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Head in Pillow X-ray Inspection at Flextronics

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Abstract

Manufacturing technology faces challenges with new packages/process when confronting the need for high yields. Identifying product defects associated with the manufacturing process is a critical part of electronics manufacturing. In this project, we focus on how to use AXI to identify BGA Head-in-Pillow (HIP), which is challenging for AXI testing. Our goal is to help us understand the capabilities of current AXI machines.

For the study we used two boards exhibiting HIP defects with four types of AXI machines at four sites in Flextronics manufacturing, or vendor laboratory. The AXI machines used have different X-ray technologies: Laminography and Tomosynthesis. We collected three sets of data with AXI 1 machine (Laminography), and AXI 4 machines (Tomosynthesis); one set of data with AXI2 (Tomosynthesis); and 4 sets data for AXI3 (Tomosynthesis). We studied AXI measurement data with the different AXI Algorithm Threshold settings. The data indicated clearly that the Algorithm Threshold settings are very critical for detecting HIP, including open. The defective HIP pins are validated by using 2DX and CT scan.

The test data consist of Defects Escaped %, False call PPM and also Gage R & R. The AXI images for HIP pins, false call pins and defects escaped pins are presented in the paper. The 2DX and CT images are provided for identifying HIP type (shape and size).

Introduction

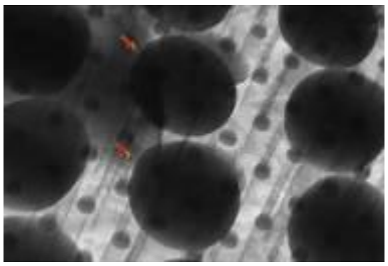
More BGA and area array devices are appearing on PCBAs as product and functional complexity increases. Furthermore, to achieve good signal integrity, more I/Os are packed in smaller areas within the available real estate. It is very important to use AXI and other Non-destructive techniques to identify BGA joint qualities and prevent escape. We did a study for BGA crack several years ago with AXI, Time Domain Reflectometry (TDR), 2DX, and Cross-section/SEM Comparison; however we didn't have good detected results from AXI[1]. During the study, we realized that 2D X-ray with tilting angle detector has the capabilities to identify BGA crack at 5 microns or higher. Recently more AXI machines using both Laminography and Tomosynthesis technologies have better capabilities to detect BGA defects; therefore we would like to develop the optimization Algorithm and Threshold settings to identify HIP on BGA for high volume products.

Based on 2DX images, we have identified two boards containing HIP: #495 with 45 HIPs, and #266 with 2 HIPs. With the HIP defective boards, we have tested them at four sites, with four different AXI machines. AXI1 is a Laminography machine; AXI2, AXI3, and AXI4 are Tomosynthesis machines from different vendors. We worked together with site engineers and vendors' support engineers for this project. We focused on HIP defects escaped %, false call PPM and Gage Repeatability & Reproducibility (Gage R&R) with that BGA.

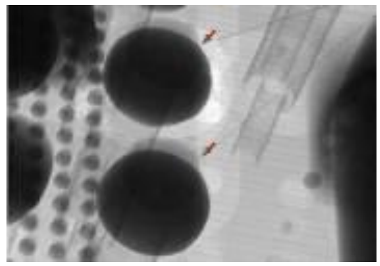
"A picture is worth a thousand words." Indeed, a high - quality microstructure of solder joint provides "sights' and "insights" into the state of solder joint integrity and its anticipated behavior[2]. Similar benefits can be achieved using high quality 2D and 3D offline X-ray inspection images and data. Through this study, we try to understand more about AXI machines capabilities, especially for improving AXI programming optimization used for our best practices. Although machine's testing conditions were not exactly the same, but close, the philosophy for achieving optimization is similar. Look at the measurement data first, finding the difference between good solder joint and defective solder joint; and then balance the defects escaped % and false call numbers to find the right threshold settings. For the high volume products, monitoring AXI programs is an ongoing process based on further fine tuning with feedback from ICT, Functional test and 2D / 3D offline X-Ray inspection.

Experiments and Analysis

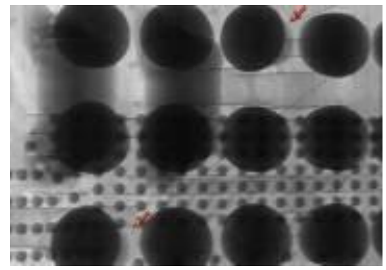
Two boards with HIP defects were from production SMT line of a different site. The BGA has 1017 balls with ball diameter of 21 mils for outer balls and 19 mils for inner balls of the pad. The HIP defective pin (ball) is identified at 2DX machine with tilting angle detector. Tilting (oblique) angle is 55 to 68 degrees; and rotation of the X-ray detector 0 to 360 degrees around the examined joint. This is not trivial, but it is very easily accomplished using the 2DX equipment. The oblique and rotation angles of the X-ray detector are key factors for identifying BGA defects, such as HIP, open, and small crack[1]. There are total 47 HIP pins on the two boards based on 2DX images (resolution 0.1µm). Some 2DX HIP images are shown in Figures 1, where pins with arrow are HIP, except for pin number G32 which is crack (9µm).



