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AOI Performance in the EMS Environment: A Two Year Review

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Introduction

Automated Optical Inspection (AOI) equipment has become an option for electronics manufacturers who are considering how to improve performance on the production line. During the last few years rapid changes have occurred in mounting technology for PCB assemblies. At the same time that equipment has changed in order to be able to build to the new market requirements, new techniques are needed to test/inspect those new products.

Over the last 5 years, technology has been changing at both the component and assembly levels. As a result, processes have been changing in order to cover all the new requirements for those new products. Some of the main challenges are:

- Increasing assembly density: component miniaturization and hand-held electronics are increasing assembly densities significantly.
- Use of microvia technology that reduces the number of vias that can be used as test pads.
- Introduction of CSP, flip-chip and COB. Usually these technologies are combined with microvia technology with the resulting consequences.
- Increasing assembly complexity: more components imply more joints to inspect and also more electrical nodes to test.
- RF boards with ground or power planes that do not allow for test pads to be provided.
- Functional test complexity is growing, including RF testing.

Currently, many companies are determining whether or not an AOI machine is suitable for their production environment, and what benefits can be obtained from this technology. For this, it is necessary to understand this technology to know its capabilities and its limitations. Once this is known, manufacturers can decide whether or not this technology matches their expectations.

An AOI system consists of a video camera, lens and lighting connected to an image-processing computer. Inspection systems use indexing stages to move one or more cameras over the surface of the PWB in a programmed pattern or move the PWB below the cameras in such a way as to inspect the entire surface with sufficient resolution to detect all significant defects.

Images taken by the machine are processed by software. The image is processed and a comparison is made with the component data and the algorithms used to assess solder joints. Also a specific library for components and solder exists in the machine. Based on this information, the machine will decide whether or not the inspected job is acceptable or not.

Therefore we can say that AOI can view a board in the same way that the human eye can, however it can do this in a much more efficient and faster manner than a human inspector. This can be achieved due to the fact that this technology does not suffer fatigue and smaller component sizes and increased densities do not cause a problem.

This paper will present the results of 2 years of experience with AOI systems used for post-reflow inspection in a high-volume production line, addressing advantages and disadvantages encountered in a manufacturing environment.

Included in the paper will be an analysis of selection criteria, which can help determine where, in a given manufacturing process, AOI equipment can be installed. This methodology begins with an assessment of the technology products to be processed through the AOI machine, and the benefits that may be achieved if AOI equipment is installed at every point in the manufacturing process.

Flexibility of AOI inside the Process

As stated earlier, AOI can view a board in the same way that the human eye can so defects that can be detected by an AOI machine are the same that can be detected by human eye, i.e.:

Missing components, skewed/misplaced components, tombstoning, polarity, bent/lifted leads, presence of pin through the hole, short circuit, insufficient or excess solder, not wetted, and superficial solder voids/blowhole.

On the other hand there are other problems on boards that a human inspector would identify as defects and the machine would not detect. Some examples are as follows:

- Solder spikes. If solder spikes are not joining two component leads, therefore not causing a short, the machine might not detect it.

- Solder balls. Solder balls are only taken as a defect if they are between two SMT-leaded components. If they are not forming a short, they are not always seen as a defect.
- On edge component. This requires very fine-tuning of the component body and is not always detected as a defect.
- Component cracks and damaged components.
- Component identification. Some machines do have this capability and others do not.

Looking at the type of defects listed above and what can be detected by the system, we can consider different points in the process where we can install our AOI machine:

- After paste printing
- After pick and place machines
- After reflow oven
- Before wave solder
- Before electrical test

Deciding upon the process step in which to install the machine, it is necessary to take into account a number of issues that will give maximum benefit to the company. Advantages of placing AOI at the above stages of the process are as follow: (See Figure 1.)

