Agilent Medalist 5DX, X-ray Inspection

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Selcom Evaluates Agilent 5DX and Open Outlier Technology with and without Oval Pads

Selcom Group, a large European contract electronics manufacturer (CEM), first began using the Agilent 5DX Automated X-ray Inspection (AXI) system in 1996 to improve process control and defect detection on increasingly complex printed circuit board assemblies (PCBAs). From the start, Selcom got good results with the Agilent 5DX, which proved effective in testing a wide variety of SMT components while helping the CEM meet production goals for improving process control, isolating defects and accelerating repairs.

However, the increasing popularity of ball grid arrays (BGAs) created a new challenge for Selcom. BGAs have a high number of hidden solder joints, so the ability of AXI to detect marginal and open BGA joints was limited in early versions of the Agilent 5DX. The introduction of 5DX system software revision 8 in 2002, which included Agilent's Open Outlier technology, solved many of the earlier limitations of the system, and held the promise for improved BGA coverage using AXI.

Agilent Technologies

In a bid for constant quality improvement, Selcom designed a study to evaluate the effectiveness of Agilent's Open Outlier technology when combined with traditional circular test pads and various sizes of oval test pads. The study was conceived, designed and conducted as a design-for-test study, so experiments were conducted in a controlled environment rather than a production environment. The study produced valuable data for Selcom, who learned that Agilent's Open Outlier technology combined with oval test pads has the potential to provide the most effective combination for testing BGAs.

Introduction

Prior to the introduction of Agilent's Open Outlier technology, the Agilent 5DX could quickly detect macroscopic defects such as shorts between solder balls, missing or misplaced components, large voids and more. But, like other X-ray technologies, the 5DX had limited capability for accurately detecting reflow problems such as BGA opens, one of the most critical types of defects to detect on today's complex PCBAs. Opens are a common problem for visual inspection systems: while the 5DX can easily “see” the difference in diameter between good joints and open joints, it was difficult, prior to the introduction of Open Outlier technology, to identify when those differences were significanti.e., legitimate opensversus when they were simply part of the normal variations in the manufacturing process.

The Challenge

Figure 1 demonstrates the magnitude of the challenge for AXI in visualizing solder opens on BGAs. This diagram plots the diameter of all solder balls within a package that has 369 pins. The red data point is a known defect, an open solder joint. Prior to the development of Open Outlier technology, the 5DX would attempt to separate good joints from defective joints by making a judgment on the diameter of each and every solder joint. Note how hard it would be to identify the red pin as defective: its diameter of 33 mils is well within the high and low range of all of the other good joints on the board, which range from under 28 mils to over 36 mils. This known defective joint could not have been detected by older 5DX technology.

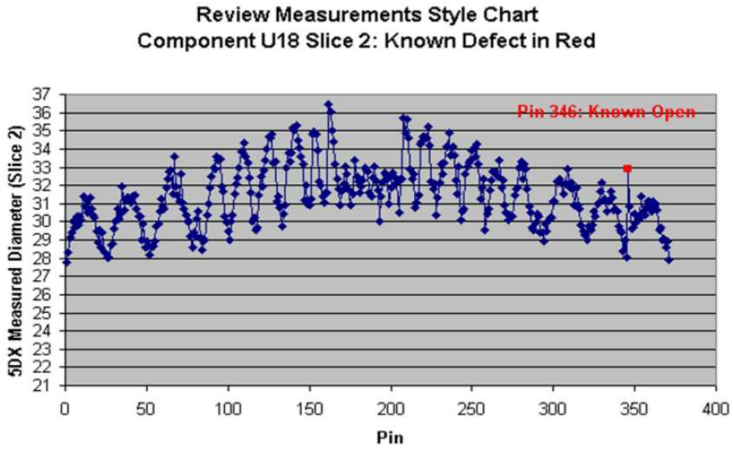

Fig. 1. Plot of ball joint diameters. Known open is in red.

