Improved Fault Coverage in a Combined X-Ray and In-Circuit Test Environment

[Using Agilent AwareTest xi]

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Abstract

Cutting functional test failures in half and doubling the faults detected at process test! These are some of the case study results observed in combined x-ray and in-circuit test environments [e.g., including use of Agilent AwareTest xi software].

Today's complex and high node count Printed Circuit Boards (PCBs) can be difficult to test. With increasing component and node counts, these complex PCBs also increase the opportunities for board manufacturing defects, difficulty in isolating these potential defects, and challenges to reliably create fixtures. To accurately detect, diagnose and repair their manufacturing faults, several manufacturers test these PCBs with multiple types of test systems. This multiple tester style environment combines two or more different types of PCB testers. Currently one strategy combines automatic x-ray inspection with a modification of traditional in-circuit testing.

While this strategy changes the manufacturing test paradigm, it also:

- Increases overall fault coverage
- Better isolates defects on complex PCBs
- Decreases in-circuit fixture complexity, improving probe contact, while reducing fixture shorts, cost and weight
- Addresses limited in-circuit test access regardless of the PCB complexity

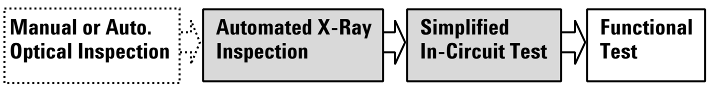
This paper compares a traditional in-circuit test strategy to this combined x-ray/in-circuit test environment. It examines and summarizes results of fault coverage and functional test yield studies. [Three of the four case studies used Agilent AwareTest xi to reduce in-circuit test probes.] In this context, this paper also describes the testing concepts and types of defects detected with this combined test environment.

The Test Strategy

Over time, increasingly complex PCBs have dictated changes in manufacturing test methodologies. Test methods have evolved from manual visual inspection, to include some combination of automatic optical inspection, in-circuit test and functional test.

With today's continued increases in PCB complexity, some manufacturers employ a strategy of automated x-ray inspection followed by simplified in-circuit test (and functional testing), as illustrated in Figure 1. This test strategy exploits the strengths of both x-ray inspection and in-circuit test to improve fault coverage. A few manufacturers also precede this strategy with either manual or automated optical inspection.

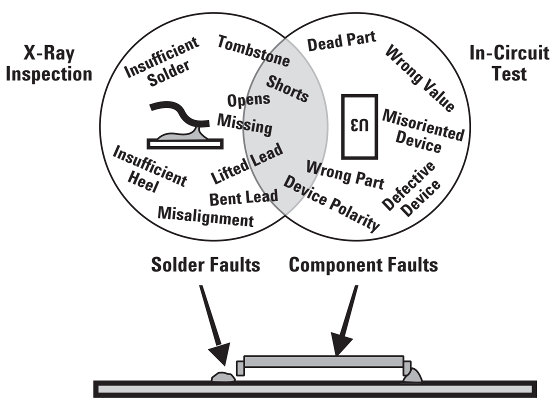
Figure 1 - Combined X-Ray & In-Circuit Test Environment



Fault Coverage

This test strategy capitalizes on the strengths of each test technique, maximizing fault detection while minimizing test redundancy. Figure 2 illustrates the faults detected by each test technique.

Figure 2 - Combined X-Ray & In-Circuit Test Environment



With this strategy, x-ray inspection is focused on its strength, identifying manufacturing solder defects (shorts, opens, insufficient or excess solder). The in-circuit test verifies device faults (device type, orientation and operation). Combining these test techniques improves overall fault detection. The x-ray inspection increases the number of inspected solder joints over those tested by only in-circuit test, while in-circuit test identifies device faults which are invisible to x-ray inspection. This test strategy also improves defect isolation. X-ray inspection identifies solder defects to the device pin level. In-circuit test identifies device defects to at least the device level.

When combining these two test methods, there will be some overlap of fault coverage (shorts, missing components, device polarity, etc.). Because of this, in-circuit testing can be simplified.

