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AOI in EMS

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Abstract
As outsource to EMS, the requirement for Automated Optical Inspection (AOI) equipment changes as well. Due to the diversity of the business, EMS providers require equipment that can handle a myriad of different components. The need for frequent programming, program portability and repeatability, and the establishment of common equipment platform become more important than before. To understand the capability of current AOI technology, equipment from four manufacturers were installed at a test site for a post-reflow benchmark test. Two test vehicles were used for eight different tests. Test results were recorded and analyzed. Each machine was rated for its performance in each individual test. The result shows that no single machine outperforms others in every category. The best performance from each category is, 99.89% portability for general SMT components, 99.95% for small chips, 99.16% for program repeatability, 84% defect detection rate, and 28-second inspection cycle time for motherboard type assembly. Angle measurement was performed on three machines. The model with best performance reported the measurement within 1° difference. Based on the overall test results, AOI can be considered an efficient tool for catching post reflow defect and improving process yield. As the renovation continues in AOI technology during the past few years, we should expect to see an increase in AOI implementation in the EMS industry.

Introduction

During the past decade, we have witnessed a rapid outsourcing trend in the electronics sector. In response to this growth, many Electronics Manufacturing Service (EMS) providers have expanded their presence from regional to global. This brings along many challenges. One of which is the ability to conduct a seamless transfer of the manufacturing process from a site where the product was introduced (commonly referred to as New Product Introduction (NPI) sites) to production sites in other parts of the world without any sacrifice in quality. Some EMS corporations adopt the common equipment approach to reduce turn around time. This way, they would be able to smoothly transfer manufacturing capacity to lower cost regions.

To guarantee the success of the common equipment process, one needs to ensure program portability; this means the ability to get the same results from the same program from a different machine of the same model regardless of where physically the machine resides.

Common equipment process also dictates the use of the same machine for high or low volume production. In a high mix low volume environment, the challenge for pick-and-place is on quick kit preparation and change over. For AOI, it is on false call rate decay and stabilization. A model suits a high volume motherboard assembly line may not be ideal for high-end server board. The trade-off has to be made based on priority.

As a service provider, an EMS has to provide service to multiple customers. This involves dealing with multiple component vendors and different component variations. To keep the false call rate down, AOI equipment has to be able to detect the differences between vendors, but also accept the variations. In other words, AOI has to be sensitive and flexible.

EMS is a very competitive business operating at very low profit margin. The work is extremely demanding because of the constant need to meet shipment deadline and quality requirement. As a result, time is a major concern and the ease of programming becomes a vital factor which impacts the bottom line. The turn over rate of manufacturing engineers is higher in EMS. As the duration of an engineer staying on the same position becomes shorter, the learning curve has to be reduced as well. Therefore, ease of programming becomes a key for a successful implementation.

In addition to these requirement changes due to the differences between the OEM and EMS environment, there are also fundamental AOI requirements, which are the same for both. Such as defect coverage, false reject rate, escape rate, program repeatability, inspection cycle time, and reporting utility.

To understand how the AOI equipment fit into EMS production environment as described above, an evaluation was planned and performed.

Objective and Methodology

The primary objective of this work is to search for an AOI technology best suited for general application in an EMS environment. The secondary objective is to understand the uniqueness of each approach required by different applications.

Based on the market research and trial runs conducted during the past three years, the plan is to invite a limited number of manufacturers to install machines in-production for a benchmark test. The machine has to be formally released to the market with stable performance. No software or hardware upgrade or modification is allowed during the test period.

All machines were under access control. The manufacturers were given the same amount of time for preparation. Test vehicle and tooling were distributed to each manufacturer according to prior released schedule; and test procedures were reviewed and accepted by all manufacturers. The inspection programs were prepared by the manufacturers and test data and calculation results were all checked and approved by them.

Based on the preset defect spectrum, all defects were populated before reflow by either modifying the SMT program or by removing solder paste manually. True defect list included defects from the defect spectrum and from the manufacturing process. Defects were verified by inspectors and AOI machines. ICT data was not available during the test period.

Four machines from different manufacturers were installed. Each manufacturer provides parallel training, one at the test site and the other at their US training center. The inspection program prepared in US was hand carried to the test site for program portability test.

