AOI/AXI Combinational Inspection Strategy

Graeme Struthers
Solectron Scotland Ltd
Dunfermline, Scotland

Abstract
The purpose of this study is to understand the capability of both AOI and AXI machines and where the two could be combined to increase the inspection coverage, reduce the overall cycle time of the inspection process and provide the most cost effective solution.

Introduction
Due to the PCB industry trends moving to more complex devices and the reduction in overall package size and pitch it has, for some time now, been accepted that visual inspection is not repeatable and is proving more difficult with the reducing component geometries. Therefore some form of automated inspection requires to be carried out in order to repeatedly and reliably detect faults.

At the present time there are two basic technologies with which to facilitate automated inspection. Automated Optical Inspection (AOI) and Automated X-Ray Inspection (AXI).

AOI systems use a variety of different lighting and camera assemblies, ranging from single vertical camera systems with lighting rings around the camera to multiple angled cameras with a variety of angled lighting sources.

There are two types of AXI systems:
- 2D transmission x-ray where a single image is taken through the board
- 3D X-ray systems using either laminography or tomosynthesis that can focus on either the topside or bottomside of the board.

With all these technologies, images are captured and then interpreted using algorithms with certain user-defined thresholds and parameters set to differentiate between good and bad components/joints.

For the purposes of this trial the AOI system used was the Agilent Technologies SJ-10 (formerly MVT), the AXI system used was the Agilent Technologies 5DX Series 2L.

Agilent SJ-10
The SJ-10 is a single camera AOI system, with a multiple angle LED lighting head, which is positioned around the camera lens.

For the pre-reflow application, a system with coloured LED's was used. The unit under test (UUT) is clamped within the machine and the camera moves to capture the images for processing. Figure 1 shows the SJ-10 machine.

Figure 1 - Agilent SJ-10

Agilent 5DX
The 5DX uses X-ray laminography to acquire 3D images of the UUT, again the system is a single camera unit, whilst there is a rotating scintillator that converts the x-rays to gray-scale for the camera to capture. The camera itself is in a fixed position, the UUT is moved in the X,Y and Z axis. Figure 2 shows the Agilent 5DX Series 2L.

Figure 2 - Agilent 5DX

Programs
Agilent Application Engineers were responsible for creating the programs for the boards to be used for the trial, in order to utilise the latest best practices and features for both machines.

Automated Inspection Strategy

Requirements

Before considering the capabilities of each form of inspection, it is first worth establishing what is required, realistically, from Automated Inspection (AI). Although most AOI and AXI systems are capable of consistent, repeatable inspection, there are limitations to the capabilities and to what can be inspected at each stage.

The purpose of implementing an AI solution is twofold, to increase inspection coverage and to increase throughput. In order to achieve this cycle time improvement, implementation of an AI solution has to reduce the amount of human intervention required to an absolute minimum. Therefore the AI process has to be able to cover as large a part of the fault spectrum as possible.

Potential faults that manual inspection can capture include:

- Component Faults
  - Missing components
  - Offset component
  - Skew components
  - Polarity issues
  - Tombstone components
  - Billboard components
  - Flipped components
  - Lifted leads
  - Damaged components

- Solder Faults
  - Insufficient solder
  - Excess solder
  - Solder shorts/bridging
  - Open Joints

From this list the only defect type that either an AOI or AXI process would not practically be able to detect would be damaged components. This would depend on the type of damage to the component and whether this made the component visually different enough for the process to pick up. There is more chance of an AOI system picking up damaged components than the x-ray system, as the x-ray system cannot, for the most part 'see' the component body. Damage to the component leads could be caught if they were damaged enough to alter the characteristics of the joint.
In addition to this the x-ray system can only detect polarities on tantalum capacitors as again it cannot 'see' the components themselves to distinguish the polarity mark.

There are several issues that can impact the inspection process. The main detractor is material supply. In order to have consistent, reliable inspection programs, the programmer has to be aware of all variations of a component in order that the system can be tuned to take these into account. This also includes alternative polarity marks on components. Without careful consideration of this from the material supply, polarity checking of some components may have to be removed from some programs as the alternative components can often have 180° rotated polarity marks.

Alternative components do not impact the x-ray system as much, as only changes in the component leads and therefore joint characteristics would cause a problem for the machine. However there is currently no facility to add alternative components, therefore a separate program has to be written if alternatives are to be used.

Changes in raw card such as changes in board thickness and board finish can also impact the inspection program, as can changes in the solder paste used. PCB bow, warp and twist during the reflow process can also impact the machines ability to perform a reliable, repeatable inspection.