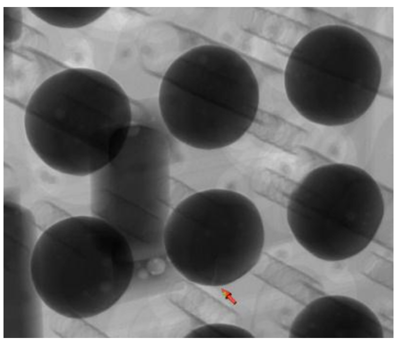
HIP: AA15, AB15



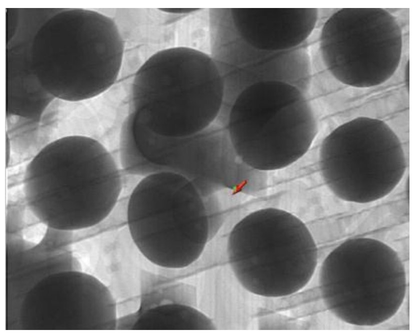
HIP: Z24, AA24



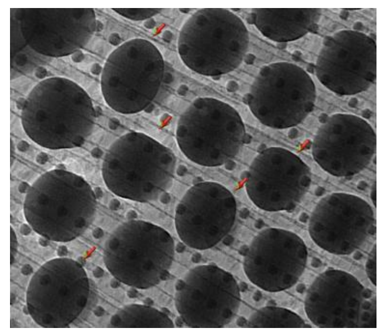
HIP: L13, N11



Crack: G32



HIP: N30



HIP: V17, W17, Z16, Z18, Z19

Figure 1. Samples of 2DX Images of Defective Pins (Board #495)

For this project, the "Defects escaped %" and "False Call PPM" are calculated with the equations listed below:

Defects Escaped % = # of HIP escaped / Total # of HIPs, where Total # of HIPs is 47. (Equation 1)

False Call PPM = (Total # of False call / Total Pins # tested) X10^6, where Total tested pins number is 2034 for two boards. (Equation 2)

The Gage R&R results are calculated with SPC tool Minitab with nine sets of variable data by three operators from each machine. Data of BGA diameter for pad & middle slice, and some main AXI Algorithm (Open outlier, Neighbor Outlier, Solder area pad…) are collected during the studies.

A. AXI 1 (Laminography)

AXI 1 type is the largest number of AXI machines in our worldwide manufacturing sites. From our experience, AXI 1 plays a good role of detecting various solder joint defective types (Solder Bridge, Insufficient, Excess …) based on experience during the last 15 years; it does not detect 100% of BGA HiP defects effectively. At Flextronics, we encourage engineers from different sites to share good knowledge, such as an experience with latest software, and new Algorithm's features. We want to have the best performance by maximizing the machine's capabilities in every site inside of Flextronics.

First, we tested two boards with AXI 1 type at site 1; then used the same program to test the same boards at sites 2 and 3 with a little bit of fine-tuning (editing of Threshold settings). The main thresholds which we focused on are: 1. Open Outlier for Pad slice; 2. Open Outlier for Middle ball slice.

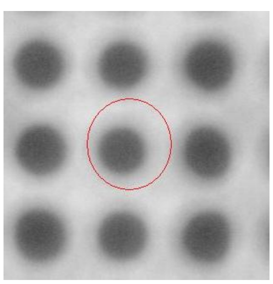
As we know, each AXI machine flags a pin as a defect if the measurement falls outside of the Algorithm Threshold limit. So it is important to know the difference between a good and bad solder joint with various measurements data for each Algorithm. It is easy to have optimization Threshold setting if the measurement difference has a big gap; otherwise it is challenging to make AXI program detecting defects with low false call rate.