Two test vehicles TV1 and TV2 were selected. There were five tests on TV2, which includes defect coverage, false reject rate, escape rate, repeatability, and inspection cycle time. TV1 has three tests; namely, program portability, inspection cycle time, and angle measurement.

It has to be emphasized that the test results and comments made in this paper pertain only to the two test vehicles used. Due to the limited fine tuning allowed during the test, the false call rate may be higher and defect coverage may be lower than what we would expect from normal production process.

Results from each test are rated as A, B, C, and D with A being the best. Please note that A in one test may not be equivalent to the A in another test.

Test Vehicles and Program Preparation
TV1 (Figure 1) is a 120mm by 120mm two-up panelized board with water-soluble anti-heat flux surface finish. It has 824 0201 capacitors, 532 0402 resistors, and four BGAs on the topside. The four BGAs were not included in the test. On the bottom side, there are 562 0201 capacitors, 462 0402 resistors, SOT, Figure LED, tantalum, odd shape connector, TSOP48, and five IC devices.

The program for TV1 was prepared and fine tuned using three boards. Data was collected from the eight boards including the three fine tune boards.

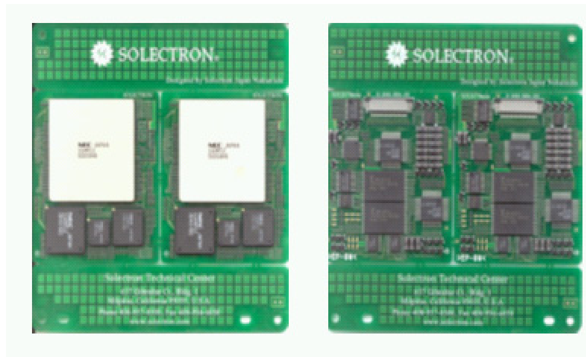

Figure 1 – TV1 Top (Left) and Bottom (Right) Configuration

TV2 (Figure 2) is a 190mm by 260mm doubled sided board with 1114 components loaded on the topside. A pallet was used to accommodate the irregular board shape.

The inspection program for TV2 was prepared in the week before starting the test. 100 boards were provided to each manufacturer in rotating basis for fine tuning.

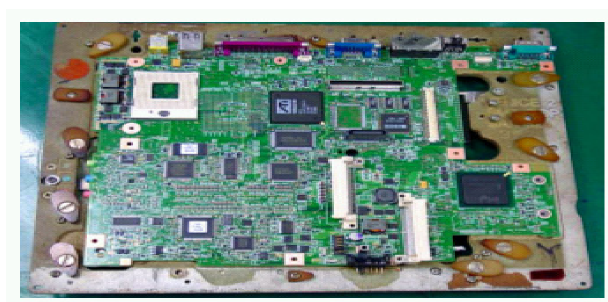

Figure 2 - TV2 Configuration

Program Portability
To test program portability, TV1 inspection program was prepared in US using one machine. Then, the program along with library and necessary files was hand carried to the test site, loaded into the other machine and run. No modification or adjustment was allowed.

For a multiple machine capability comparison, portability is also affected by threshold setting. Portability is better if threshold setting is loose. To have a fair comparison, position thresholds for 0201, 0402, SOT, LED, and tantalum were specified and provided to each manufacturer. The test results were also checked against true defect list.

The portability is calculated in component level as

$$\text{Portability\%} = \frac{\text{Total No of Components Consistenly Called}}{\text{Total No of Components Inspected}} \times 100\%$$

As shown in Table 1, all four machines have better portability on the topside. This may be due to the fact that the topside has only chip components. It does not have more complex components like fine pitch leaded component or SOT dark body component.

