

Adding AXI to a PCBA Test Process

More PCB manufacturers are considering automated X-ray inspection (AXI) to solve inspection problems. This article offers models to calculate the real economic impact of adding AXI to the test mix based on machine performance, volume, failure rates, repair cost, and other factors that affect the overall return on investment of an inspection system.

By Paul R. Groome, Teradyne, Inc.

When considering the test-and-inspection mix, it is best to first look at AXI, automated optical inspection (AOI), and in-circuit test (ICT), as well as their basic capabilities. This is important because the economics of AXI should be evaluated in the context of complementary test-and-inspection operations. Figure 1 shows that AXI can better complement electrical testing than AOI, primarily because AXI is not affected by the lack of electrical and optical access. AXI better detects voids, solder quality defects, hidden joints, and V_{CC} and G_{ND} pins that are otherwise inaccessible using AOI. Combining AXI and some form of ICT has proven to raise the fault coverage of process and electrical defect classes to nearly 100%.

Test-and-Inspection Flow

Before analyzing the economics of AXI, it is important to note that the workflow of test-and-inspection processes also influences cost. ICT is a closed-loop process in which the board is tested and repaired. Boards that fail a second time typically will be repaired and tested again, or scrapped. In this scenario, boards are inspected, debugged, and repaired, if necessary, then passed to ICT for electrical and functional test. The re-inspection of repaired boards is not common because a manually produced solder joint is structurally different from one produced using a reflow oven. Therefore, it cannot be inspected by either AXI or AOI reliably.

With these factors in mind, let's examine the economics of AXI. The first step is to determine test access, or the level of physical access an inspection or test stage has to the PCB. In this case, we assume that ICT has 80% test access, functional test (FT) has 50%, environmental stress screening (ESS) has 50%, and system test has 25%.

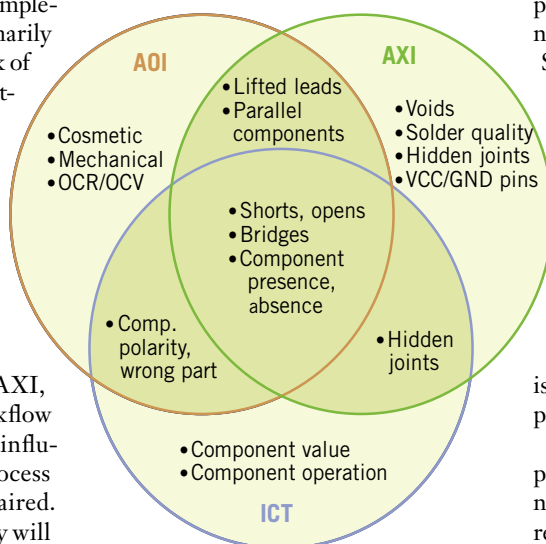


Figure 1. Defect coverage of popular test-and-inspection solutions.

Fault coverage, on the other hand, refers to the effectiveness of a test stage in detecting a specific defect type on a fully accessible location. The test coverage is the product of fault coverage and test access. Figure 2 shows assumptions that have been made

for structural and electrical fault coverage for each stage of testing. Test coverage is the average of the structural and electrical test weighted by the number of opportunities for error in each area.

The example is based on conditions that a typical low-volume North American or European assembler would face. The company produces a board with 2,000 components; 15,000 solder joints; and a value of \$5,000 at a volume of 10,000 per year.

The board has a repair yield of 85%, and up to five repair cycles are permissible — yielding a calculated scrap rate of 0.0076%. The electrical defect rate, expressed in defects per million opportunities (DPMO), is 160 parts per million components (ppmC), and the structural defect rate is 235 parts per million joints (ppmJ). The average number of structural defects per board is 3.525; the number of electrical defects per board is 0.32.

Figure 3 shows the cost involved in each phase of the testing cycle. It's important to note that the cost of verification/diagnosis, repair, and retest increases substantially at each successive stage in the testing cycle, from ICT to FT to ESS to system test. This explains why overall costs can be reduced by identifying more defects in the early stages of test and inspection, when they can be diagnosed and repaired at a lower cost.

AXI System Performance

The performance of the AXI system, particularly the false failure rate, has a

major effect on economics. Current AXI systems can be divided into three basic types. Two-dimensional (2-D) and 2.5-D AXI systems use a stationary source beam and detector plate located perpendicular to the board's surface. They provide good

FOVs and are re-arranged to combine with FOVs that belong together. The final step of combining the images to generate a horizontal slice is carried out by shifting the images according to their unique reconstruction vectors, and then using the max-

required to obtain an unobstructed view of every solder connection are captured simultaneously, rather than sequentially.

As shown in Figure 4, the static image-capture method that is used in off-center tomography increases image quality, especially edge definition. Eliminating moving parts during image capture prevents smearing. This approach also provides a large FOV with the resolution needed to inspect 0201s. Using computational techniques to reconstruct images eliminates artifacts. Eliminating moving parts and expediting laser mapping cycle time makes it possible to operate at beat rates. Removing mechanical errors and averaging means that false calls are almost always below 500 ppmJ.