- After paste printing: detection of paste problems, that is excess, insufficient or lack of paste.
- After pick and place machines: detection of missing or misplaced components, polarity, bent/lifted leads.
- After reflow oven: detection of missing components, skewed/misplaced components, tombstoning, polarity, bent/lifted leads, short circuit, insufficient or excess solder, not wetted, superficial solder voids/blowhole.
- Before wave solder-detection of presence of pin through hole.
- Before electrical test: detection of presence of pin through hole and also the same coverage spectrum as after reflow for the side that is under inspection.

On the other hand, there are two possibilities for installing the machine: in-line or off-line.

Installing the machine in-line has several advantages:

- Handling is reduced as boards are not removing from production line
- Boards are inspected as they leave the previous step
- Actions for problems in the line can be taken faster and so less rework required in the work in process

Installing the machine off-line has different advantages:

- Boards can be inspected from different steps of the process and changes to the inspection process can be made as many times as necessary
- Put under control out of control process. This means that if the problem is in the solder wave process, the product can be inspected after wave, the problems can be observed, actions can be taken
- For a manufacturer with several lines, there is flexibility for building the product in any line
- Test coverage can be taken into account in order to use the AOI machine as a complement to electrical test inspecting SMT and PTH components with no test coverage

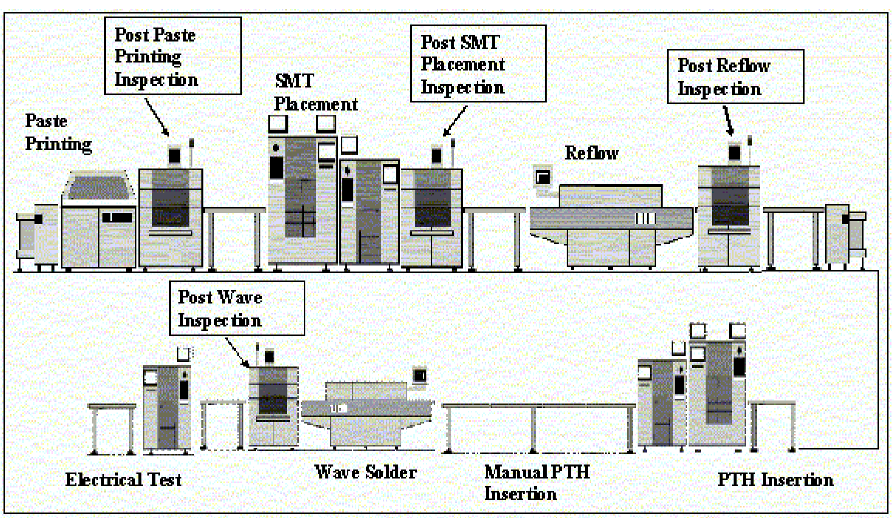

Figure 1 - Configuration Line

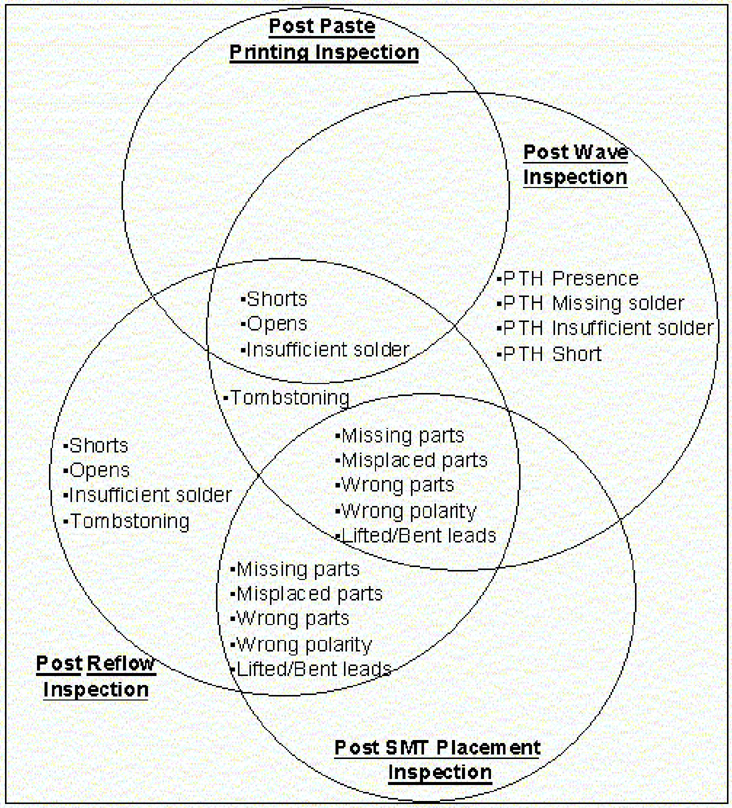

Figure 2 - Coverage Of AOI In Different Steps Of The Process

When a manufacturer, then, is thinking about the possibility of installing an AOI machine, they need to study carefully in which part of the process the benefits of the machine will be maximized. For this, it is necessary to take into account the above statements and combine them with expectations and needs. Figure 2 shows inspection coverage by process step for AOI. Looking at that figure and at the technology of products to be processed, the manufacturer can decide which is the best option so that its expectations can be realized.

Decision Criteria for Using AOI in a High Volume Production Line

In the paper, *Challenges in High-Density PCB Assembly: New Strategies for Improving Quality Inspection and Test*, results were presented comparing AOI and human visual inspection. Three test vehicles were used, two of them were simulating a low volume, high-complexity environment and the last one represented a high volume low complexity environment.

Based on the data and conclusions obtained in that paper, it was decided to install an AOI machine in a high volume line. Summaries of the results obtained in this paper which were used to consider on deciding to install AOI in the production line are presented here.