Table 1 – Test Data for Program Portability

Program Portability Test Using 0201TV - Top				
	A	B	C	D
No of Boards Tested	8	8	8	8
Component per Board	1356	1356	1356	1356
Total Inconsistent Calls (Pass/Fail)	5	9	19	33
Portability % (Pass/Fail)	99.95%	99.92%	99.82%	99.70%
Inconsistent Call PPM (Pass/Fail)	461	830	1751	3042

Program Portability Test Using 0201TV - Bottom				
	A	B	C	D
No of Boards Tested	8	8	8	8
Component per Board	1162	1162	1162	1162
Total Inconsistent Calls (Pass/Fail)	10	35	47	56
Portability (Pass/Fail)	99.89%	99.62%	99.49%	99.40%
Inconsistent Call PPM (Pass/Fail)	1076	3765	5056	6024

Program Repeatability

Three defect populated TV2 boards were used for the repeatability test. Each board was inspected 9 times. The repeatability is defined as the percentage of components with consistent pass/fail calls through these nine inspections.

$$\text{Repeatability\%} = \frac{\text{Total No of Components Consisteny Called}}{\text{Total Component Count}} \times 100\%$$

As shown in Table 2, among the 3342 components inspected, machine A has 28 locations having one or more inconsistent calls in these nine inspections. In other words, 99.16% components have repeatable results through these nine inspections.

Table 2 – Three Boards Repeatability Test Results

3 Boards Repeatability Test				
	A	B	C	D
Component Count per Board	1114	1114	1114	1114
Total Inconsistent Call Locations	28	32	41	78
Repeatability %	99.16%	99.04%	98.77%	97.67%

More analysis has to be done to understand if a pattern can be identified that singles out the component type that shows non-repeatability. It was noted that the dark color small chips and skewed chip components presented challenges for most AOI machines. Leaded component with minimum toe and side fillets, such as fine pitch connector with small thick lead and large pad, is also very challenging.

Defect Coverage

Defect coverage includes three tests, which are defect detection rate, escape rate, and false reject rate. Five TV2s manufactured per preset defect spectrum were used for the test. All defects were manufactured before reflow process.

The defect distribution and detection rate by each machine are shown in Table 3. Due to the nature of evaluation, there is no real time fine tuning allowed as is possible in normal production mode. At that

Table 3 - Defect Distribution and Detection Rate

		A		B		C		D	
Defect type	Qty on boards	No. caught	% caught	No. caught	% caught	No. caught	% caught	No. caught	% caught
Missing	197	196	99%	191	97%	192	97%	179	91%
Misaligned	153	125	82%	132	86%	86	56%	63	41%
Bridging	86	86	100%	66	77%	58	67%	84	98%
Polarity	74	49	66%	43	58%	22	30%	29	39%
Insufficient	69	8	12%	18	26%	4	6%	6	9%
Lifted Lead	34	30	88%	1	3%	19	56%	6	18%
Flip (reverse)	30	22	73%	13	43%	19	63%	12	40%
Billboard (sidewise)	23	23	100%	13	57%	15	65%	0	0%
Tombstone	10	9	90%	7	70%	8	80%	5	50%
Excess (RP touching chip	7	0	0%	0	0%	4	57%	2	29%
Open	1	1	100%	0	0%	0	0%	1	100%
Total	684	549	80%	484	71%	427	62%	387	57%

point, machine may consistently make false calls on the same type of component without allowing the engineer to make any fine tuning. Therefore, the results shown in Table 3 and Table 4 may be worse than what can be expected under normal circumstances.

For polarity, all four machines experienced difficulty in two package types, which are black body diode and SOIC8 (Figure 3). The diode is smaller than 0603 with a white polarity mark on one end. For human inspector, it has to be inspected under magnifier with lighting.

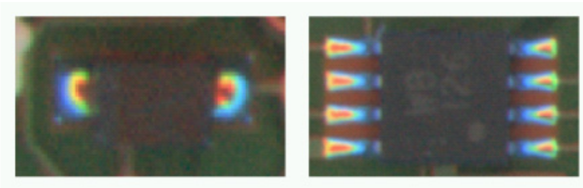

Figure 3 - Polarity Mark on Black Diode and SOIC8

The SSOP8 has a white dot polarity mark. The marking is very light and floating in a wide range of area. In the wrong polarity situation, the text printing in opposite corner may be caught mistakenly as a polarity mark, which results in an escape.

Insufficient solder is one of the most controversial defect category often discussed by the AOI community, especially for fine pitch leaded components. Other than equipment capability, an agreeable and well-defined threshold setting for toe joint is usually the vortex of argument. Though toe joint is not required by IPC-A-610C, it is still an indicator widely used by the industry. In borderline cases, inspector may take multiple checkpoints, such as side fillet or neighborhood joints, into consideration instead. A more advanced and friendly algorithm still needs to be developed.