Mechanism #1: Open Outlier Technology

Open Outlier technology took the first step in addressing the problem. It takes a micro view rather than a macro view: rather than looking at all ball diameters across the package, it evaluates small sections of a board, so each solder joint in the test section is compared to the joints around it (figure 3). This “near neighbor analysis” is much more effective than a macro analysis of all ball joints on a board.

Near neighbor analysis achieves good test coverage and improves the accuracy of defect calls by accounting for normal variations in solder, packages and boards across a production line (figure 2). Since solder joints are compared to their closest neighbors, anomalies in solder ball diameter are more obvious. Anomaliesjoints that are significantly different from their neighborsrepresent true defects that must be repaired; joints that fit into a progression of steadily increasing or decreasing diameters are passed as “good ” joints, regardless of individual diameter. In other words, by using near neighbor analysis, Open Outlier technology can correctly ignore large-diameter solder balls that are part of a steady pattern of large-diameter solder balls in that region of the board. At the same time, it can accurately flag large-diameter solder ballsopensthat demonstrate a sudden variation in diameter, and thus don't fit the pattern of the nearest neighbors.

This technique makes use of the unique capabilities of the Agilent 5DX to measure every joint in comparison to its neighbors, whether in the center, corner, or edge of the component. Once the “expected ” diameter size is subtracted from all joints, the remaining number can clearly pinpoint anomalies that represent solder opens.

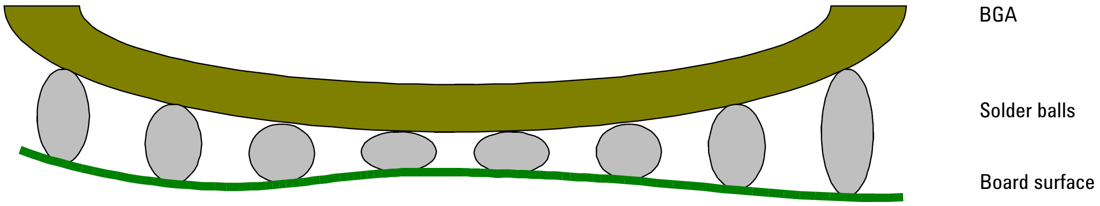

Fig. 2. Solder ball diameters tend to fluctuate across regions of a board or package. For example, if a board is warped in a certain way, the diameters of ball joints in one part of a board will differ from diameters in another part of the board. This diagram exaggerates the effect of warping to show how “good” joints can have varying diameters across a board.

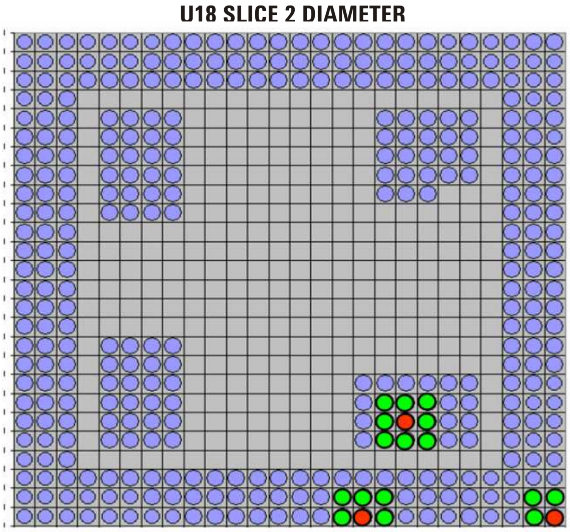

Fig. 3. Open Outlier technology uses “near neighbor analysis” to measure one solder joint in relation to its nearest neighbors, negating the effects of board warp, package warp, or process variations. Analysis is localized, so anomalies within a certain region are easier to spot.

Mechanism #2: Oval Pads

Another possible solution to the problem of detecting BGA opens involves the use of oval rather than circular pads. Oval pads represented a leap in creativity on the part of Selcom. The idea was to change the shape of pads so that, during reflow, wet solder will have one shape when it makes contact with a pad, and have a significantly different shape if it does not make contact. In the case of oval pads, wet solder will acquire an oval shape when it makes contact but will retain a circular shape if it does not make contact. This makes it easy for repair operators to differentiate between good (oval) and open (circular) solder joints, so they can quickly verify defect calls from the X-ray system (figure 4).