To be able to establish an effective AI solution all the above factors must be given due consideration.

In addition to this the technology present on the board must be analysed to provide the best AI solution based on the capabilities of the machines.

Standard Solutions

AOI

For conventional technology, where all joints are visible, AOI could provide the best solution for inspection, giving complete coverage of the fault spectrum (bearing in mind the provisos above).

AXI

If there are hidden joints on the board – J-leads, BGA, odd-form connectors etc where the joint is not visible, AOI will, at best be able to provide position and polarity information only for those components. AXI will require to be used to inspect the hidden joints. AXI is capable of inspecting all component types, however at a slower cycle time than that of AOI, inspecting all components on AXI may mean that the inspection process cannot keep up with the line cycle speed.

Combined Solution

There are two ways in which AOI, AXI and manual inspection can be combined to give an improved inspection process:

- Pre-reflow AOI, Post-reflow AXI
- Post-reflow AOI, Post-reflow AXI

Pre- Reflow AOI Post-reflow AXI

By placing the AOI system prior to the oven, the advantages of improved real-time process feedback can be realised, whilst still covering the weaker areas of the AXI system (i.e. polarities). The AOI system will provide feedback relating to placement, rotation and polarity of the components on the board. From this point the hidden joint issue with AOI does not become a problem, as there are no joints for the system to check. Any calls made by the pre-reflow system can be assessed as to whether they should be repaired at this stage or left to be repaired at the Post-reflow stage.

Post-reflow AXI would then be set-up to inspect all solder joints on the board, including hidden joints, giving the fullest possible joint inspection coverage. Depending on the SMD configuration for the board the AXI could be set-up as shown in Figure 3. Using this system, there is no way of increasing the throughput of the AXI by removing any components from its inspection, as the joints are not being checked elsewhere.

Post-reflow AOI, Post-reflow AXI

With this system some components could be removed from the AXI inspection, thus increasing the throughput of the machine, without impacting on inspection coverage. Polarities would still be checked on the AOI machine, as well as presence, placement and solder joints components whose joints can be seen.

AOI cycle times are, for the most part, able to keep up with the beat rate of the line, so it may be prudent to inspect 100% of the board with AOI, even on just a presence/placement basis for the components that will be inspected using AXI. This will add level of redundancy to the process, but will also provide backup to the process.

The same choices are available for the AXI inspection, however it should be noted that having an AOI before the AXI, may enable removing the bottomside inspection completely from AXI. This is obviously dependent on the package technology on the board, but this can have a significant impact on the cycle time of the AXI process, and therefore the overall inspection process. Wave soldered boards

Wave Soldered Boards

An additional advantage of having the combination strategy is for components placed during the surface mount process that will then be wave soldered. When these components are placed on the board during the surface mount process, they are glued in place. There is no solder added to the components at this point in production, therefore there is no solder joint formed at this stage. This means that the AXI cannot inspect these components, even on a presence/placement basis as, as previously stated, AXI cannot 'see' the components themselves, but the solder joint of the component. Having an AOI system before the AXI means that all SMT components on a glued board can be inspected for presence/placement and polarity, despite having no solder joint.