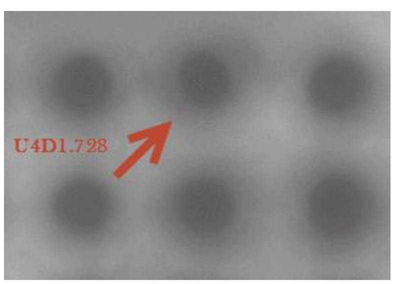
The main thresholds of adjustment are: 1. Open Outlier for Pad slice; 2. Open Outlier for Middle ball slice. The Threshold setting is < -3 for “Open Outlier Lower Sensitivity for Pad slice”, and is > 3 for “Open Outlier Sensitivity for Middle ball slice”. These should be good threshold numbers for many products (BGA packages). Table 1 listed the pins which are called defect from site 2 based on their Threshold settings: Open Outlier Sensitivity for slice 1 (MidBall) is **3;** Open Outlier Lower Sensitivity for slice 2 (Pad) is **-3**. The program detected 17 HIP pins from 45 defects (board # 495); and it had 7 pins as false calls, and had escaped 28 HIP defects. The detected HIP pins (labeled in green color), escaped HIP (labeled in red color), and false call pins (labeled in orange color) are listed in Figure 2. There are no significant differences between the good and HIP pins based on the AXI 1 images. This may be the effect of AXI1 HIP detection capabilities.

Table 1. AXI 1 Open Outlier Measurement Data for Pad and Middle Ball slices (Board #495)

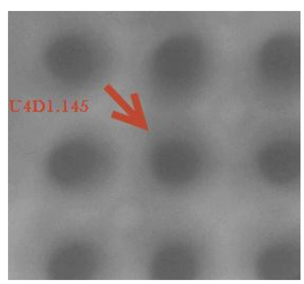
BGA U4D1 Pin #	Pin Type	OpenOutlier (MidBall)
T24	HIP	3.11
Z18	HIP	3.17
N30	HIP	3.27
N11	HIP	3.3
P13	HIP	3.3
AH13	HIP	3.31
W14	HIP	3.36
U8	HIP	3.39
T12	HIP	3.48
AK18	HIP	3.73
AG16	HIP	3.93
AH19	HIP	4.34
AL11	HIP	4.62
AA27	HIP	4.71
AJ10	HIP	4.73

BGA U4D1 Pin #	Pin Type	OpenOutlier (Pad)
AD28	False call	-4.06
Z12	False call	-3.77
Z23	False call	-3.37
AB15	HIP	-3.29
AD15	HIP	-3.24
A23	False call	-3.14
L13	HIP	-3.13
AC15	False call	-3.09
G28	False call	-3.05
M15	False call	-3.05

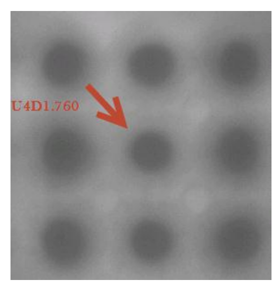

AB15 (escaped)



L13 (detected)



AD28 (false call)



M15(false call)

Figure 2: AXI 1 Images of detected HIP; escaped HIP, and False Call Pins

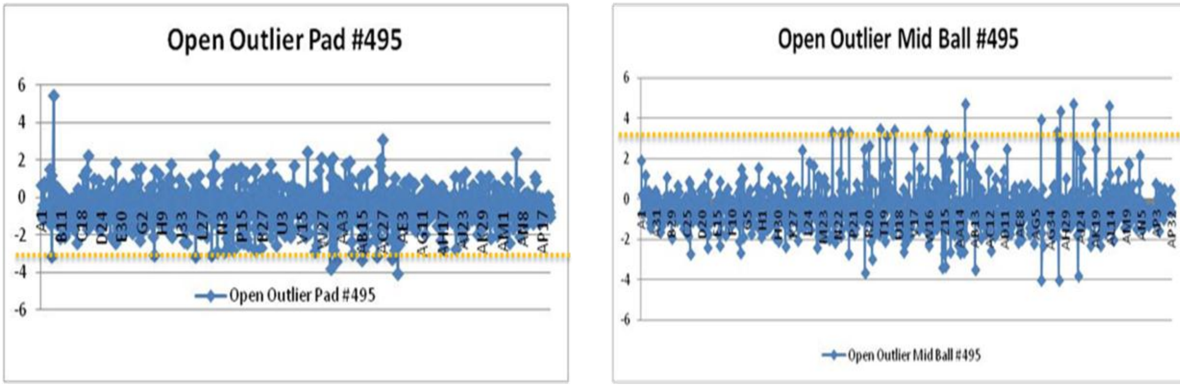


Figure 3: AXI 1 "Open Outlier" measurement data for Middle Ball and Pad slices (Board #495)

Figure 3 shows "Open Outlier" measurement data for Middle Ball and Pad slices of board #495. The measurement data tells us that AXI1 has the capabilities to detect some HIP pins. However, there is no clear measurement data gap between the good and HIP pins with the current version AXI software as it is reflected on AXI 1 images. Therefore, we understand why some HIP pins escaped, and also has difficulty to have zero false call. Table 2 lists the number of Detected HIP, False call, and HIP escaped with different Threshold settings at site 2. With the Default Threshold settings from AXI 1, the program didn't detect any HIP with zero false call. If we tighten the Threshold from < -3 to < -2.5 for pad slice, and from >3 to >2 for middle ball, the detected HIP increased from 18 to 29, however the false call increased from 7 to 17 with the same program. As a recommendation, we suggest the settings for Open outlier < -3 for pad slice, and > 3 for middle ball slice which are the main Algorithms that can detect HIP. The rest of the parameters for Open outlier can be used with default numbers if the test results are fine.