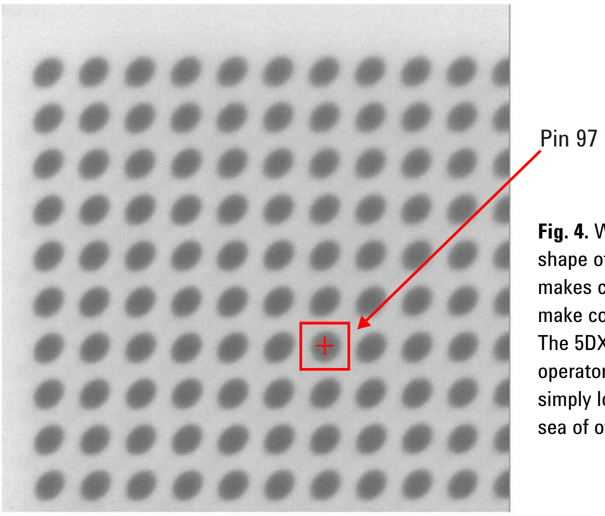

Fig. 4. Wet solder takes the shape of the oval pad when it makes contact. If it doesn't make contact, it stays round. The 5DXas well as repair operatorscan spot opens by simply looking for circles in a sea of ovals.

Study Design

For AXI to accurately identify oval versus circular pads in board test, the shapes must be translated into numerical values. So Selcom used the “flattening open signal,” which is part of the 5DX's BGA Open Algorithm threshold, to differentiate between oval and circular shapes (figure 5).

The flattening calculation puts a quantifiable value on oval versus round shapes. The more oval the shape, the higher the numerical value; the more circular the shape, the lower the numerical value. Using this calculation, the 5DX is able to effectively measure pad shape during test. The 5DX ignores pads that have a high flattening signal, indicating an oval or “good” joint; it detects pads that have a low flattening signal, indicating a round or open joint.

In designing this study, Selcom evaluated various sizes of oval pads to determine the optimum ratio between X and Y axes. This degree of ovalization is important from a test perspective: the more oval the shape, the easier it is to distinguish from a round shape, so the accuracy of test is improved. However, there is a point of limited test returns when defining the size of oval pads. Also, pad size has implications for the robustness and durability of solder joints (sidebar) as well as for overall board design. Considerations include:

- Durability: the strength of joints depends in part on the size of the pads used. If pads are too small, shear strength is compromised and joint integrity can be reduced.
- Board design: The ability to fit vias, traces and test points on the boards is affected by board occupancy. If pads are too large, board design is affected.
- Testability: If the degree of ovalization is too slight, then oval pads will be harder to distinguish from round open joints, so test system accuracy will be compromised and false calls might increase.

In conducting this study, Selcom induced defects on a variety of test PCBs by coating selected pads with a thin layer of solder-resistant material. This prevented joints from forming properly. The boards were then sent through reflow, and Selcom analyzed how many induced defects were caught by Open Outlier alone, how many were caught by flattening/oval techniques alone, and how many were caught by both mechanisms together.

Fig. 5. Flattening Calculation

The flattening calculation is simply “1 minus the ratio of the axis.” So the theoretical F value for a joint is:

F = 1 m/M
(where “F” is flattening, “m” is the minor axis of the oval, and “M” is the major axis of the oval).

For example: on oval pads that have a minor axis of 24 mils and a major axis of 40 mils, the flattening signal for a perfectly formed oval joint would be:

F = 1 24/40 = **0.4**

But the flattening signal for a round or “open” joint would be:

F = 1 d/d = **0.0**
(where “d” is the diameter of a round joint whose minor and major axes are the same).

The difference between 0.4 and 0.0 mils is highly visible to the 5DX, making opens detection simple and effective.