Inspection Efficiency

Inspection efficiency was defined as the percentage of defects detected by visual inspectors at the appropriate step of the process.

For comparing this quantity before and after AOI, historic quality data was taken from the process control database. Efficiency of AOI was obtained by calculating the percentage of defects detected by AOI out of the total quantity of defects of the boards inspected by AOI. Comparison of efficiency with AOI and without AOI is shown in Table 1.

Table 1 - Comparison of Efficiency

	Human Visual Inspection	AOI System
Job #1	35 %	88.4 %
Job #2	18.7 %	98.62 %
Job #3	6 %	99 %

Yield Improvement

Table 2 shows improvement of ICT and functional test yield for the 3 products used test vehicle.

Table 2 - Yield Improvement

	ICT Yield	Functional Yield
Job #1	2.31 %	0.3 %
Job #2	12.22 %	3.24 %
Job #3	6.4 %	N/A

System Level Test Improvement

Due to the fact that ICT and functional test do not have 100 percent coverage, some of the defects in the process will be caught at system-level test. An estimation of improvement was made using a model to predict the expected yield at different steps of the process. Inputs for the model included, quality levels at different process steps, inspection efficiency and test coverage. Due to less than 100 percent coverage at board level test, some of the defects were seen at system-level test. Table 3 shows that comparison.

Table 3 - Comparison for System-Level Test Yield

	Visual Inspection	AOI equipment
Job #1	99.2 %	99.86 %
Job #2	98.6 %	99.97 %
Job #3	99 %	99.9 %

Cycle time

Cycle time was measured in terms of time for inspection plus time spent in debug and repair for defective boards found in the test area.

To compare cycle time before and after installation of AOI, only operator time was considered. It was assumed that AOI cycle time was the same as the production line cycle time and that the AOI machine is in line so no handling time is considered.

Cycle time with no AOI = (inspection time required per board + time in repairing defects detected at the line) + (defects detected at ICT * time for repair/debug) + (defects detected at Functional test * time for repair/debug).

Cycle time with AOI = (operator inspection time + time in repairing defects detected at the line) + (defects detected at ICT * time for repair/debug) + (defects detected at Functional test * time for repair/debug). (See Table 4.)

Table 4 - Comparison For Cycle Time

	Total Cycle Time whith No-AOI	Total Cycle Time with AOI
Job #1	115 sec/board	25 sec/board
Job #2	388 sec/board	53 sec/board
Job #3	75 sec/board	17 sec/board

After comparing results obtained for the different test vehicles, AOI always performs better than human visual inspection in terms of efficiency. This increased efficiency translates into a reduced cycle time and yield improvements.