Table 3 listed AXI 1 testing results summary by using equations 1 and 2 from site 1; site 2; and site 3. The site 1 used Default Threshold setting; site 2 and site 3 use the same Threshold settings which are listed in the first two lows of Table 2 for testing two boards. The data tells us that AXI 1 has the capabilities to detect HIP with the right Algorithm Thresholds settings.

Table 2. AXI 1 Detected HIP and False Call Vary with Threshold Settings (Board #495)

Board #	Open Outlier Threshold Settings	Detected	False Call	Escaped
266	Pad < -3 as defect; Mid Ball > 3 as defect	1	5	1
495	Pad < -3 as defect; Mid Ball > 3 as defect	18	7	27
495	Pad < -2.5 as defect; Mid Ball > 2 as defect	29	17	16
266	Pad < -6 as defect; Mid Ball > 6 as defect	0	0	2
495	Pad < -6 as defect; Mid Ball > 6 as defect	0	0	45

Table 3. Testing Summary with of AXI 1

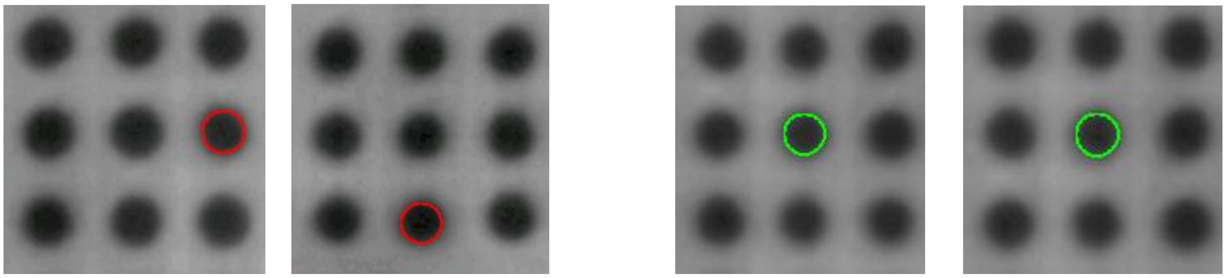
Site	# of Total Escaped Defects	Defects Escaped %	# of Total False Call	False Call PPM
1	46	97.87%	0	0
2	28	59.57%	12	5900
3	24	51.06%	13	6391

B. AXI 2 (Tomosynthesis)

There are a few AXI 2 machines at Flextronics manufacturing. For AXI 2 machine, the Threshold settings for Neighbour outlier is < **-3.5** for pad, and > **4.5** for middle ball. Table 4 listed AXI 2 test results summary from site 1. Two detected HIP pins (labeled as green color), and two escaped HIP (labeled red color), are listed in Figure 4. Similarly, there is not a huge difference on pin images between good and HIP pins. In comparisons to AXI1 versus AXI2, the AXI 2 (Tomosynthesis) seems to have better HIP detection than AXI 1 (Laminography).

Table 4. Testing Summary with AXI 2

Site	# of Total Escaped Defects	Defects Escaped %	# of Total False Call	False Call PPM
1	16	34.04%	3	1475



T24(detected) L13(detected) AA15 (escaped) AB15(escaped)

Figure 4: AXI 2 Images of detected HIP; escaped HIP pins (Board #495)

C. AXI 3 (Tomosynthesis)

AXI 3 machine uses Tomosynthesis technology which is similar to AXI 2 machine. The AXI 3 has faster testing speed than AXI 1, and AXI 2. We used the same HIP boards tested at four sites, and worked with the vendor to have Algorithm and Threshold settings studies. The Algorithm Threshold settings are different when we tested the boards at different site with the latest software at that time. The main Algorithm Thresholds for detecting HIP with AXI 3 are listed in Table 5. Because board #495 and #266 were built at different manufacturing facilities with little different solder shape and volume, so different Algorithm Thresholds were set to detect HIP effectively at site 3 and site 4.

Figure 5 shows detecting HIP pins, escaped pins, and false call pins for board # 495, and all pins for board #266 which is from site 2. The AXI 3 flagged pin as HIP when its pad Neighbor Outlier > 2.2 with multi-pass Algorithm. AXI3 detected 38 HIPs (escaped 7) with 6 false calls for board # 495, and detected 2 HIP (no escaped) with 6 false calls for board # 266. Table 6 listed the test summary from each site with AXI 3 which has better performance than AXI 1 for both HIP detection percentage and false call PPM.