Results

Oval Pads: Size Matters

As expected, pad size and the degree of ovalization proved to have a dramatic effect on testability in AXI. In plotting the flattening signals across all joints (Figure 6), the 5DX was able to clearly identify six open pins whose values were near zero. In this example, good joints on a test board with 24x40 oval pads have an average flattening signal of about 0.3 mils, so this level of ovalization (24x40) proved to create a dramatic separation between good and bad joints.

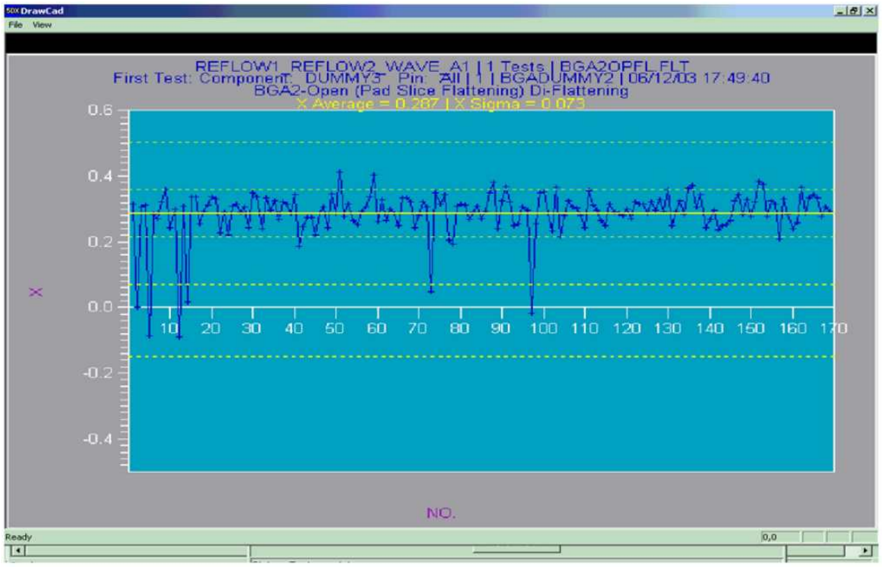

Fig. 6. Flattening signals show a dramatic separation between good joints (average value around 0.3 mils) and open joints (value near 0.0). Oval pads make opens easier to see with AXI.

A pad with a smaller degree of ovalization, say 35x40 mils, would still show a difference between good and bad joints, but the difference would be less pronounced. In such a case, a good joint would have a flattening signal of about 0.125 (1 35/40 = 0.125) and an open joint would still be at or near zero. There would be less separation between oval and round, good and bad, making bad joints harder to visualize with AXI.

At the same time, the test showed that elongated pads with a greater degree of ovalization at 24x47 mils did not materially improve test accuracy beyond the 24x40 mil pads. In terms of ovalization, 24x40 mil pads appear to be the ideal size.

Oval vs. Round: Oval Wins

A variety of component types were tested with and without Open Outlier technology and with and without oval pads (Figure 7). The study suggests that oval pads improve the accuracy of AXI, especially when used in combination with Open Outlier technology.

Component Type	Pad Type	# Defects Created	# Open Outlier Detected Defects	# Flattening Detected Defects	Total # of Detected Defects (open outlier OR flattening)	Total Effectiveness %
BGA 169 pin, pitch 1.5mm, ball 29,5 mils	Circular 24 mils	10	9	N.A	9	90
	Oval 40x24 mils	10	10	10	10	100
	Oval 47x24 mils	10	10	10	10	100
BGA 225 pin, pitch 1.5mm, ball 29,5 mils	Circular 24 mils	10	8	N.A	8	80
	Oval 40x24 mils	10	9	10	10	100
	Oval 47x24 mils	10	9	10	10	100
BGA 484 pin, pitch 1.0mm ball 23,6 mils	Circular 16mils	15	12	N.A	12	80
	Oval 23x20 mils	15	14	N.A	14	93
BGA 208 pin, pitch 0,8 mm ball 17,7 mils	Circular 14 mils	19	15	N.A	15	79
	Circular 16 mils	19	16	N.A	16	84

On a 169-pin BGA:
- With round pads of 24 mils, Open Outlier technology alone caught 9 of 10 defects for a test effectiveness of 90%.
- With 40x24 oval pads, Open Outlier technology alone caught 10 of 10 defects, and the flattening algorithm alone caught 10 of 10 defects, for 100% test effectiveness with either technology.
- With 47x24 oval pads, Open Outlier technology caught 10 of 10 defects and the flattening algorithm caught 10 of 10 defects, for 100% test effectiveness with either technology.