Maximizing Benefits from the AOI Machine

The use of AOI in various steps of the EMS process has advantages and disadvantages that must be taken into account. Each manufacturer should ask, “What are the expected benefits from AOI and compare them with the capabilities of the machine at every step of the process?”

For getting that it is necessary to look carefully at the points already stated in this paper.

In order to decide the process step in which to install the system we must look at Figure 2. Installing after wave solder and before electrical test, is probably the best point in which the manufacturer can get reap more benefits in terms of coverage. An EMS producer however, has to look for more options and balance both quality and productivity. So the manufacturer needs to go further than previously stated.

First we need to look at the technology of the products produced in the line. Table 5 includes the technology of products built in the high volume line. There are no limitations for using the machine due to the technology of the products.

Taking into account Figure 2 two options were considered to place the machine:

1. After reflow oven (placing the machine in line) (See Figure 3.)
2. After wave solder, before electrical test (See Figure 4.)

Inspection after reflow oven would be in line, so boards would pass automatically from reflow oven to AOI, only rejected boards from AOI would need an action from operators. Also SMT defects are detected at the earlier step of the process. For the technology of products for which this study was done, coverage given by the machine in all products is above 80 %. This coverage is calculated assuming that all SMT components can be tested by AOI, so table 6 shows the percentage of components that will be tested by AOI after reflow over total number of components in the board.

Table 5 - Technology Of Products To Be Processed In A High Volume Line

Product		N.SMT Components	N. PTH Components	N.SMT Solder Joints	N.PTH Solder Joints
# 1	Top side only	50	8	315	20
# 2	Top side only	37	7	182	16
# 3	Top side only	169	14	845	126
# 4	Top side only	158	11	766	268
# 5	Top side only	189	0	657	0

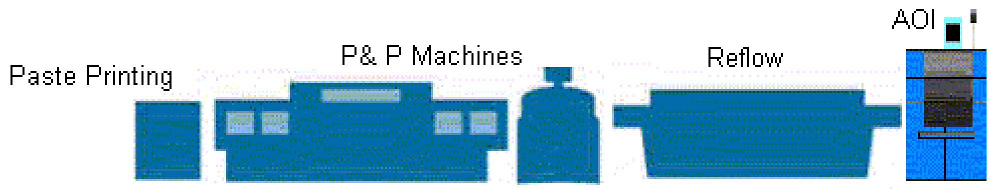

Figure 3 - Configuration Line-AOI After Reflow

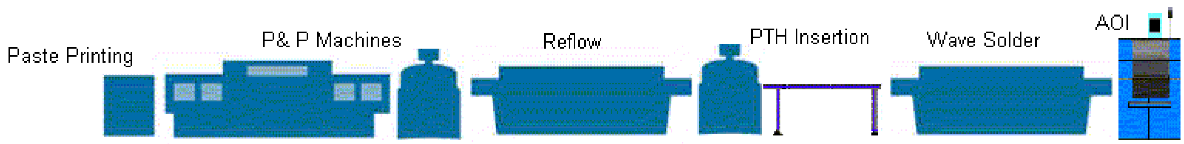

Figure 4 - Configuration Line-AOI Before Electrical Test

Table 6 - Coverage For AOI After Reflow Oven

Product		Coverage Placement (%)	Coverage Solder (%)	Total SMT Coverage (%)
# 1	Top side only	86	94	92.8
# 2	Top side only	84	92	90.5
# 3	Top side only	92	87	87.8
# 4	Top side only	93	74	80
# 5	Top side only	100	100	100

If AOI is placed after wave solder and before electrical test, looking at the kind of defects that it is able to detect, theoretically coverage would be 100%. But it is necessary to point out, that depending on the lay out of components, some tall components may shadow smaller ones and in that case inspection of shadowed components is not possible. On the other hand, there are a number of issues that we need to take into account, these are:

- Increase in process time. The possibility of having AOI as the bottleneck of the line exist.
- To achieve full coverage, it is necessary to inspect the board on both sides, so board manipulation also increases.
- The machine needs to be placed off line.
- SMT associated defects, which are the higher opportunities for defects are not detected at the earlier step of the process (no efficient SPC can be generated).

