Analysis of AXI Test on Fine Pitch Components between Lead Free and Tin/Lead Assembly

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Abstract
By now, most people in the industry understand how complex it is to convert a factory from using a Tin-Lead (Eutectic) Solder process to a Lead Free process. The implementation of this change requires more than just developing a new process to replace the current one that companies have spent years optimizing. The Lead Free implementation also brings up a new challenge in calibrating and adjusting the equipment on the production lines to optimize their performance with the Lead Free process[1]. For several years now, Flextronics has been using Automated X-ray Inspection (AXI) as effective test equipment for the inspection of PCBA solder quality, as well as a process improvement tool. By analyzing the variable measurements provided by AXI, Flextronics has been able to improve the SMT process[2-3]. Recently, Flextronics wanted to determine if there was any difference in the AXI measurements of Lead Free and Tin-Lead solder joints. In order to do so, a Flextronics team used AXI to measure two types of solder or "Test Vehicles:" a Test Vehicle that consisted strictly of Lead Free solder joints/processes and a Test Vehicle that consisted strictly of Tin/lead solder joints/processes. Testing was conducted under two different "Test Conditions." This phrase refers to the manner in which the equipment was calibrated. Under Test Condition #1, the AXI machine was calibrated with a Lead Free Calibration and Adjustment (C&A) panel. Under Test Condition #2, the AXI machine was calibrated with a Tin/Lead C&A panel.

The objective of this study was to:
(1) Assess the current AXI Gage Repeatability & Reproducibility for Lead Free Test Vehicle with Lead Free Test Condition.
(2) Compare and correlate several measurements, including BGA Ball diameter, BGA Ball Thickness, Fine Pitch Gullwing Heel Thickness, Center Thickness, and Fillet Length, and Resistor 0402 Pad Thickness, for the two types of Test Vehicles (Lead Free and Tin/Lead) under both the Lead Free and Tin/Lead C&A Calibration Test Conditions.

The Test Vehicle boards contained 12 BGAs and two FPGullwing devices with a pitch size of 16 mils. More than 240,000 data points were collected for the study. We analyzed the data collected for BGA diameter, BGA Thickness, Fine Pitch Gullwing Heel thickness, Center thickness, and Fillet Length, and Resistor 0402 pad thickness using the SPC tool MINITAB and its Mood's Median Test tool. The results showed a statistical difference for most of the measurements under both test conditions, Lead Free and Tin/Lead C&A**.** The majority of the differences for the measurements averaged in the range of 5% to 10% for the same type of Test Vehicle boards under the different Test Conditions.

The AXI test results not only report attribute data; it also provides variable data (the actual numerical measurements). With the variable data obtained from this automatic test method, the AXI can be used as a good SMT process improvement tool, as well as a tool for process defect detection. The variable data has been used to help Flextronics effectively control its SMT processes. Based on our studies, we found that it is better to test Lead Free or Tin/Lead product boards with corresponding test condition. For example, the FPGullwing average open signal of a Lead Free board using Test Condition #2 should be 16.5% higher than when using Test Condition #1. The FPGullwing average open signal of the Tin/Lead board using Test Condition #1 should be 15.5% lower than when using Test Condition #2.

Introduction
In recent years, the use of Automated X-ray Inspection (AXI) for printed circuit board inspection has continued to grow in manufacturing, especially on high-density/high complexity boards. AXI system can detect most solder-related defects, including shorts, excess solders, misalignment, voids, insufficient solder, open/lifted solder joints, and marginally accepted joints, which pass ICT/Functional Test but often result in Field Returns. Lead Free and Tin/Lead are different materials, and their grey level, or x-ray images, are different at AXI system due to their composition. Lead Free solder joint defects were detected by AXI as shown in Figure 1. One of the frequently asked questions is, "What is the difference of the measurement data between Lead Free and Tin/Lead assembly?" To determine the answer, we completed an experiment with Lead Free test vehicle, and Tin/Lead test vehicle under Test condition #1 (Lead Free C&A panel) and Test condition #2 (Tin/Lead C&A panel).