On a 225-pin BGA:
- With round pads of 24 mils, Open Outlier technology caught 8 of 10 defects for 80% test effectiveness.
- With 40x24 oval pads, Open Outlier technology caught 9 of 10 defects for 90% test effectiveness. Flattening caught 10 of 10 defects for 100% test effectiveness.
- With 47x24 oval pads, Open Outlier technology caught 9 of 10 defects for 90% test effectiveness. Flattening caught 10 of 10 defects for 100% test effectiveness.

On a 484-pin BGA:
- With round pads of 16 mils, Open Outlier technology caught 12 of 15 defects for 80% test effectiveness.
- With 23x20 oval pads, the ovalization was too small to allow the flattening signal to provide good differentiation between good and bad joints. Open Outlier, however, caught 14 of 15 defects for 93% test effectiveness.

On a 208-pin BGA:
- With round pads of 14 mils, Open Outlier technology caught 15 of 19 defects for 79% test effectiveness.
- With round pads of 16 mils, Open Outlier technology caught 16 of 19 defects for 84% test effectiveness.

Conclusions

- By itself, Open Outlier Technology provides test effectiveness of greater than 80%, sometimes better than 90%.
- The combination of Open Outlier Technology and flattening signals on oval pads provides the highest level of test effectiveness with the Agilent 5DX.
- The combination of oval pads and Open Outlier technology also improves repair effectiveness since repair operators can more easily confirm defects. Oval pads create a nice visible separation, so operators can visually differentiate between oval (good) and round (open) joints.
- A ratio of 1.6 between the minor and major axes is adequate for defect detection. A ratio of 24x40 provided 100% defect coverage in this test. An elongated pad with a ratio of 24x47 did not improve coverage.
- Both Open Outlier Technology and flattening signals are extremely accurate mechanisms for defect detection. No false calls were found during the test.
- Open Outlier Technology appears to have a better success rate with oval pads vs. circular pads. This is most likely due to the larger surface area of oval pads.

Caveats: This was a design-for-test study, not a production study. It was intended to compare solutions in a controlled environment and evaluate their potential application in a production environment. The controlled environment had significant differences from a production setting, including:

- Tests were carried out on prototypes, not production boards.
- Boards were single-sided, so the AXI system did not have to contend with shading. No voiding effects were present after the reflow process.
- Defects were intentionally induced, and are therefore different from real-world production defects.
- Defects were in known positions to help with program debug.

Durability of Oval Pads

Pad size has a direct effect on joint strength, so a switch from circular to oval pads is not taken lightly by board designers. In the paper A Study of High Density and Reliability BGA Package with Solder Ball Lands of Oval Type by S. J. Kim, C. H. Lee and S. G. Lee, the robustness of circular and oval pads was compared and quantified.

The following table shows the results of shear strength tests conducted over hundreds of thermo cycles. The BGA used in the test had solder balls of 0.76 mm mounted on circular pads of 0.635 mm in diameter and on elongated pads of 0.764 x 0.47 mm.

Measures of shear strength were obtained using Keller Technology's Bond Test-30. The thermo cycles were executed according to the level C of the JEDEC A104-A Standard (-65°C/150°C). X is the minor axis and Y is the major axis.

T/C	Ball Shear Strength (g)		
	Circular	**Oval -X**	**Oval -Y**
0	1650	1747	1683
100	1578	1637	1552
200	1516	1619	1514
300	1512	1570	1493
400	1489	1561	1450
500	1451	1552	1405

Results of the study showed an increase of 7% in shear strength along the minor axis and a decrease of 3% along the major. In general the strength of this oval pad is at least equal to if not greater than the circular pad.

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