The above points are going to influence two major issues, that were considered in deciding the process step in which to install the AOI machine. Those points are yield at ICT test and cycle time of products.

Yield at ICT Test

Yield at ICT test can be estimated using a mathematical model to predict the expected yield at different steps of the process. Inputs for the model, included: quality levels at different process steps, inspection efficiency and test coverage. Some of the defects of the process were eliminated at visual inspection, both at AOI machine and human visual inspection. The remaining defects reached ICT test. The quantity of these defects depended on the efficiency of the visual inspection. Table 7 shows the expected results of different products to be run.

Table 7 - Comparison Of Expected Yield At ICT Test

Product	ICT Yield – AOI after reflow	ICT Yield – AOI after wave Solder
# 1	98 %	98.4 %
# 2	97 %	97.3 %
# 3	96 %	97.1 %
# 4	95 %	96.9 %
# 5	97.7 %	N/A

Cycle Time

Cycle is considered in terms of:

- Time for inspection spent by an operator. This time is different depending on the position of the machine in the process.
- The time for inspection when the machine is after reflow oven, is the required time to confirm the boards rejected by the machine. In this paper we will assume that 60% of boards pass the test.
- Time for inspection when the machine is placed before ICT test is considered to be the machine time for processing both top and bottom side. For comparison purposes, no operator handling time will be considered.
- Time spent in debug and repair defective boards found in the test area. The time assumed to repair the failing boards at ICT test is 140 sec/board. The quantity of boards failing at test will be different for any configuration, as it is dependent on the ICT yield.

With above considerations, the Table 8 shows the different cycle times for the boards processed in the line for the 2 possible configurations.

Table 8 - Comparison Of Expected Cycle Time

Product	Cycle Time for AOI after reflow (sec/board)	Cycle time for AOI before ICT test (sec/board)
#1	18	92
#2	20	63
#3	23	115
#4	25	86
#5	20	20

After comparing results shown in Table 7 and table 8, we can see how a higher yield at test comes together with a much more higher cycle time and so increases quantity of operators required.

Results From Two Year Experience With AOI In A High Volume Line

After the study was completed, the final configuration chosen for installing the AOI machine was after reflow oven. In that configuration the expected yield at test is lower. On the other hand, lower cycle time translated into savings.

The machine works in line, so boards go out from the oven and pass forward to AOI. When the machine detects defects during inspection, it sends the board to the off line repair station. On the other hand, if the board is found good, it continues to the following process step. In our case, this is the automatic PTH insertion.

In any case AOI is not a bottleneck for the boards processed in our manufacturing line. In the future, if a new product results in a bottle neck, we would ask the question: “Is it possible to reduce inspection time by avoiding inspecting a certain amount of components that have coverage at test?” If the answer is yes, this is what we would most probably do.

The graphs below show the yield at ICT for the products run in the line. As we can see, the values for the yield are quite near to the ones predicted with the mathematical model (Table 7). Also the graph with results at ICT for a product that does not have AOI is shown. This product is similar to products #3 and #4. Comparing results at ICT for products that pass through AOI and products not tested at AOI we can point out 2 things:

1. The average ICT yield is lower for the product that does not go through AOI
2. There are more variations in ICT yield for the product not tested in AOI

Apart from improvements in test and in production cycle times, there is another question that manufacturers will ask themselves: “Is it possible to eliminate ICT and substitute it by AOI?”

Looking at the defects found at ICT in the boards processed in our line, configured as shown in Figure 3, we can see that the majority of defects detected at ICT would not be detected by AOI. This is independent of which step in the process it would be placed.

Table 9 shows figures for the quantity of defects found in ICT that could not be detected in AOI.
The reason for this is the type of defects such as defective components, damaged components and also the technology of the boards and the technology of the machine will have an influence over the results shown in Table 9.