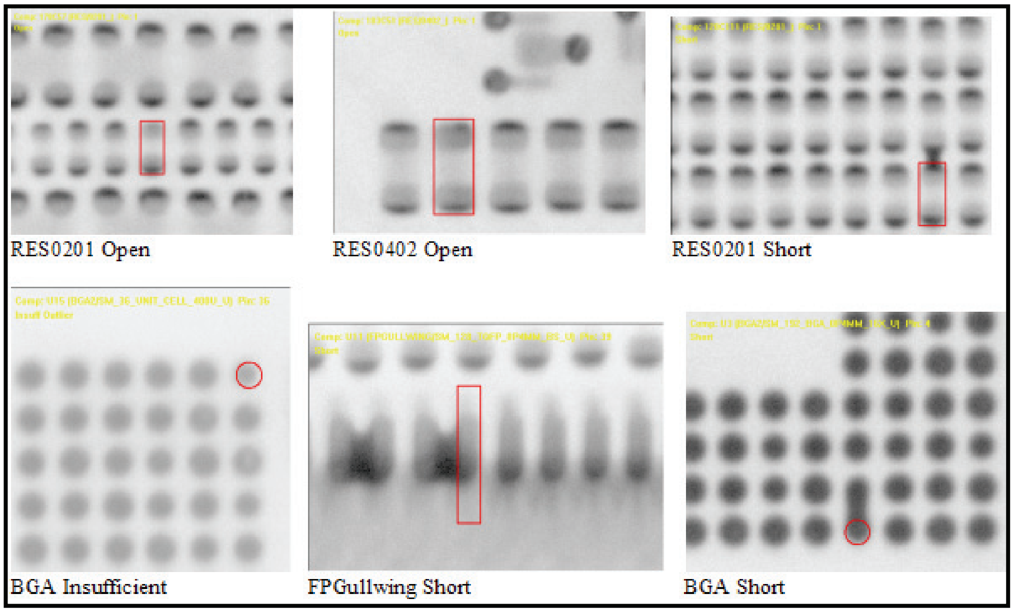

Figure 1 - Lead Free solder defects were detected by AXI

Experiments and Analysis

The Flextronics test vehicle board (Figure 2) was chosen for this experiment. The thickness of the board was 1.2 mm with Organic Solder Preservative (OSP) surface finish. We collected measurements for 12 CSP components, two FPGullwing, and 443 resistors (0402) for measurement comparison (see Table 1 for more information on selected components). The characteristics of Lead Free and Tin/Lead solder are listed in Table 2. The Lead Free solder TLF-93-206 is from Tamura. All experiments were performed using an Agilent 5DX Series 3 system.

Table 1 - Tested Components Information

Location:	Part Name	I/O	Pitch
U3,U13	CSP-Amkor	192	.4mm
U4,U14	CSP-Amkor	288	.4mm
U5,U15	CSP-Unitive	36	.4mm
U6,U16	CSP-Unitive	144	.4mm
U7,U17	CSP-Unitive	324	.4mm
U10,U20	CSP-M2CSP	340	.5mm
U1, U11	FPG	128	.4mm

Table 2 - Characteristics of Lead Free and Tin/Lead Solder

Item	TLF-206-93F	AIM NC 251
Alloy composition	Sn95.5/Ag3.9/Cu0.6	Sn62/Pb36/Ag2
	Tin 84.4%	Tin 54-60%
	Silver 3.5%	Lead 32-35%
	Copper 0.5%	Ag 2%
Melting point	216-221^{o}C	179 ^{o}C
Boiling point	>250^{o}C	N/A
Particle size of solder powder	20-41 10^{-6}m	45 10^{-6}m
Flux content	Modified rosin, Glycol ether 11.6%	Rosin 1-5%
Density	Approx. 4.2g/cm^3 (at 20^{o}C)	8.421g/cm^3
Viscosity	200Pa•s	350-1200KcPs