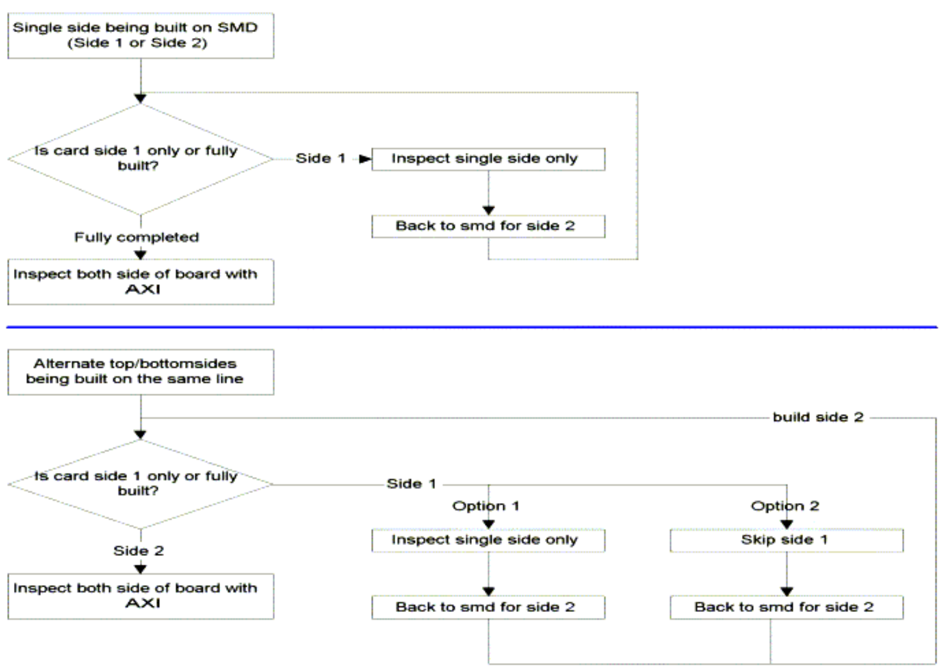

Figure 3 – AXI Process Flow

Process Indicators

Automated machines cannot make the judgement calls that the human inspector will make on a component's fail condition based on where the component is placed, the surrounding components and how bad the fault is actually perceived. The machine makes a good/bad decision based on the parameters and thresholds that forms the basis of its program.

Consider a 100 pin QFP. If the standard for placement of this device is that no more than 25% of the lead can be off the pad, what if the component is 27% off the pad? Should the component be reworked, bearing in mind the complexity of the device, the extra thermal cycling the component would go through during repair, and the fact that the final joints on the newly, correctly placed component will be more likely to cause field failures than the original offset joint?

A manual inspector may take the decision to let this component pass, but be aware to look for similar faults in the following boards to ensure that the fault was a one off. Obviously if the components are continually off, or even just less than 25% off the pad continually, this would get fed back to the line as a process issue. The AI machines cannot make this distinction. If a component is less than the tolerance it has been set to use, the component passes, if it is greater than that figure it fails.

Another example of this is voids in the solder joint of a component. This does not commonly affect the AOI system, unless the void is big enough to form a blowhole in the joint itself, thereby reducing the overall pad coverage of the joint. Under AXI however, voids can make a significant difference to the inspection process. If the void is in the heel of the joint, then the system will note that the heel is of a lighter grey and therefore not have as much solder present. The system could then fail for insufficient heel, or indeed on slightly larger voids, assume that the joint is open.

Figure 4 shows a void in the heel of a resistor network.

At what point does a fail become a reworkable fault? Further investigation is required into where the line should fall between what is a fault that will be picked up by the AI process as being something that is not visually correct, based on the thresholds and parameters that the machine has been programmed with and something that is actually different enough that it should be repaired. It should be noted that these calls by the machine, although not always acted upon, should not be classified as 'False calls'. The machine has correctly flagged a potential issue with the board, it is then up to the machine operator to decide whether or not to take action on the basis of this information. These calls are referred to by various names; process indicator, repair not required, not repaired, etc.

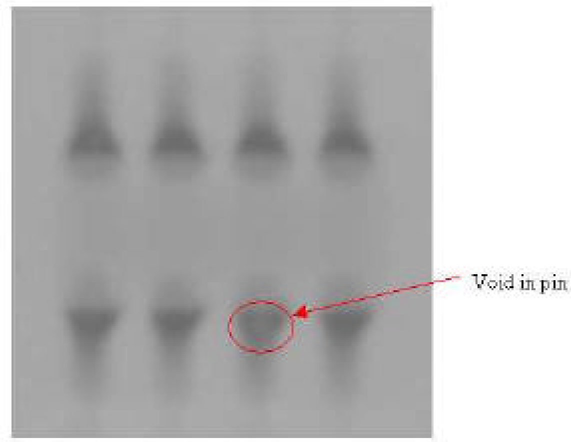

Figure 4 - Void in Resistor Network

Tolerances

When programming an AI machine for combination strategy, it is important that the same values are used for the tolerancing of the components. This should ideally be automatically calculated for both machines in order to remove the programmers opinion of what the tolerances should be for example 25% off the pad. Different programmers may have slightly different values for this, with automated tolerancing using the pad and lead size this is removed.

Trial Procedure

Figure 5 gives a graphical representation of the trial that was carried out to determine the capability of both machines, and the possibility of combining the two machines together. Faults were induced throughout the surface mount process, in order to ensure that as complete a fault spectrum as possible was covered. Components were removed, misplaced, bridged and rotated 180°. An alternative stencil with various apertures reduced at either the heel or toe of the pad was manufactured to induce insufficient/open joints of a variety of component and package types.

There were two trials carried out. The first included pre-reflow AOI inspection, carried out after any induced faults had been made on the board. All the faults were then correlated to establish the total number of faults found through inspection from the AOI, AXI machines and manual inspection.

