

Selecting the Optimal Test Strategy

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**How to find
the right
balance
among
all the
choices—
ICT, AOI
and AXI.**

Today's printed circuit board (PCB) assembly test engineers face significantly more test challenges than just a few years ago. Board complexity is dramatically increasing with more components, more joints, higher densities and new package technologies. The higher component and joint counts create more defect opportunities, which lead to lower yields for a given defect level. Fortunately, test and inspection methods such as solder paste inspection (SPI), automatic x-ray inspection (AXI) and automatic optical inspection (AOI) have emerged over the past several years. These techniques are providing effective additions to traditional test technologies at in-circuit test (ICT) and functional test.

Although these new tools give more choices, they also pose new dilemmas. What is the right test/inspection strategy? And what is the right combination of these tools? Several factors influence what test technologies are the right selection for a particular PCB assembly. These factors include the degree of complexity of the boards, the dominant manufacturing process (no wave, wave, selective wave) and the primary goal of the testing effort—defect containment, process improvement or both.

Determining PCB Complexity

The complexity of the PCB assembly directly impacts the number of defects it has, which, in turn, affects the test strategy selection. The higher the complexity of a PCB assembly, the more high yields are difficult to achieve without additional test and inspection. A complexity index introduced in 1999 has been recently updated to include the effect of joint density on the PCB assembly's overall complexity (see Sidebar). To illustrate how complexity affects yields, compare three different assemblies with low-, medium-



and high-complexity. Assume all are double-sided with a joint density of 100 joints per sq. in. in a high-mix production environment; all have a defect level of 200 defects per million opportunities (DPMO) for both components and solder joints:

- low-complexity board: 100 components and 500 solder joints for a total of 600 defect opportunities (100 components + 500 solder joints)
- medium-complexity board: 1,000 components and 5,000 solder joints for a total of 6,000 defect opportunities
- high-complexity board—3,000 components and 21,000 solder joints for a total of 24,000 defect opportunities.

$$\text{Yield} = [1 - (\text{DPMO}/1,000,000)]^N$$

(DPMO=defects per million opportunities;
N=defect opportunities)

The formula above results in a yield out of the surface-mount process of: 89% for the low-com-

plexity board; 30% for the medium-complexity board; and 1% for the high-complexity board.

Almost all of the low-complexity boards will be good, while almost all of the high-complexity boards will have at least one failure per board. Yield drops exponentially when defect opportunities increase linearly, even with the same number of defect opportunities per year. Thus, higher complexity boards demand a more effective test strategy to ensure defects are detected and repaired before shipping the board.

Manufacturing Process and Defects

Along with complexity, the manufacturing process also influences the number of defects. In several studies we found that defects are added at every process step and especially at reflow and wave soldering. The reflow oven essentially works like a defect transformation box. That is, many defects going into the reflow oven will be corrected, while other defects, like opens and shorts, will be created or at least only become noticeable after reflow. Examples of defects that change include misaligned parts that self-align, insufficient solder paste that can form acceptable joints, parts that fall off and seemingly good parts that do not solder. At the same time, some defects are the same both before and after the reflow oven—missing parts will still be missing.

The wave process also introduces significant numbers of defects. On the average around 50 percent of all defects appear to be introduced at the wave process. These data point to the need for having effective defect containment at the end of the manufacturing process, either after reflow or after wave.

Test Effectiveness Studies

Armed with the knowledge of where defects occur and how they correlate to higher levels of board complexity, the next step is to examine what test technologies are the most effective and where to use them. The key insights have been gained by doing test effectiveness studies¹ and studies of overall effectiveness when a combined strategy of x-ray test and simplified ICT test is evaluated.²

These studies were done on a smaller sample of boards, typically between 20 to 100 boards to ensure the integrity of the resulting data. The same set of boards was inspected by the dif-

Defining High Complexity

High complexity is a very subjective term. To promote a more objective standard, a Complexity Index has been developed [3] that is based on the number of components, joints and board sides and low-volume/high-volume production batches.

A recent, key enhancement was to reflect the impact of component joint density on the complexity of a PCB assembly. The new, updated Complexity Index is:

$$Ci = ((\#C + \#J)/100) * S * M * D$$

Ci = Complexity Index

#C = Number of components

#J = Number of joints

S = Board sides (1 for double, _ for single)

M = Mix (1 for high mix, _ for low mix)

D = Density ((joints/sq. in.)/100) or (joints/square cm/15.5)

If the resulting Complexity Index is:

- below 50, the assembly is considered a low-complexity board.
- between 50 and 125, the assembly is considered a medium-complexity board
- above or equal to 125, the assembly is a high-complexity board.

ferent methods—AOI, AXI and ICT—separately to see how many defects each technology could uncover. Between inspections, none of the defects were repaired to ensure each system was examining the same board. AOI, AXI and ICT were performed after the following process (Table 1).

The test effectiveness studies clearly revealed the relative capabilities of the different types of test inspection equipment and gave some insights on the optimal placement for these inspection systems.¹ The Venn diagram in Figure 1 shows the defect coverage for each type of equipment in one such study. Here, ICT is only catching 22% of all defects. Adding AOI to this test process increases the test effectiveness to 46%. Adding AXI to ICT increases the test effectiveness to 95%.

Next, the study looked more closely at the AOI and AXI results at each process step. Figure 2a reveals that AOI post-

Process step	AOI	AXI	ICT
Post-pick-and-place, Pre-reflow	X		
Post-reflow, Pre-wave	X	X	
Post-wave		X	X

TABLE 1: The experiment's test/inspection process.