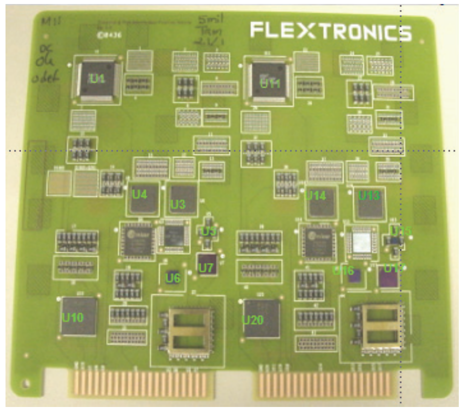

Figure 2 - Test vehicle

Gage R &R Study

The team understands that one of the weaknesses of AXI is the consistency of its results. Defect numbers are not the same when the same board is tested on the same AXI system several times for Tin/Lead assemblies. Therefore, we wanted to see how the Gage Repeatability & Reproducibility would differ for Lead Free solder joints. We tested one board with three operators, and the tests were repeated three times by each operator. The AXI machine was calibrated with Lead Free C&A panel first. We chose 30 pins for data analysis on the specific components (BGA, FPGullwing, RES0402) with SPC tool MINITAB. Figure 3 shows the Gage R & R results for the BGA diameter from MINITAB. The standard deviation [StdDev(SD)] for a source is the square root of the variance component for that source. Study Var is six times the standard deviation for a source, which means the calculation is based on 6 σ. The % Study Var is the % study variation, which estimates how well the measurement system performs with respect to the overall process variation and is independent of the Tolerance. The % Tolerance (SV/Toler) is the Precision/Tolerance (P/T) ratio that is appropriate for evaluating how well the measurement system can perform with respect to the specification, which is dependent on the Process Tolerance. We use the specification tolerance ± 20% for the BGA diameter. The total Gage R&R is 10.84 for the % Tolerance (SV/Tolerance).

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0065536	17.22
Repeatability	0.0062425	16.40
Reproducibility	0.0003111	0.82
Operator	0.0003111	0.82
Part-To-Part	0.0315106	82.78
Total Variation	0.0380642	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0.080954	0.48573	41.49	10.84
Repeatability	0.079010	0.47406	40.50	10.58
Reproducibility	0.017637	0.10582	9.04	2.36
Operator	0.017637	0.10582	9.04	2.36
Part-To-Part	0.177512	1.06507	90.99	23.76
Total Variation	0.195101	1.17060	100.00	26.11

Figure 3 - Gage R & R of BGA U3 diameter

We input different specification tolerance numbers (± 20% to 65%) into MINITAB for Gage R & R and wanted to have the total Gage R & R number less than 30% as shown in Table 3. We expected that Gage R&R results would be less than 30% with tolerance ± 20%. In Table 3, the reproducibility variations are less than 10% for all joint parameter measurements that were taken. However, the repeatability variation showed good results only for BGA diameter mils, BGA thickness, FPGullwing Fillet Length and resistor pad solder thickness with tolerances less than 30%. The results of the Gage R&R for BGA voiding percentages, FPGullwing Heel Thickness and Center Thickness needs improvement. The results are not surprising since all our experiments for Tin/Lead showed that the repeatability of measurements for these particular components was not a strength for the AXI system. The BGA voids of the Lead Free test vehicle are very small with diameter less than 5 mils. It has not been proven that AXI can detect voids this small in size. For this particular size BGA, AXI can detect voids that do not meet IPC 7095 Standards. Therefore, some false calls are expected from AXI. We use a transmission X-ray as a complementary tool to verify these small size BGA voids.