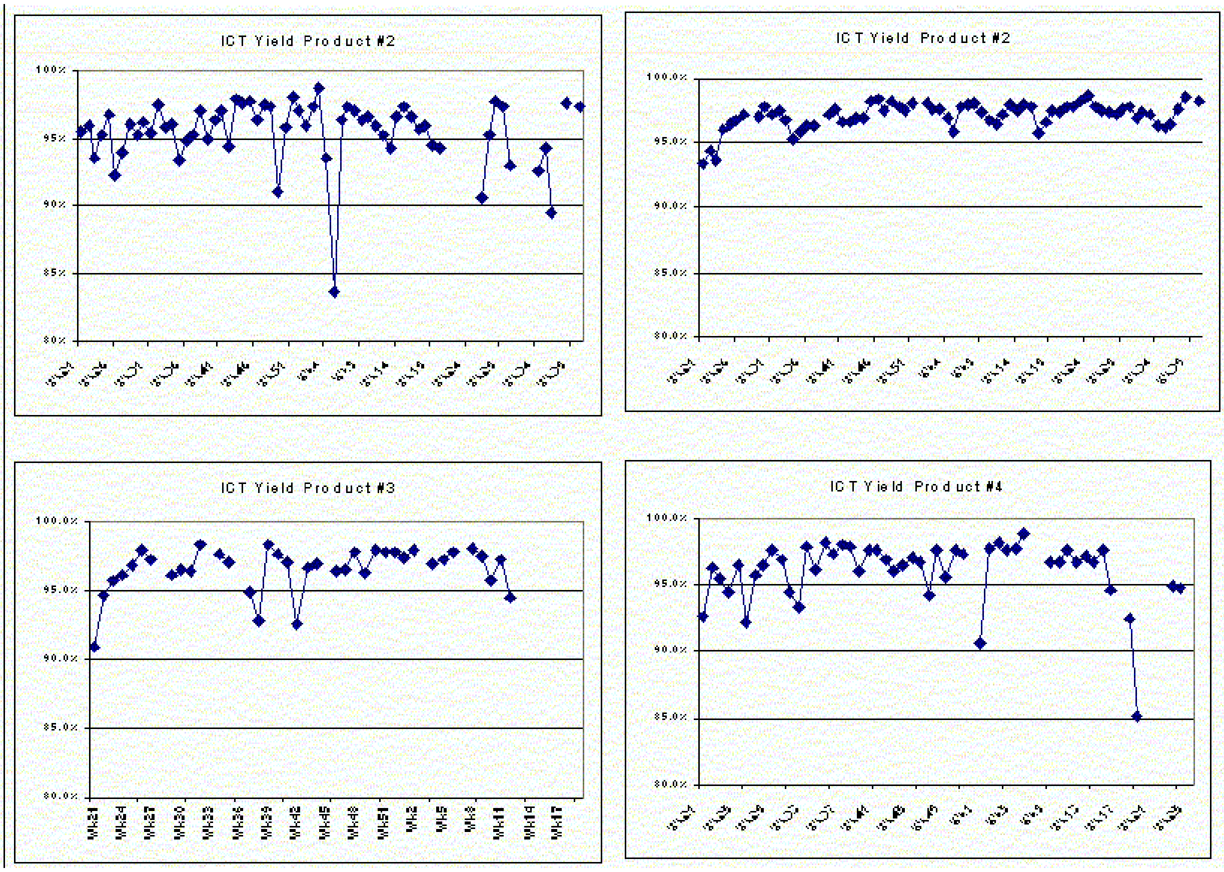

Figure 5 - ICT Results

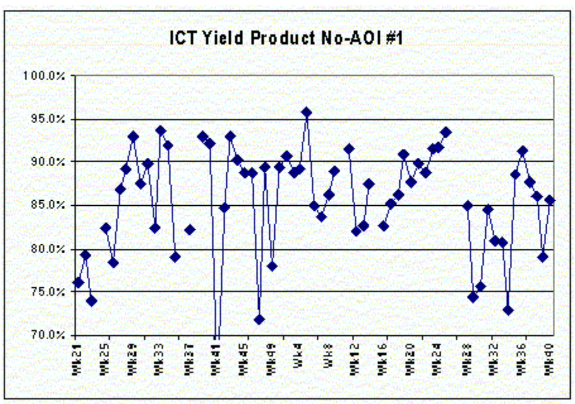

Figure 6 - ICT Results Product No-AOI (comparison)