Simplified In-Circuit Test

X-ray inspection verifies that all devices are present, that no device pins have open solder joints, and that there are no shorts on the PCB. Following this, the in-circuit test only needs to ensure that the component is:

- The correct type
- Oriented properly
- Operational

Since we do not need to test every device pin in order to detect these faults, in-circuit test probe access can be intelligently removed. Figure 3 illustrates examples of required and non-required PCB access for 4 devices.

- U1 – This device requires access to only the boundary-scan TAP signals.
- U2 – This device requires access to only 1 of the 4 AND gates.
- RP1 – This device requires access to only 1 of the 4 resistors.
- CR1 – This device requires full access for the discrete analog test.

Figure 3 - Required Node Accessibility for Simplified In-Circuit Tests

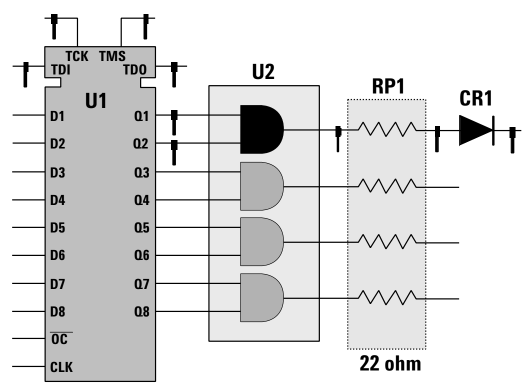


Table 1 summarizes the probing access required at in-circuit test when implementing this strategy, assuming an x-ray inspection of 100% of the board's solder joints. These general rules can be modified to probe all device pins if the x-ray system does not inspect the device (e.g. press-fit connectors) or does not fully test all pins (e.g. some plated through-hole devices).

Executing intelligent probe reduction analysis on a suite of boards has reduced required probe access anywhere from 23% to 77%. Functional test then concentrates on verifying the PCB's overall operation, with a lower incidence of board failures and a higher yield resulting from the previous test steps.

Table 1 – Required Probing Access for Simplified In-Circuit Test

Tests or Devices	Required Access
Shorts/Opens	None
Analog	
Discrete Analog Devices	Full Access
Resistor Packages	Access for 1 Resistor per Package Only
Digital	
Standard Devices	Access for 1 Function per Device Only
Boundary Scan Devices	Access for TAP Signals Only
Powered Analog/Mixed Signal	Full Access
Connectors	None
Power Nodes	Full Access

When testing high complexity boards, this probe reduction can have many positive impacts on the in-circuit test. These include:

- Reduced fixture cost
- Reduced fixture weight
- Reduced fixture complexity (i.e. vector-less tests for standard digital devices are not necessary as they are redundant with x-ray inspection)
- Improved probe contact
- Reduced fixture shorts

In-circuit probe reduction also assists testing of less complex boards with limited test access. During the design phase, this analysis can also be performed on smaller boards to intelligently identify nodes for probe removal.

Combined Test Strategy Benefits

Using this combined x-ray/simplified in-circuit test strategy can improve board test in the following areas:

- Higher overall fault coverage compared to a traditional visual inspection/in-circuit test strategy
- Improved quality in reducing both field board failures and fixture contact problems (when reducing fixture probes)
- Reduced cost of fixturing, programming and repairing
- Capability to test larger PCBs (beyond the capability of current in-circuit test systems without resorting to split fixture tests)
- Faster time-to-market
- Design for Test (DFT) tools to intelligently remove in-circuit probing access

This paper focuses on fault coverage improvements with this test strategy. The best way to measure fault coverage is to examine functional test yield, as this is where undetected faults show up. In these studies, some of the other benefits will also be covered.

This paper presents the results of 4 case studies using this combined x-ray/in-circuit test environment. Each case study was designed and executed by different users, with different project goals. All of them, however, compare full in-circuit test with the combined x-ray inspection/in-circuit test environment, usually using the simplified in-circuit test. Although each case study measures different parameters and the measurement methods differ, each study does show differences in functional test yield with each test method.