The resulting difference in the false fail rate has an effect on AXI economics. Inspection systems such as AXI and AOI present each individual defect to an operator for review. As the number of false fails rises, operators have more opportunities to make mistakes, so even if they are able to maintain performance, the number of escapes rises, as does the number of false repairs. The pressure of diagnosing a larger volume of failures often causes verification accuracy to suffer as well. In this example, at a 500-ppmJ false failure rate, AXI finds 3.42 real defects and 7.5 false failures per board. It passes 0.77 defects per board to ICT. On the other hand, the laminography-based AXI system with a 4,000-ppm false failure rate also finds 3.42 real defects, but finds 60 false failures per board. In this example, the operator could pass

| | 2-D AXI | 3-D AXI | ICT | FT | ESS | System |
|---|---------|---------------------------------|-----|---------------------------------|-----|--------|
| Test access | 72% | 99% | 80% | 50% | 50% | 25% |
| Fault coverage structure | 98% | 98% | 80% | 60% | 70% | 60% |
| Fault coverage electrical | | | 89% | 85% | 95% | 99% |
| Test coverage structural | 71% | 97% | 64% | 30% | 35% | 15% |
| Test coverage electrical | 0% | 0% | 71% | 43% | 48% | 25% |
| Test coverage | 62% | 86% | 65% | 31% | 36% | 16% |
| False fail rate (ppmJ)* | 100 | 500 | | | | |
| AXI false fail rate (ppmJ)-laminography | | 4,000 | | | | |
| False fail rate (ppm) | | | 50 | 10 | 5 | 2 |
| Verification error rate- AXI | 10% | % of escapes due to false fails | 2% | % of false fails sent to repair | | |
| Verification error rate-laminography | 25% | % of escapes due to false fails | 5% | % of false fails sent to repair | | |

Figure 2. Defect coverage and system capability data.

edge contrast and resolution on single-sided boards, but their capability is much lower on double-sided boards because components and features on either side of the board can overlap, becoming impossible to distinguish.

The traditional 3-D approach to AXI is based on laminography, a method used to inspect double-sided boards that requires motion of the X-ray source, detector, and board. The X-ray source is placed above the board and rotates at high speed in synchronization with a detector plate below the board. The board is moved in its Z-axis to achieve the desired focal plane. Object structures above and below the focal slice are blurred behind the focused level, leading to low-contrast resolution. The combination of mechanical movement and low resolution increases false call rates to between 2,000 and 10,000 ppmJ.

One approach based on the off-center tomography patent* acquires the angled images needed for 3-D inspection without mechanically moving the source and detector. It uses a stationary wide-angle X-ray source and a larger flat-panel detector. The source is positioned close to the detector, which is divided into nine equal-size sub-regions, making it possible to capture nine images simultaneously. The PCB is indexed across the field of view (FOV) of the X-ray source in a pattern called lawn-mowing. These nine images (taken at each PCB position) come from nine separate

value algorithm to eliminate "out-of-plane" objects that do not reside at the same vertical location. This ensures that at least one of the images it produces will provide an unobstructed view of every solder joint. For example, a slice can be obtained that removes all bottom-side components, so solder connections on the top side can be inspected. This approach also runs at a faster speed than previous tomographic methods because the multiple images

| Defect rate assumptions (process capability) | | | | | |
|---|------------|---------|---------|---------|--------|
| Electrical DPMO | 160 (ppmC) | | | | |
| Structural DPMO | 235 (ppmJ) | | | | |
| Board DPMO | 226 | | | | |
| # of structural defects/board | 3.525 | | | | |
| # of electrical defects/board | 0.32 | | | | |
| Debug/diagnosis and repair costs | | AXI | FT | ESS | System |
| Hourly labor cost of verification/diagnosis | \$15 | \$15 | \$15 | \$15 | \$15 |
| Hourly labor cost of repair | \$15 | \$15 | \$15 | \$15 | \$15 |
| Time to verification/diagnose one defect | 0.08 | 10 | 30 | 60 | |
| Time to repair one defect | 10 | 50 | 50 | 50 | |
| Cost to debug/diagnose one defect | \$0.02 | \$2.50 | \$7.50 | \$15.00 | |
| Cost to repair one defect | \$2.50 | \$12.50 | \$12.50 | \$12.50 | |
| Retest cost | \$0.00 | \$1.50 | \$3.00 | \$3.00 | |
| Cost of field failures/returns | \$25,000 | | | | |
| What is your current field return rate without AXI? | 0.0200% | | | | |

Figure 3. Cost assumptions used in example.

1.28 defects per board to ICT, while misdiagnosing 3 ppm of false failures as real failures — increasing component scrap.

Assembly Costs for AXI Alternatives

When considering a base case without AXI, costs were calculated according to the total cost of verification, repair, scrap, retest, and field failures — all of which are

test-and-inspection costs are \$588,969 without AXI.

In an example where a laminography-based AXI system with a false failure rate of 4,000 ppm is added prior to electrical testing, adding the AXI system reduces electrical testing costs by reducing DPMO on the board prior to test. However, the AXI system adds cost, particularly in the area of component scrap and false repair. The net result is that costs are \$137,184 higher than in the base case without AXI, with significant reductions in DPMO rates.