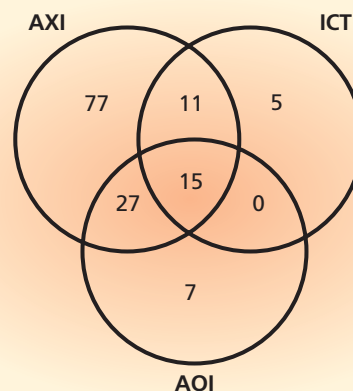


FIGURE 1: Defects found by AOI, AXI and ICT.

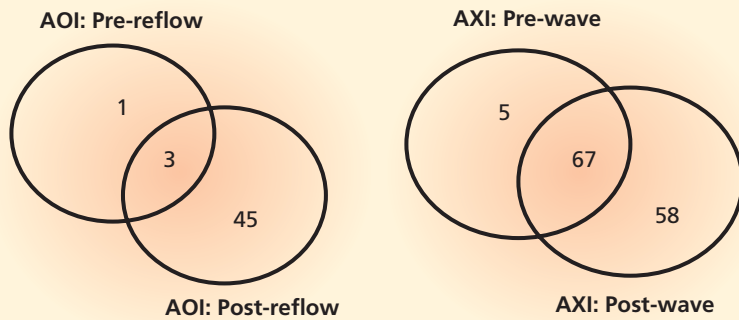


FIGURE 2: a) Defects found by AOI pre-reflow and AOI post-reflow; b) Defects found by AXI pre-wave and AXI post-wave.

reflow was more effective than AOI pre-reflow to detect final defects. Note that pre-reflow AOI detected many process indicators—for instance, misaligned components that were corrected by the surface tension at the reflow process. Thus, the AOI pre-reflow can contribute significantly to process improvements and adjustments of the placement machines.

Figure 2b indicates that AXI is more effective post-wave than pre-wave because the wave (or selective wave) process introduces a very significant number of defects.

Process Control, Defect Containment

Several general conclusions can be drawn and applied to create the optimal test strategy. First, the results clearly show that AOI and AXI have higher defect coverage than the traditional ICT approach.

In fact, all our case studies show that x-ray based inspection is the most effective automatic inspection tool, typically finding 85 to 95% of all manufacturing defects. AXI can also find visually hidden features, and three-dimensional (3-D) x-ray can test both sides of a double-sided board in one pass. AOI, although not as comprehensive in fault coverage as AXI, does provide distinct advantages such as good defect coverage with the fastest inspection per board side at a lower cost than AXI. An AOI system can give fast process feedback, pre- and post-flow, and is usually easier to program than an AXI system.

Where to deploy these tools depends on the test objectives. If the main objective is to improve process control with short feedback loops, the focus of the test strategy should be early in the manufacturing process to ensure faster process feedback. Here, SPI and AOI systems are the most useful in uncovering conditions to prevent defects further in the process.

If the foremost objective, on the other hand, is to improve defect containment, the focus of the test strategy should be at the end of the process. Here, what inspection tool to use depends on the complexity of the board assembly. For low- and medium-com-

plexity boards AOI will provide sufficient defect detection. For higher defect coverage and good throughput, AXI is the best choice. For the highest complexity boards, however, the most prudent solution is a combination of AOI and AXI to ensure optimal defect detection. Process control and defect containment do not need to be mutually exclusive. No matter how good the process control, random defects will always occur. The objective should be for all manufacturing defects to be found prior to functional and system test to have the highest yield possible into functional test.

How much inspection is implemented depends on board complexity and volume. For higher complexities and higher volume, a good strategy is to add several automatic inspection steps. In many cases having automatic inspection early in the process for prompt process control and, at the same time, at the end of the manufacturing process for defect containment makes sense. The process control versus defect containment part of this strategy is illustrated in Figure 3.

Finding the Right Balance

As the test effectiveness studies show, adding automated inspection equipment to in-circuit and functional test can dramatically improve both defect detection and process control. Depending on the board complexity and what the test objectives are, judicious use of AOI and AXI technology can offer significant additional coverage—resulting in higher quality, lower warranty, repair and scrap costs.

References

1. Tracy Ragland, "Test Effectiveness: A Metric for Comparing Apples to Oranges in Electronics Test," Proceedings of APEX 2002.
2. Joe Kirschling, "Improved Fault Coverage in a Combined X-ray and In-circuit Test Environment," Proceedings of EtroniX 2001.
3. Stig Oresjo, "A New Test Strategy for Complex Printed Circuit Board Assemblies," Proceedings of Nepcon 1999.

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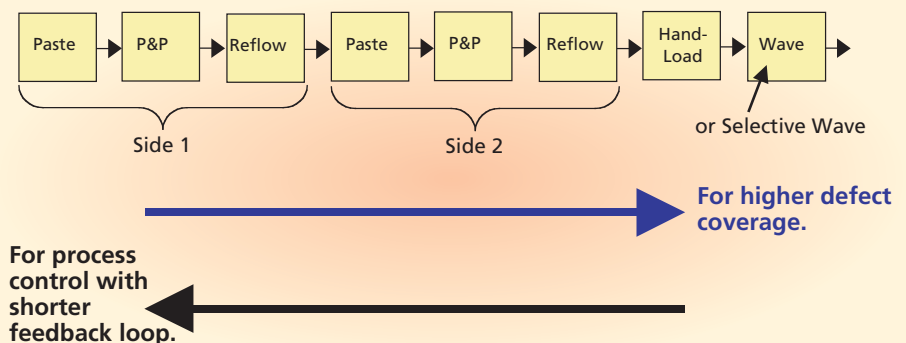


FIGURE 3: The concept of automatic inspection for process control vs. defect containment.