Table 5. Algorithm Thresholds with AXI 3

Site	Algorithm (Neighbor Outlier)	Threshold
1	Minimum and Maximum for Pad	< - 3.2 ; > 4.5
2	Neighbor Outlier - Pad (multi-pass)	> 2.2
3	Neighbor Outlier - Pad	> 2.2 (#495); >3.3(#266)
4	Neighbor Outlier - Pad	> 2.2 (#495); >3.3(#266)

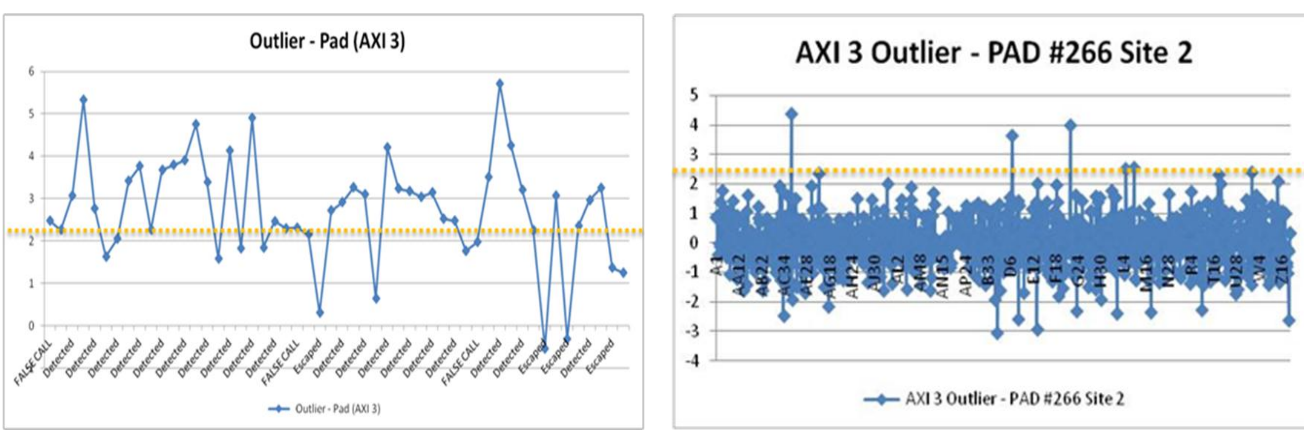
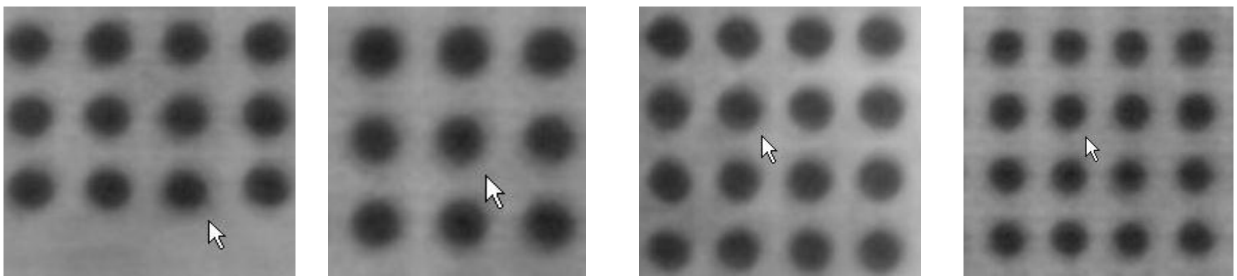


Figure 5. AXI 3 "Open Outlier" Measurement Data for Pad Slices from Site 2 (Board #495 & #266)

Table 6. Test Summary with AXI 3

Site	# of Total Escaped Defects	Defects Escaped %	# of Total False Call	False Call PPM
1	13	27.66%	9	4425
2	7	14.89%	12	5900
3	5	10.64%	7	3441
4	8	17.02%	12	5900

The AXI 3 images for detected HIP, escaped HIP and false calls are shown in Figure 6. There is no very clear difference between good and HIP pins similar to AXI 1, and AXI 2. It is not easy for operators to indentify real defective HIP defects based on these images from the repair station. Therefore we should be very carefully to set Threshold correctly to detect HIP. We prefer to detect some HIP without high rate of false calls on one BGA especially for large volume production line based on current AXI capabilities.