The second trial followed the same process as above, without the pre-reflow inspection.

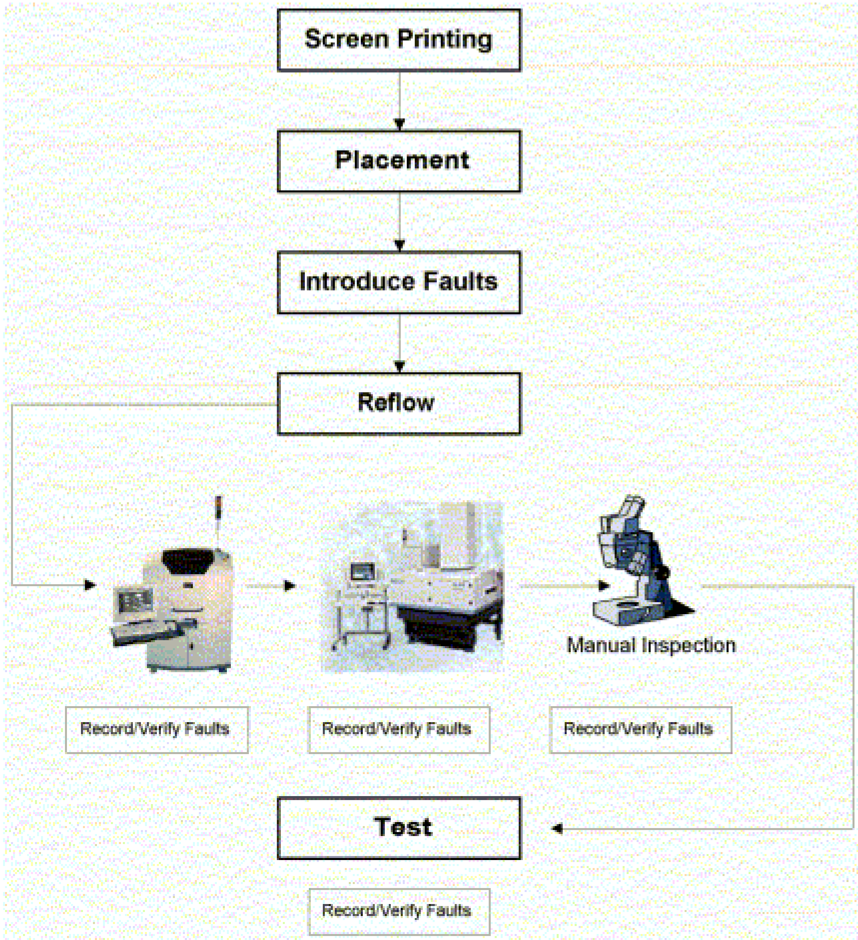

Figure 5 - Trial Procedure Flow

This data was then analysed for trends regarding the inspection of specific failures or packages on each machine.

This was to determine whether or not it would be practical to be able to remove certain components from one of the machines without impacting the inspection process.

Trial 1

This trial, as already noted, included pre and Post-reflow AOI, AXI and manual inspection. The board for this trial was a communications board, very densely populated on one half top and bottom. There were two boards in the panel, shown in Figure 6. There is a total of 924 components per board (1848 per panel). There were a total of 83 boards (43 panels) inspected during the trial.

The results for this trial, on initial analysis were disappointing, both Post-reflow AOI and AXI returned a lower than expected fault detection over the whole range of the fault spectrum. However, during this trial there was an issue with the raw card of this particular product that was causing the board to shrink and warp during reflow. Although the boards themselves weren't actually warping, they were warping within the breakout. This significant warpage was often throwing areas of the board outside the focal range of the AOI system (warping down out of range on first side, then up out of range on the other side).

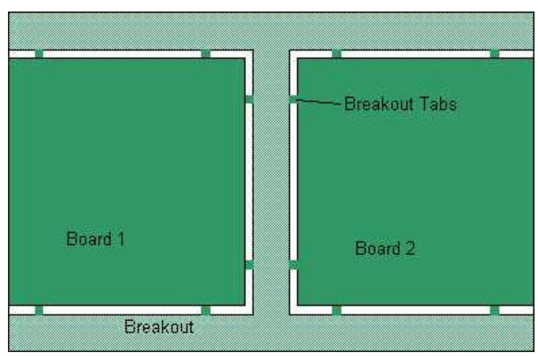

Figure 6 - Trial 1 Board

This could have been improved by reducing the resolution of the camera and therefore increasing the focal range, however this reduction in resolution would reduce the functionality of the machine on the finer pitch devices. In a few limited cases the board would not actually fit into machine due to the warpage, or it had broken itself out of one or more the breakouts. This would also then cause the board to vibrate inside the AXI, again throwing the images out of focus, or in some cases the excessive warpage on the board would mean that across a single image on the AXI, the image would go out of focus. Therefore although the fault detection of these components is not nearly as high as would be expected, the machines, actually performed well under these circumstances. Between the two machines, only 18 faults out of 226 were missed (7.9%).