Figure 5 shows the manufacturing cost of off-center tomosynthesis AXI with a false fail rate of 500 ppm. In this case, the

DPMO remaining on the board after AXI is reduced to 14.9 because operators have an easier verification task with less than one-sixth as many defects to verify compared to laminography. The cost of false repairs and component scrap also are lower due to the reduced volume of false fails. Electrical testing costs are reduced below the level of laminography because of reduced

DPMO after completing AXI. The result is that costs are reduced to \$491,024 — a reduction of \$97,946 compared to the non-AXI case.

Conclusion

In all examples, AXI provides significant increases in delivered quality; however, the cost of delivering that quality varies with the technology used. The methods presented can be used to analyze the economic impact of adding AXI to virtually any PCB manufacturing process. This economic analysis illustrates the critical importance of the false failure rate of the AXI system being analyzed, as well as the initial fault coverage achieved. Reducing false failure rates will, in turn, reduce the number of decisions presented to the operator, the opportunity to make errors, and scrap and field returns. The effects of adding various types of AXI systems should be considered carefully in any PCBA application because of the potential for substantial reductions in manufacturing costs. **SMT**

*ClearVue and TraX, Teradyne, Inc., North Reading, Mass.

Paul Groome, manager, Teradyne, Inc., may be contacted at (858) 391-3810; paul.groome@teradyne.com.

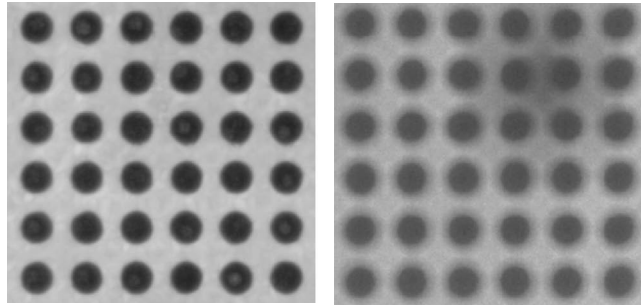


Figure 4. Off-center tomosynthesis (left) provides sharper images than laminography (right).

influenced by test and inspection. If the DPMO is 80.1 prior to testing and 30.1 after all tests are completed, that would indicate that field failures and returns should about \$100,000,000. However, they actually are much lower because many defects, such as redundant power connections, decoupling capacitors, and unused parts do not cause failures. Total

Figure 5. Cost calculations for off-center tomosynthesis-based AXI.

| | AXI | ICT | FT | ESS | System | | |
|--|------------------|-----------------|-----------------|-----------------|----------------|------------------|--------------------|
| Structural defects before test (per board) | 3.525 | 0.447 | 0.161 | 0.113 | 0.073 | | |
| Structural defects after test (per board) | 0.447 | 0.161 | 0.113 | 0.073 | 0.062 | | |
| Electrical defects before tests (per board) | 0.320 | 0.320 | 0.092 | 0.053 | 0.028 | | |
| Electrical defects after test (per board) | 0.320 | 0.092 | 0.053 | 0.028 | 0.021 | | |
| Structural defects (per board) | 3.078 | 0.286 | 0.048 | 0.039 | 0.011 | | |
| Electrical defects (per board) | 0.000 | 0.228 | 0.039 | 0.025 | 0.007 | | |
| Total defects (per board) | 3.078 | 0.514 | 0.087 | 0.065 | 0.018 | | |
| First pass yield | 4.65 | 59.8% | 91.6% | 93.7% | 98.2% | | |
| Overall total effectiveness | 80% | 67% | 35% | 39% | 19% | | |
| DPMO remaining on board after test | 45.1 | 14.9 | 9.7 | 5.9 | 4.9 | Total | Savings |
| Annual cost of false fails at verification | \$1,563 | | | | | \$1,563 | (\$1,563) |
| Annual cost of false reports | \$3,750 | | | | | \$3,750 | (\$3,750) |
| Annual cost of AXI system | | | | | | \$110,000 | (\$110,000) |
| Programming cost | | | | | | \$12,800 | (\$12,800) |
| Annual cost of verification | \$712 | \$5,996 | \$2,186 | \$4,845 | \$2,680 | \$16,420 | \$62,285 |
| Annual cost of repair | \$76,949 | \$29,980 | \$10,931 | \$8,075 | \$2,234 | \$128,169 | \$122,902 |
| Annual cost of component scrap | \$161,398 | \$25,697 | \$4,372 | \$3,230 | \$893 | \$195,591 | (\$28,927) |
| Annual cost of PCB scrap | | \$5,179 | \$977 | \$568 | \$197 | \$6,921 | \$10,059 |
| Annual cost of retest | | \$4,019 | \$1,256 | \$1,877 | \$531 | \$7,683 | \$17,867 |
| Annual cost of field failure rates & returns | | | | | | \$8,127 | \$41,873 |
| Total | \$244,372 | \$66,852 | \$18,467 | \$16,718 | \$6,005 | \$491,024 | \$97,946 |