L13(detected) R15(detected) G32 (escaped) T20 (false call)

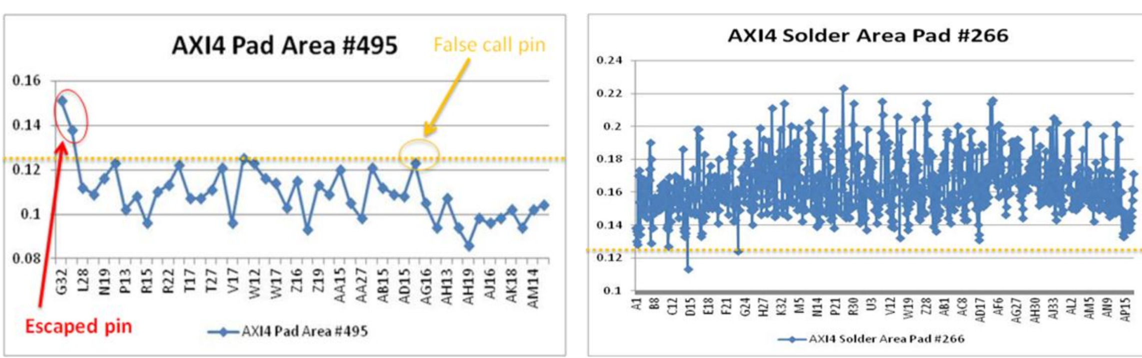
Figure 6: AXI 3 Images of detected HIP; escaped HIP, and False Call Pin (Board #495)

D. AXI 4 (Tomosynthesis)

AXI 4 uses Tomosynthesis technology also. Its resolution can be adjusted per different package or solder joints. We had test data from three sites with little fine tuning for the program. The AXI 4 main Algorithm Thresholds for detecting HIP are listed in Table 7. Similarly, different Algorithm Thresholds for two boards are adjusted to detect HIP effectively.

Table 7. Algorithm Thresholds with AXI 4

Site	Algorithm	Threshold	Note
2	Solder Area Pad	< 83% ; >130%	< 0.129 or < 0.144 mm^2
3	Solder Area Pad	< 70% ; >130%	< 0.125mm^2
4	Solder Area Pad	< 70% ; >130%	< 0.130mm^2 ; < 0.142 mm^2

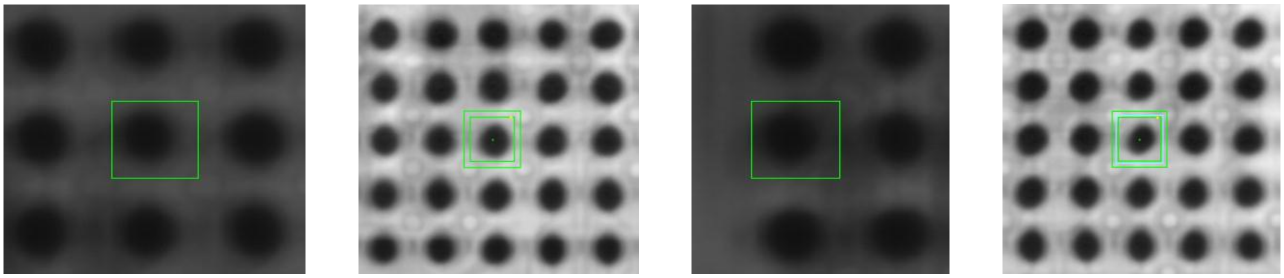


Board #495 with partial pins Board #266 with all pins

Figure 7. AXI 4 "Solder Area" Measurement Data for Pad Slice from Site 3 (Boards #495 & #266)

Figure 7 shows AXI 4 measurement Solder Area at pad level for detected pins, escaped HIP pins, and false call pins for board #495; and all pins for # 266. At Site 3, with the settings listed in Table 7, AXI 4 detected two HIP pins (no escaped) for board

266 without any false call; and detected 43 HIPs (escaped 2 HIP) with one false call for board # 495. The two escaped and one false call images are listed on Figure 8. As other AXI machine, there is still no very clear difference between good and detective HIP pins as shown in Figure 8.



R15 (detected) G32 (escaped) L13 (escaped) AD31 (false call)

Figure 8: AXI 4 Images of detected HIP; escaped HIP, and False Call Pin (Board #495)

Table 8. Test Summary with AXI 4

Site	# of Total Escaped Defects	Defects Escaped %	# of Total False Call	False Call PPM
2	2	4.26%	4	1967
3	2	4.26%	1	492
4	1	2.13%	4	1967

Table 8 listed the test summary from each site with AXI 4 which has better performance than AXI 1 for both detection percentage and false call.

Comparison and Improvement

All four AXI machines have capability to detect BGA HIP defect with different success levels. The AXI performance is based on program Algorithms, its thresholds' setting, and machine testing conditions. We also collected data for Gage R&R from these AXI machines from the different sites. The Gage R&R for BGA ball diameters are less than 30% for all AXI machines. The Gage R&R for middle ball diameters are less than 10% for some AXI machines. However the Gage R&R for Open outlier, Solder area, Neighbor outlier are not what we expected because most of them are at the boundary level: around 30%. This is why AXI testing results are not repeatable. For example, please refer to the AXI 1 test summary shown in Table 9. There are nine test cycle results with board # 266 and #499 at AXI 1 machine in our manufacturing (Table 9). It is easy to see the difference of AXI 1 test results with the same Algorithm Thresholds settings (Pad < -3 as defect; Mid Ball > 2 as defect).