Loose Chip adhering to the pad of another component can pose another challenge for AOI inspection. As shown in Figure 4, a 0402 resistor is sitting on the pad of another 0402 resistor.

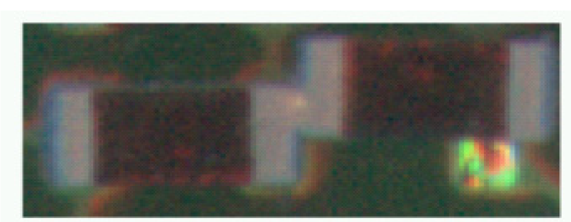

Figure 4 – Loose Chip Sitting on the Pad of Other Components

The summary of defect detection rate is shown in Table 4. The defect detection rate in component level ranges from 84% to 57%. The percentage may be higher in production mode since fine tuning in real time is possible.

Table 4 - Summary of Defect Detection Rate

5 Boards Defect Coverage Test	A	B	C	D
Total Defects on boards - Component level Ex: 5 lifted leads on same component = 1 defect	558	558	558	558
Total Calls by machine (real defects+false calls)	487	451	476	494
Defects Caught by machine - Component level	470	411	366	319
False Reject - Component level	12	19	27	20
Escape - Component level	88	147	192	239
Total Defects on boards - Joint level Ex: 5 lifted leads on same component = 5 defects	684	684	684	684
Defect Caught by machine - Joint level	549	484	427	389
by percentage	80%	71%	62%	57%
Escape - Joint level	135	198	257	296

The Total Call is traditionally the sum of Defect Caught, False Reject, and Escape. However, for multi-leaded components, i.e. SSOP48, different defect categories can occur on different pins of the same component making the sum of the defect categories a higher number than the total call.

Inspection Cycle Time

The inspection cycle starts from the time the first fiducial is read to the time the last component is inspected. Time spent on handling and defect review are not included. For the model with inspection cycle time proportional to the number of locations re-inspected. The cycle time recorded for the TVs is for typical number of defects which is 4-5 for that assembly.

Resolution and table acceleration were programmed by manufacturers. They take both defect detection and defect coverage into consideration.

Table 5 captures the inspection cycle time of all the equipment evaluated.

Table 5 - Inspection Cycle Time Comparison

Cycle Time Comparison	Board Size (mm)	Component Count	A	B	C	D
TV1 (Top)	12 X 12	1364	9	20	26	14
TV1 (Bot)	12 X 12	1162	9	22	22	16
TV2	250 X 170	1114	28	38	52	46

Our goal is to have AOI inspection cycle time 30% less than the pick & place cycle time or line beat rate.

Angle Measurement

Feeding AOI inspection results back to pick&place equipment for process improvement was one of the topics receiving much attention recently. Is the positioning information provided by AOI accurate enough to satisfy the requirements of the pick&place equipment? Some high precision pick&place equipment has placement accuracy requirement as stringent as ±0.04mm at 3σ for 4-sided leaded component.

To obviate the tedious metrology process in finding the centroid of a rectangular component, a more straightforward angle measurement was selected for the test. The goal is to understand AOI capability in measuring angle offset and detecting rotational defect Three 0201 capacitors (as shown in Figure 5) on TV1 were inspected by AOI. The data were verified using high precision optical gauge measurement equipment. The pass/fail threshold for AOI was set at 10°. And, the angle measurements for all three capacitors are greater than 10°.

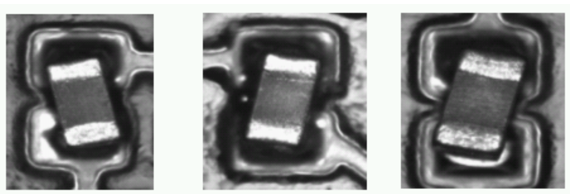

Figure 5 – Angle Measurement by OGP ATS800, C99a at 12.49°(Left), C195a at 10.73° (Center), C226aat 13.95° (Right)

The angle readings from three AOI machines together with the OGP measurement are shown in Table 6. C99a and C195a should fail the angle measurement. Yet, both machines A and B read the angle on the low side and passed both. They were counted as escapes. Machine C made a fairly close reading and failed both components for angle. For C226a, Machine B and C did not report angle reading because the component failed for either open joint or missing component.