Table 9 - Defects Detected At ICT That Would Not Be Detected At ICT

Product	Defects detected at ICT not possible to detect in AOI
#1	58.9 %
#2	58.4 %
#3	61 %
#4	58 %

Summary

AOI machines can be used in several stages of the manufacturing process. Independent of the process step in which the machine is installed. There is always an improvement in terms of inspection efficiency and test yield is seen to increase. This improvement will be higher or lower depending on the step in which AOI is installed. We can get better results in terms of quality if the inspection is done in the later steps in the process, as the coverage will be higher.

An EMS provider should also take into account other factors. After further study and considering several options, it has been seen that installing the AOI system after reflow oven for the products processed in the high volume line; a balance can be reached between quality and cost.

Another important point that has not been considered in the study, is the fact that having this technology can attract new customers, especially when their products do not have electrical test. This is the case of the product #5.

Once it has been decided to implement AOI, and after it has been running for some time in the manufacturing line, a verification of the results expected and those achieved must be made. Looking at the results at ICT test, it has been seen that the yields are very similar to those expected. On the other hand comparing the yields of the products processed through AOI with other similar products that do not go through AOI, two things come to our attention: ICT yield is lower and it is also more variable for products that are not processed through AOI.

In considering removing ICT, the defects detected here have been analysed to see if they could have been detected in AOI. Results show that more than 50% of defects found in ICT could not have been detected in AOI, so if this test process were to be removed, these defects would arrive at the customer site.

ICT coverage for products presented in this paper is between 74.6% and 89.7%. If a new product is introduced for which ICT coverage is very low, and keeping in mind the process to be followed and also taking into account the data recorded for current production, the possibility of eliminating ICT could be considered. In that case the manufacturer will have an additional benefit that is savings in fixtures and programs for ICT and also the lower time required for debugging defective boards.

This paper has described the benefits of AOI in a high volume environment. A question about AOI technology in a low volume and high complexity environment may come out. The conclusions of the paper "Challenges in High-Density PCB Assembly: New Strategies for Improving Quality Inspection and Test" showed how for this type of production, with AOI we get improvements in efficiency and test yields.

On the other hand it should be taken into account the engineering time required for developing and fine-tuning of programs. Also to be confident in AOI faults detection, it is necessary to ensure all manufacturing defects within its fault spectrum are defined as defects at AOI. To reach this level, several manufacturing lots should be passed through AOI with visual inspection and checked such that the system is detecting all defects under its coverage. So to decide whether or not the use of AOI for a certain job is justifiable as it is important to take into consideration the total lifetime volume of the product and the size of production lots.

Manufacturers should also be aware that changes in process have a lot of influence in AOI performance. So every time that a change in the process takes place (solder paste change, stencil, oven, etc) it is necessary new fine-tuning of the system.

Considering the last paragraphs, for a low volume environment, most of the times it is not justified. In monetary terms, an AOI machine on every production line does not have 100% of the products going through it. On the other hand manufacturing people will not accept limitations for always building the same products in the same lines, so AOI will be used off line in most of the cases. This means an increment in time due to the handling of the boards.

AOI suppliers are working continuously in improving their systems. New versions of software for current machines are coming out in order to obtain improvements in programming (new components in the standard library, better optimization of programs, etc.) and also improvements in fine-tuning by changing test algorithms. Technology is also changing including the introduction of new technology for cameras and lighting. Some manufacturers are introducing colour in their systems, recognition of characters, etc. All of these changes, in effect, solve problems and reduce limitations of the manufacturers and further accommodate market requirements.

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