fabrication drawings, bill of materials, schematic capture files, Gerber files, CAD designs, or drill data [19]. PCBs are cleaned up, then layers are removed to be scanned and converted to create file types. Netlists are extracted, which enables a schematic design and Gerbers to be created. Integrated Sensor Technologies also has automatic optical inspection capabilities that are able to compare Gerber images and PCB images, which is a method of defect detection for operations in possession of multiple circuit boards.

B. Defect Detection in Academia

Weibo Huang et al. [20] presents a convolutional neural network (CNN) based model to classify defects in PCBs. A test image and template image are preprocessed to locate defects, where the trained model then classifies the defect. The network is comprised of convolutional layers, pooling layers, BN-ReLU-Conv (1×1) layers, and BN-ReLU-Conv (3×3) layers. A synthesized PCB data set is also made public. A challenge to this method is that results can produce false detections or duplicate detections from a single defect. This method is also limited to applications where a template board and test board are available. Abdul Mujeeb et al. [12] focuses on detecting defects in an environment similar to a manufacturing assembly line, as it proposes unsupervised defect detection with little to no defect data. An automatic optical inspection system uses autoencoders and feature extractors on a reference and test image to then produce a pass or fail decision from a feature comparator. As this method revolves around an assembly line style, a template and test board must be available. The proposed method is also limited in nature as the similarity score of the matching algorithm is dependent on the size of the defect region, which may not be ideal for the diverse taxonomy of defects. Lastly, Volkau Ihar et al. [21] proposes a one-class training model that uses unsupervised transfer learning based on VGG16 for defect detection on printed circuit board regions. The model consists of frozen convolutional layers for feature extraction and unsupervised representation learning from simple geometric transformations. Test images are preprocessed and the model is run, where a test result will then produce a threshold based confidence value on segments of the image to indicate a defect. One limitation of this model is the process of generalizing the trained model in order to not overfit during learning. Failed training could also occur, as occurred in one of the experiments, as the result of a large number of trainable parameters not reaching an optimal state with only a few training samples.

IV. Conclusion

In this paper, we proposed a taxonomy to organize 45 PCBs defects using common features to classify them. Along with descriptions and images of the defects, possible causes, effects, and priorities were discussed. It is important to note that many defect categories can be generalized, as there is an abundance of defects specialized for individual, unique components. These particular defects are outside the scope of this paper. Providing a concentrated and robust taxonomy of defects aims to assist approaches used for defect detection and classification purposes. Future work may focus on developing low-cost, automated methods to detect all these defects.

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