Table 6 – Angle Measurement

Angle Measurement				
	OGP	A	B	C
C99a	12.49	3	4.5	12
C195a	10.73	7.3	4	10
C226a	13.95	7.7	-	-

Conclusion

Users of AOI often complain about its many shortcomings. Some of the commonly expressed ones are:

1. Poor repeatability
2. Inability to transfer inspection program to other machines
3. Difficulty in detecting insufficient solder
4. Unacceptably high false call rate

To verify the validity of these complaints, a systematic test on machines from four different equipment manufacturers was conducted in an EMS environment. A total of eight tests were performed using two test vehicles.

Repeatability

After nine repeated inspections, the repeatability ranges from 99.16% to 97.67%. In other words, in the best case, a machine has the same inspection results for 99.16% of the components. Less than 1% of the components (0.84% to be exact) have one or more unrepeatable calls.

Portability

For the Portability measured on the pass/fail calls for 0201 capacitors and 0402 resistors, the results range from 99.95% to 99.70% or 461ppm to 3042ppm. In other words, the machine with the best performance has inconsistent pass/fail calls on only 5 out of the 10,848 components inspected.

For general SMT components, portability ranges from 99.89% to 99.40%, which is lower than that for small chips only.

Defect Coverage

The defect detection rate on a component level ranges from 84% to 57%. The worst performance is in the detection of insufficient solder, which is also a function of the threshold setting. Small dark body diodes and SOTs are the most challenging among the various types of packages inspected. More effort needs to be placed on the detection of inconsistent printing of marking and polarity.

Inspection Cycle Time

The inspection cycle time for a motherboard type board, such as TV2, ranges from 28 to 52 seconds. For the mobile phone type board, such as TV1, the cycle time ranges from 9 to 26 seconds. The machine with 9 second cycle time far outperforms others. Inspection cycle time is really a function of board size, component count, and component distribution. Picking the fastest and the slowest machine is straightforward. Deciding on the two middle ratings B and C is much more complicated. One machine may be faster in certain application, but slower in another.

Due to time limitation, optical character recognition (OCR) and verification (OCV) were not tested. However, OCR/OCV can be arranged as an independent, offline test. The criteria commonly used for OCR/OCV are increase in inspection cycle time, effectiveness on IC marking, effectiveness on chip printing, and ability to locate the component accurately after reflow.

As the major EMS providers grow and become global corporations, the ability to purchase equipment wisely, use equipment efficiently, and transfer equipment quickly is key to quality assurance and inventory reduction. In the vision of these three challenges, some leading EMS companies implemented the common equipment process. During this economy down turn, this common equipment process can streamline capacity transfer from Europe and US to Asia. It helped company in reducing new equipment purchase by transferring excess equipment. It also helped the company in relocating the manufacturing expert from the shrinking to the expanding site, which makes internal transfer possible. However, common equipment process must be based on reliable equipment performance, such as program portability and repeatability.

EMS has to manage the service to multiple customers in one production floor. The line configuration has to be flexible enough to guarantee on-time delivery. Therefore, the product ran in line A yesterday may have to run in line B today. This is another indication of how important program portability is. Portability has been tested in this study. However, a straightforward procedure to ensure hardware similarity needs to be investigated and defined.

EMS, as a service provider, also has to provide a quick response to customer's request. Instead of adding new AOI features in assembly design stage, EMS often send in the requests in NPI or even manufacturing stage. Late request results in limited development time, which AOI manufacturers have to find a way to solve.

The current AOI programming technology is still too time consuming for an average engineer. The goal is to complete CAD translation and finish one-board fine tuning for a motherboard type assembly within 2 hours by an average engineer 3 months after initial training.

To achieve this, AOI manufacturers need to add more default thresholds based on package type and pad information. For fix algorithm approach, it may require more sophisticated statistical modeling in the algorithm to solve the overlapped pass/fail dome using single parameter classification.

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