It should be noted that these problems were only actually experienced during one run of the board, the raw card issue has now been resolved.

Figure 7 shows a graphical representation of the data from trial 1, Table 1 shows the actual data obtained from the trial. The data in this table and figure represent the data for Post-reflow inspection only.
The pre-reflow AOI system picked up a total of 69 faults, with no corresponding false accepts. The false call rates for each machine during this trial are detailed in Table 2. These false call rates are at a component level only.

Note - The polarity faults in this trial were tantalum capacitors

Table 1 – Trial 1 Results Data

%Faults Found	Post AOI	AXI	Manual
Bridging	40%	90%	100%
Billboard	100%	100%	100%
Excess	60%	47%	93%
Flipped	0%	0%	100%
Insufficient	37%	17%	65%
Lifted Lead	100%	100%	78%
Missing	78%	67%	67%
Offset	73%	68%	45%
Open	25%	98%	21%
Polarity	100%	100%	0%
Skew	100%	0%	0%
Tombstone	88%	69%	88%
Total	52%	62%	58%

Table 2 – False Call Rates Trial 1

Machine	No of False calls	PPM
Pre AOI	251	3158.7
Post AOI	228	2869.2
Post 5DX	598	7525.4

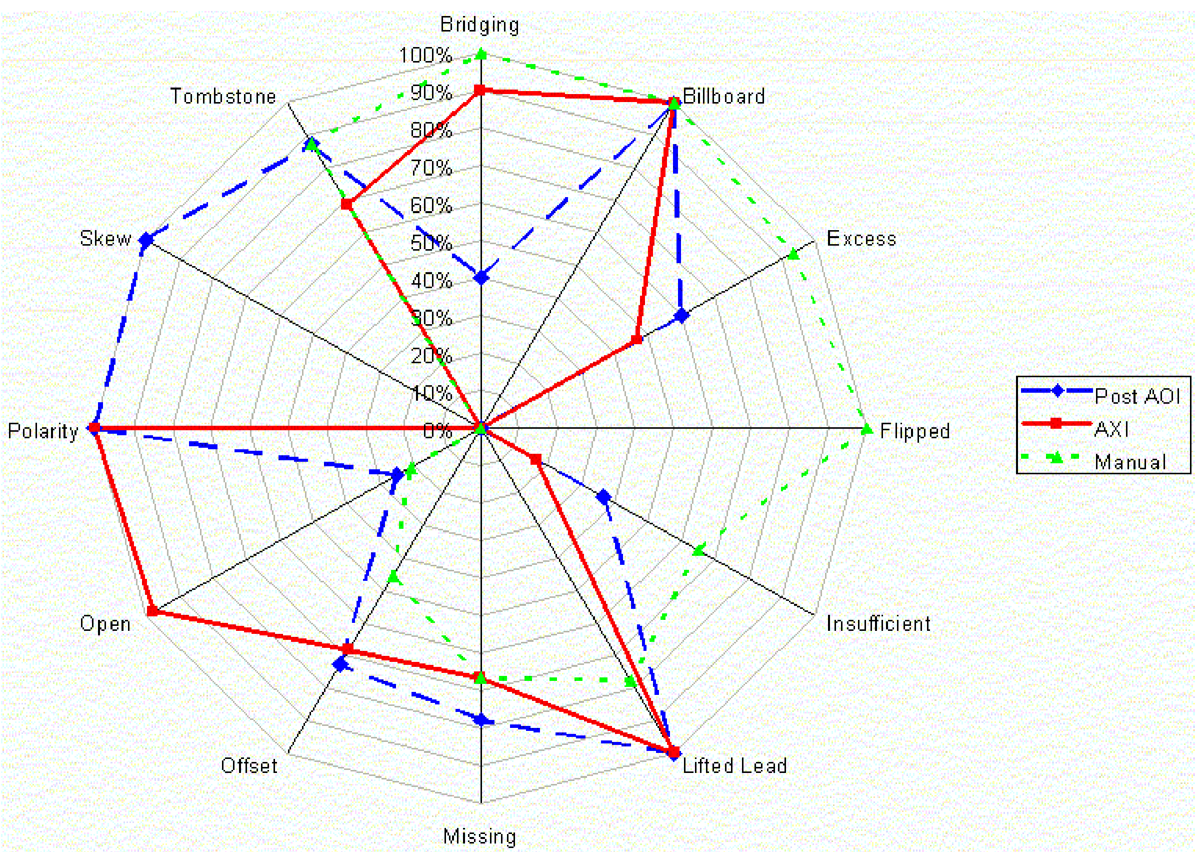

Figure 7 – Post-reflow Results – from Trial 1

Trial 2

The board used for this was a large server style with approximately the same number of components (1855) as the board used in trial 1, however the trial 2 board has a lower mix of component types. There was a total of 52 boards run through for trial 2. Table 3 and Figure 8 shows the initial fault detection results for this second trial, this includes all types of faults that were on the board. Table 4 shows the detection rates once items such as damaged components and polarities (AXI only) are removed from the figures. These are also displayed in Figure 9 and Table 5.

Table 3 – Trial 2 Results Data

%Faults Found	Post AOI	AXI	Manual
Bridging	63%	100%	50%
Damaged	38%	0%	100%
Flipped	50%	0%	50%
Insufficient	37%	79%	0%
Lifted Lead	43%	100%	14%
Missing	78%	91%	35%
Offset	29%	86%	29%
Open	81%	67%	6%
Polarity	100%	0%	0%
Skew	38%	88%	13%
Tombstone	100%	89%	44%
Total	69%	72%	24%

Table 4 - Adjusted Figures for Trial 2

	Post AOI	AXI	Manual
Bridging	63%	100%	50%
Flipped	50%	0%	50%
Insufficient	37%	79%	0%
Lifted Lead	43%	100%	14%
Missing	78%	91%	35%
Offset	29%	86%	29%
Open	81%	67%	6%
Polarity	100%	0%	0%
Skew	38%	88%	13%
Tombstone	100%	89%	44%
Total	71%	78%	18%