Table 9. Testing Summary with AXI 1

# of Testing	Board #266 has 2 HIP pins					Board #495 has 45 HIP pins			
	AXI 1 Results	Detected HIP	Escaped HIP	False calls		AXI 1 Results	Detected HIP	Escaped HIP	False calls
1	7	1	1	6		28	18	27	10
2	7	1	1	6		32	18	27	14
3	10	1	1	9		29	17	28	12
4	9	2	0	7		29	18	27	11
5	8	1	1	7		31	17	28	14
6	12	1	1	11		30	18	27	12
7	11	2	0	9		31	18	27	13
8	8	1	1	7		30	18	27	12
9	8	1	1	7		28	18	27	10

Current AXI technology still has plenty of room for improvement in detecting HIP due to its hardware and software limitations. So, what can we do in order to optimize the AXI HIP detection capabilities? In Flextronics, we share our best practice from site to site; such as this project, we suggest setting these Algorithm Thresholds settings (Pad < -3 as defect; Middle Ball > 3 as defect) as a start, then look at the measurement data to adjust according to the process. We also share our experience with AXI vendors, and provide feedback to them as well as working together with them for better and improved AXI performance.

Table 10 listed below uses two subtypes for this BGA due to two different types of pad on the board: pad diameter is 19 mils for inner balls, and 21 mils for outer balls on BGA. For AXI 1, we have reduced HIP escaped number from 27 to 15 with the same false calls; for AXI 4, we have reduced false call number from 4 to 1 with the same defects escaped. This best practice shows good results with the two different AXI machines.

Table 10. AXI 1 and AXI 4 Test Summary with 1 and 2 Types Algorithm Threshold Settings

Site	AXI	Type of Algorithm Threshold	# of Total Escaped Defects	Defect escaped %	# of Total False Call	False Call PPM
2	AXI 1	1	27	60.0%	7	6883
2	AXI 1	2	15	33.3%	7	6883
4	AXI 4	1	1	2.2%	4	3933
4	AXI 4	2	1	2.2%	1	983

In order to verify our AXI / 2DX results, we performed 3D CT Board Level X-Ray Inspection (Limited Angle Computer Tomography). This is a novel technique permitting areas of a very large board to be examined using 3D CT without cutting the board. Figures 9-12 show the CT images and results. Figure 9 demonstrates clearly that pin G32 has a 9 micron crack. This potentially critical defect was identified with offline 2D X-Ray (2DX image, Figure 1) and confirmed using large board CT. However none of the AXI machines detect it as defect.

There are varying types of HIP defects with different size and shape as shown in Figures 10 and 11. All current AXI machines have capabilities to detect HIP N30 shown on Figure 10, however not all machines detected HIP pins Z15, AA 15, and AB15 (Figure 11). Laminography AXI 1 machine detects HIP type defects as pin AB15; however it is challenging for AXI 1 to detect HIP type as Z15. Tomosynthesis AXI machines do not easily detect HIP type as AB15.