Table 3 - AXI Gage R & R for Lead Free solder Joint with Tolerance ± 20% to 65%

% Tolerance (Study Variation / Tolerance)							
(SV/Toler)	BGA Diameter	BGA Thks	Void Percentage	FPG Heel Thks	Center Thks	Fillet length	RES Pad Thks
Total Gage R&R	10.84	28.66	29.07	30	28.43	22.36	19.81
Repeatability	10.58	28.2	28.96	29.27	27.66	21.33	18.87
Reproducibility	2.36	5.09	2.5	6.55	6.57	6.72	6.05
% Of Tolerance	20	25	65	50	40	20	20

Lead Free Test Vehicle Study

The team measured 12 BGAs (2648 pins) from nine Lead Free Test Vehicles with Test condition #1 (Lead Free) and #2 (Tin/Lead). The 47664 data points were for BGA diameter measurement, and another 47664 data points were for BGA thickness. We used MINITAB Mood Median test for the analysis with 95% confidence level. If P <0.05, there is statistical difference; If P>= 0.05, there is not statistical difference. Most BGA diameter measurements appeared different with different test conditions except U10, U20, and U15. U10 and U20 were the same package type with a pitch size 0.5mm. The rest of the BGAs were of a pitch size of 0.4 mm. [NOTE: U5 (P=0.041) and U15 (P=0.157) have only 36 pins]. By calculating the percentage difference, we concluded that the measurement data collected under Test condition #1 was almost the same as that collected under Test condition #2. The average difference observed was –0.62% by using equation 1. The difference of other parameter is given using this equation in this section. All BGA thickness measurements were statistically different under Test condition #1 versus #2. The measurement data with Lead Free test condition #1 was larger than with Tin/Lead test condition #2. The average difference was 5.09% with different test condition. The smallest is U3 with 1.43%, and the largest is U10 with 9.76%.

% Difference = 100 X (Average Test #1 - Average Test #2) / Average Test #2 ----- (Equation 1)

For FPGullwing, we tested two components with 256 pins for 9 boards. A total of 13824 data points were analyzed for Heel Thickness, Center Thickness, and Fillet Length measurement. The average measurement of Heel and Center Thickness is listed in table 4 and 5. The last column is the Grand Average and Stand Deviation respectively. With Mood's Median Test method of the SPC tool MINITAB, FPGullwing Heel Thickness, Center Thickness, and Fillet Length of Lead Free test vehicles were different under the different test conditions #1 and #2. The average difference of Test Condition #1 vs. #2 was 8.89%, and 7.35% respectively for the Heel Thickness and Center Thickness respectively. It is not surprising that the average of difference is –1.46% for the FPGullwing Fillet Length because different test condition should not affect to the fillet length measurement.

For the resistor, 7974 data points (joints) of 443 RES0402 components were analyzed with MINITAB. The resistor pad thickness was different under the different test condition. The average difference was 8.81% using equation 1 with different test conditions. It indicated that resistor pad thickness was larger with Lead Free Test condition #1.

Table 4 - FPGullwing Heel Thickness Average Under Lead Free Test Condition #1 and Tin/Lead Test Condition #1

Test Condition	Heel Thickness	LF2	LF3	LF6	LF7	LF8	LF10	LF13	LF14	LF20	Average	StDev
U1_L	Average	2.51	2.43	2.41	2.45	2.40	2.33	2.39	2.39	2.39	**2.41**	**0.05**
U1_L	StDev	0.19	0.20	0.22	0.19	0.17	0.18	0.28	0.28	0.23	**0.22**	**0.04**
U11_L	Average	2.50	2.55	2.51	2.52	2.43	2.45	2.49	2.49	2.45	**2.49**	**0.04**
U11_L	StDev	0.22	0.35	0.25	0.17	0.27	0.22	0.18	0.18	0.29	**0.24**	**0.06**
U1_LF	Average	2.71	2.49	2.63	2.69	2.68	2.59	2.68	2.60	2.64	**2.63**	**0.07**
U1_LF	StDev	0.23	0.21	0.18	0.21	0.18	0.22	0.22	0.23	0.24	**0.21**	**0.02**
U11_LF	Average	2.76	2.69	2.79	2.70	2.66	2.61	2.71	2.68	2.71	**2.70**	**0.05**
U11_LF	StDev	0.22	0.35	0.28	0.24	0.32	0.24	0.22	0.22	0.30	**0.26**	**0.05**