Table 5 – False Call Rate Trial 2

Machine	False Calls	PPM
Post AOI	418	4333
5DX	591	6127

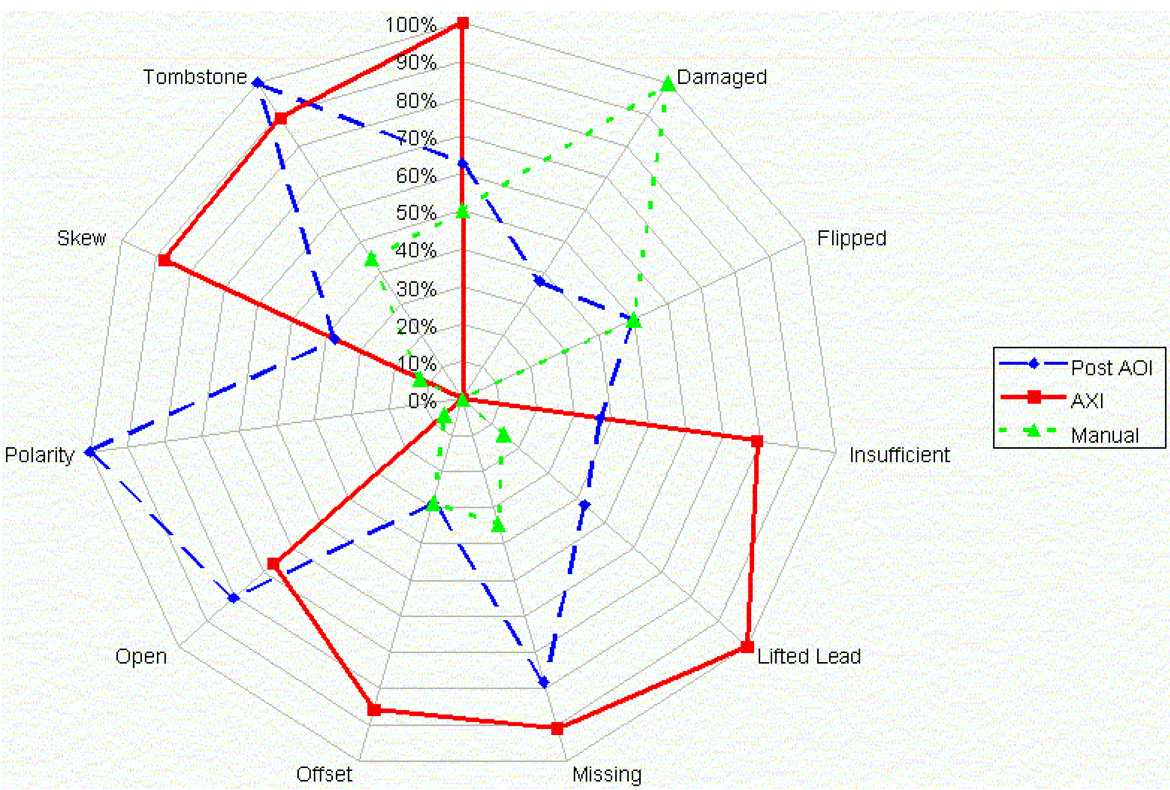

Figure 8 - Radar Chart - Post-reflow results Trial 2

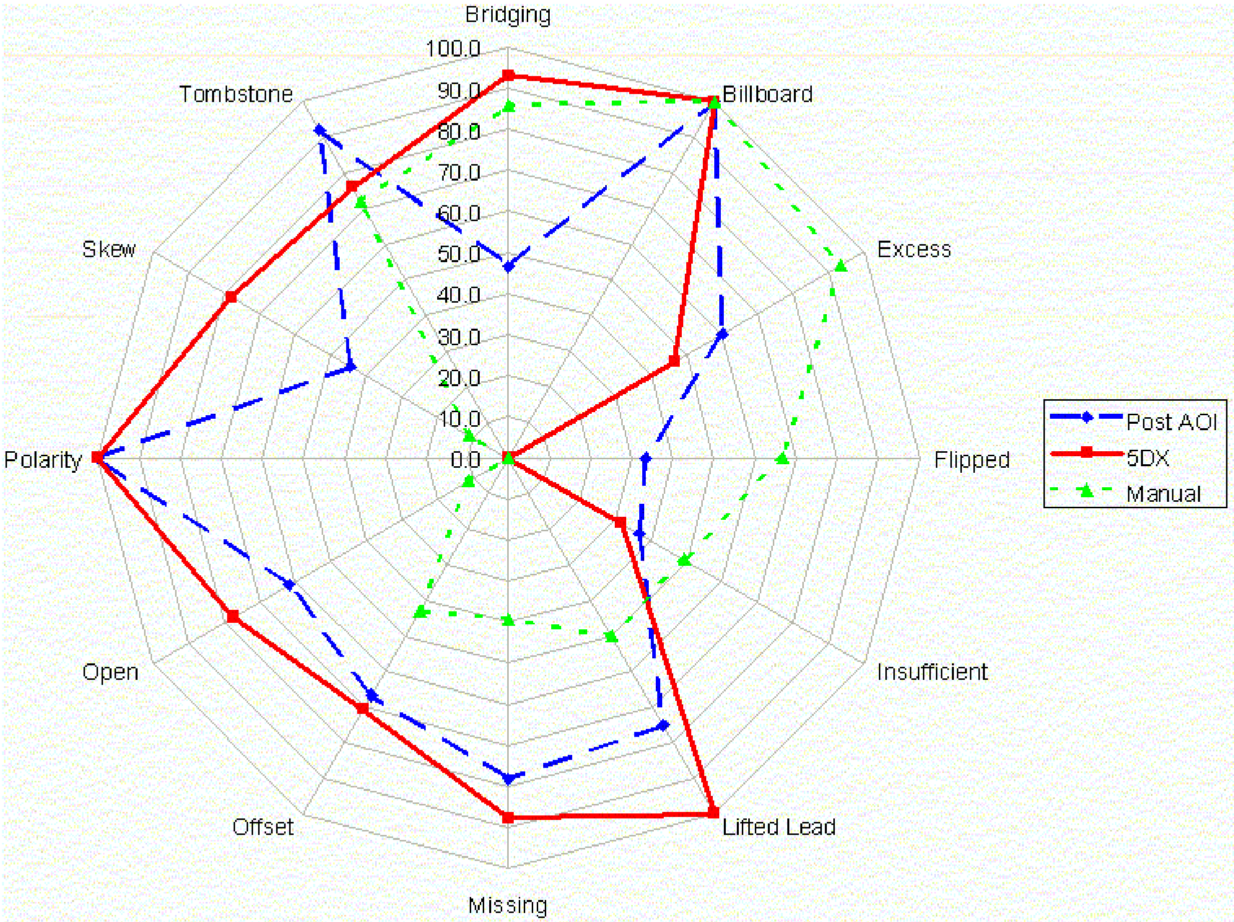

Figure 9 – Adjusted Data for Trial 2

Interpretation of Trial Data

Due to the problems experienced in trial 1, the Post-reflow data from this trial should be re-evaluated on further runs of the board, now that the raw card issue is resolved.