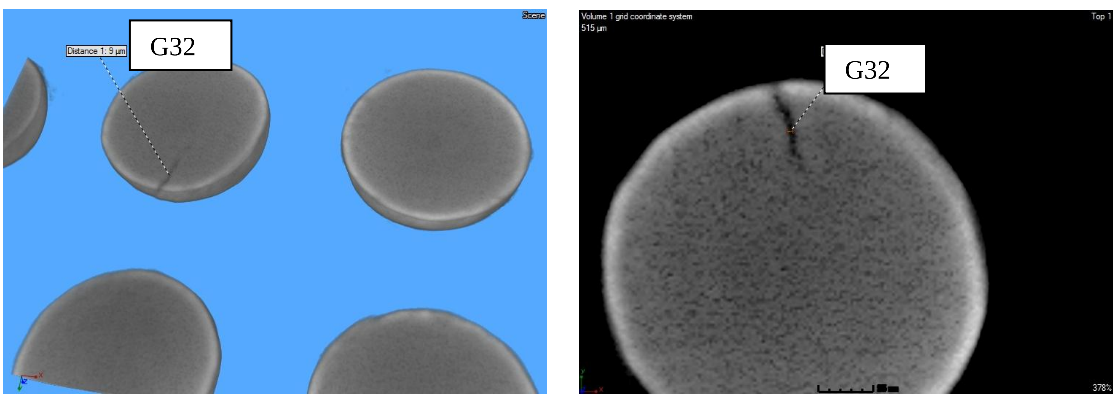


Figure 9. CT Image for BGA Crack with 9 µm

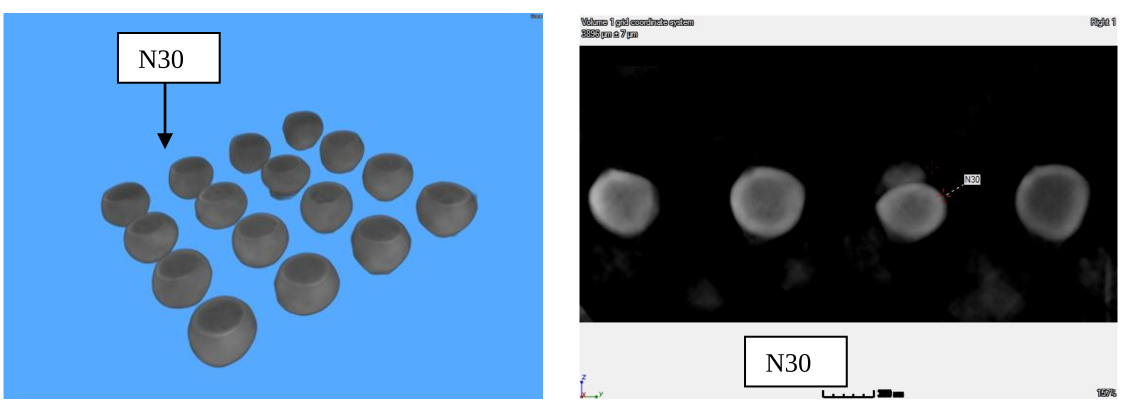


Figure 10. CT Images for HIP N30

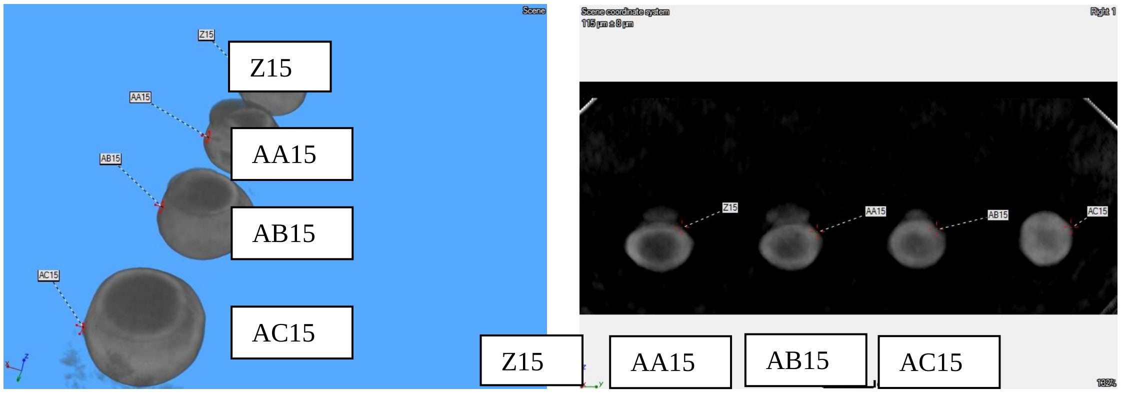


Figure 11. CT Images for HIP (AB15, Z15 and AA15), AC15 is good.

Summary

- Current AXI has capabilities to detect some HIP with right Algorithm threshold settings. The Tomosynthesis technology looks better than Laminography technology for detecting HIP as the Tomosynthesis technology are utilizing digital technology as compared to the analog Laminography technology.
- The Algorithm threshold settings are very critical for detecting HIP. The false call number has to be reasonable for the production line. The AXI program optimization is based on its measurement data analysis.
- There are no clear image differences between good solder joint and HIP with current AXI machine, especially for HIP type defect AA15 shown as in Fugue 11. Therefore we have to have good balance between HIP defect escaped and false call.
- We are looking forward to see AXI machine with more accurate and repeatable measurement data, and better image separation between good solder joint and HIP pins.
- 2DX and Large Board CT are very important techniques used to verify the AXI results and fine tune the algorithms.

Reference

1. Zhen (Jane) Feng, Juan Carlos Gonzalez, Evstatin Krastev, Sea Tang, and Murad Kurwa, “Non-Destructive Techniques for Identifying Crack Defect in BGA Joints: TDR, 2DX, and Cross-section/SEM Comparison”, SMTA Proceeding, August, 2008.
2. Jennie S. Huang, “Can Microstructure Indicate a Good Solder Joint? Part III”, SMT Magazine, October, 2012.
3. Flextronics ATG, “CT versus AXI with HIP”, project is ongoing, Oct., 2012

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