Table 4 - FPGullwing Heel thickness Average under Lead Free test condition #1 and Tin/Lead test condition #2

Test Condition	Heel Thickness	LF2	LF3	LF6	LF7	LF8	LF10	LF13	LF14	LF20	Average	StDev
U1_L	Average	2.51	2.43	2.41	2.45	2.40	2.33	2.39	2.39	2.39	**2.41**	**0.05**
U1_L	StDev	0.19	0.20	0.22	0.19	0.17	0.18	0.28	0.28	0.23	**0.22**	**0.04**
U11_L	Average	2.50	2.55	2.51	2.52	2.43	2.45	2.49	2.49	2.45	**2.49**	**0.04**
U11_L	StDev	0.22	0.35	0.25	0.17	0.27	0.22	0.18	0.18	0.29	**0.24**	**0.06**
U1_LF	Average	2.71	2.49	2.63	2.69	2.68	2.59	2.68	2.60	2.64	**2.63**	**0.07**
U1_LF	StDev	0.23	0.21	0.18	0.21	0.18	0.22	0.22	0.23	0.24	**0.21**	**0.02**
U11_LF	Average	2.76	2.69	2.79	2.70	2.66	2.61	2.71	2.68	2.71	**2.70**	**0.05**
U11_LF	StDev	0.22	0.35	0.28	0.24	0.32	0.24	0.22	0.22	0.30	**0.26**	**0.05**

Table 5 - FPGullwing Center thickness Average under Lead Free test condition #1 and Tin/Lead test condition #2

Test Condi	Center Thickness	LF2	LF3	LF6	LF7	LF8	LF10	LF13	LF14	LF20	Average	StDev
U1_L	Average	2.11	2.06	2.03	2.07	2.02	2.04	1.90	1.90	1.95	**2.01**	**0.08**
U1_L	StDev	0.15	0.13	0.13	0.13	0.15	0.10	0.17	0.17	0.15	**0.14**	**0.02**
U11_L	Average	2.11	2.06	2.04	2.13	1.98	2.08	1.94	1.94	2.01	**2.03**	**0.07**
U11_L	StDev	0.11	0.31	0.21	0.11	0.32	0.18	0.19	0.19	0.19	**0.20**	**0.07**
U1_LF	Average	2.18	2.14	2.20	2.22	2.19	2.22	2.16	2.07	2.08	**2.16**	**0.06**
U1_LF	StDev	0.22	0.15	0.11	0.13	0.18	0.13	0.15	0.15	0.13	**0.15**	**0.03**
U11_LF	Average	2.16	2.10	2.21	2.24	2.17	2.22	2.21	2.13	2.14	**2.18**	**0.05**
U11_LF	StDev	0.18	0.33	0.22	0.14	0.28	0.19	0.19	0.17	0.24	**0.21**	**0.06**

Tin/Lead Test Vehicle Study

Similar studies were completed with five Tin/Lead test vehicles. The difference between test condition #1 (Lead Free test condition) and test condition #2 (Tin/Lead test condition) was obtained using equation 2 in this section. The average difference of Tin/lead test vehicle was –0.14% and –7.05% for BGA diameter and thickness. The average difference was –8.85%, -6.25%, and 1.51% for FPGullwing Heel Thickness, Center Thickness, and Fillet Length respectively. The average difference of resistor pad thickness was –7.49% with test condition #1 and #2.

% Difference = 100 X (Average Test #2 - Average Test #1) / Average Test #1 -----(Equation 2)

Summary

AXI inspection is a powerful tool for process characterization during the transition to Lead Free solder. There is less than a 10% difference for both Lead Free and Tin/Lead test vehicles under different test conditions. Based on this study, to get accurate measurement data, it is recommended that each AXI machine is calibrated with either a Lead Free or a Tin/Lead C&A panel, in accordance with the Manufacturing Process being used, namely, Lead Free and Tin/Lead solder assemblies. We continue to use AXI measurement data to verify our Lead Free process, especially check BGA voids to optimize the profile.

Reference

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