The pre-reflow data from this trial is encouraging - the pre reflow AOI machine did not miss any faults on the board, and the overall performance was good. It should be noted that not all faults seen at the pre reflow stage were still present at Post-reflow.

It can be seen from Table 4 that the final adjusted fault detection rates are reasonably fair for trial 2. As the programs were developed further over a few runs of the board (10-15 boards per run) the false call rate would be expected to reduce considerably.

During the trial process no 'tweaking' of the programs was allowed and this did impact the functionality of the programs. Both from a false call and false accept point of view, variances were noticed within the normal, acceptable production process for which the programs could have been adjusted to account for. It is therefore reasonable to assume that due to this, and from experience running both machines that the false call/false accept performance of all machines used in the trial could be improved.

Package Capability

One of the anticipated outcomes of these trials was to create a capability by package for each machine. What the trials have in fact proved was that although the concept of removing package types was sound, further work is required to establish the true capabilities of each machine on a package by package basis. It should be noted however that initially, all chip components could be removed from the AXI as the detection rates for the fault spectrum on these components is similar for both AOI and AXI.

In order to establish the true capability by package the following trial is suggested.

Use programs that have matured in production for some time (3-4 runs of a product) and is relatively stable. Take a sample of boards from the next production run and process them through both post AOI and AXI. Note the faults reported by both machines. Retain the boards. Analyse the results from both machines and identify the differences in faults detected. Put the boards back through the machines and attempt to tweak the programs until both machines find all faults. Any faults that cannot be detected by a machine should than be removed from that fault category for that package in a capability matrix for that machine.

Time Savings
Based on the premise of being able to remove all chip and tantalum capacitor components from the AXI. Timings were taken at AXI. These are shown in Table 6.

Table 6 - Cycle Time Improvements

	Trial 1	Trial 2
With	175 secs	329.6 secs
Without	134 secs	155.3 secs
Cycle time with	20(brds/hr)	10(brds/hr)
Cycle time without	26(brds/hr)	23(brds/hr)

It can be seen from Table 6 that the cycle time-savings from the removal of components from AXI are very much board dependant. In the case of the board for trial 2, this has made the removal of bottomside inspection on AXI possible, hence the larger increase in throughput, (130%). From a costing point of view, again the advantages gained from this strategy would be board dependent - the production of a high value card (like that of trial 2) is more likely to gain cost savings from the increase in throughput.

Conclusions
In concluding, it should be restated that it is assumed for this study that the business consists of several SMT lines with a wide mix of SMT components, ranging from BGAs and QFPs down to small chip components, with sufficient volume and inspection requirements for several AI machines. Both AI technologies demonstrate viable, cost effective capabilities, some of which are complimentary and some overlapping. The challenge is to make the most appropriate use of each technology in cost effective defect detection and quality control, within typical real-time production cycle times.

The initial theory that all chip components can be removed from the AXI as they are adequately covered on AOI, has been established as valid. This alone can show significant increases in throughput for the AXI machine.

In order to fully optimise the throughput of the AI process, the inspection coverage may require to be balanced between both machines

Both AOI and AXI machines performed well, especially in the second trial. The board used in this trial was large and reasonably complex and in these circumstances, the use of some form of AI over manual inspection is greatly reinforced by the trial data.

In addition, with the AXI in particular, process indicators are logged, and can be reviewed. This can give a more effective overall view of the process, rather than simple black and white yield data. This can lead to more effective fine tuning of the production process.

The programs for the trial were created and tweaked on a relatively low number of boards (20-30). A significant time was spent tweaking the programs, yet further programming would be of benefit to improve their validity. It is probable that if the same amount of time had been spent over a larger sample of boards, a greater understanding could be built up of the normal acceptable production process, thereby reducing both false call and false accept rates.

Development of a robust program will be more difficult for low volume, high mix products, unless there is a high commonality between the components used. Under these circumstances it could take many runs of the product before a completely valid program is completed. In a high-volume environment program development may be completed over one or two runs of the board. Programming is an iterative process, using the same 10 boards 3 or 4 times to tweak a program will not produce as good results as using 30 - 40 boards.

In order to complete the proposed, package capabilities per machine type study, further fine-tuning of all programs is required.

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