Case Study #1

An Original Equipment Manufacturer (OEM) performed the first case study [1] with this combined test strategy. They monitored yields from boards produced by a Contract Manufacturer (CM). The goals of this study were to:

- Evaluate overall functional test yields when adding x-ray inspection to in-circuit test
- Evaluate the effect of adding the x-ray inspection on end customer returns

The OEM performed this evaluation on 5 different types of boards. Table 2 summarizes these boards.

Table 2 – Case Study #1 Evaluated Board Sizes

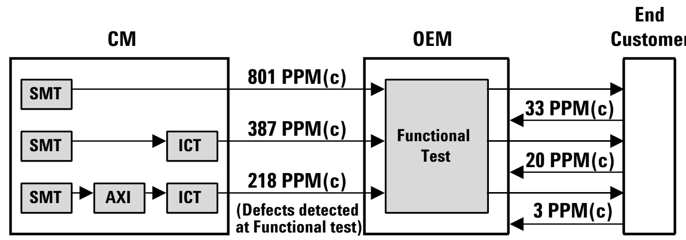
X-Ray/In-Circuit Comparison With In-Circuit Only – 5 Board Types			
	Minimum	Maximum	Average
Number of Components	200	490	353
Number of Solder Joints	1500	3654	2670
X-Ray Inspection		Production-Tuned	
In-Circuit Test		Production-Tuned	
Manual Visual Inspection Only – 1 Board Type			
Number of Components		183	
Number of Solder Joints		1321	

This case study monitored both functional test and end customer defects on approximately 4000 boards. The CM tested some of these boards (all 5 types) with only in-circuit test, and others with a combination of x-ray inspection and in-circuit test. Serial numbers identified the specific test method used for each individual board to properly track the failure data. The in-circuit test probed all accessible electrical nodes, which was most, but not all, nodes. The earlier-described simplified in-circuit test was not used in this case study. Both x-ray inspection and in-circuit test had been in use and tuned to the production process prior to this study.

In addition, this study monitored approximately 3000 of a less complex board, also shown in Table 2. This board was tested using only the manual visual inspection incorporated into the SMT manufacturing process.

This study tracked and computed parts per million failures on a component basis (PPM(c)) at functional test. Any component with multiple failures (i.e. multiple pin opens) was treated as a single fault. Figure 4 documents the results of this study. Adding in-circuit test to the process cut the defect rate at functional test in half (from 801 PPM(c) to 387 PPM(c)). Combining x-ray inspection with in-circuit test further reduced these defects detected, nearly in half again (to 218 PPM(c)).

Figure 4 - Case Study #1: Defective Rates at Functional Test



Because of the varying board size, PPM(c) provides the most accurate result comparison. To put this into perspective, these PPM(c) measurements can be used to estimate functional test yield. Assuming that the defects are distributed randomly across all components on each board, the in-circuit only test failure rate of 387 PPM(c) corresponds to a functional test yield of 86%, as follows:

(0.000387 failures/component) X (353 components/board) = 0.137 failures/board

Similarly the combined x-ray/in-circuit failure rate of 218 PPM(c) corresponds to a functional test yield of 92%, as follows:

(0.000218 failures/component) X (353 components/board) = 0.077 failures/board

As a comparison, the manual visual inspection-only failure rate of 801 PPM(c) corresponds to a functional test yield of 85%, as follows:

(0.000801 failures/component) X (183 components/board) = 0.147 failures/board

Adding x-ray inspection provided the most dramatic fault reduction with solder defects. Table 3 summarizes the solder defects detected at functional test with each of these test methods. Adding x-ray inspection eliminated or virtually eliminated board defects due to shorts, insufficient solder, opens, no solder and non-wetted pins. Coplanarity defects were also greatly reduced.

Table 3 – Case Study #1 Solder Defects Detected At Functional Test

Types of Defects	Solder Defects Detected At Functional Test (PPM(c)		
	MVI Only	In-Circuit Only	X-Ray + In-Circuit
Shorts	181	62	0
Insufficient Solder	15	9	0
Opens	10	12	3
No Solder	37	34	0
Coplanarity	160	57	17
Non-Wetted Pins	16	18	3
Total	419	192	23

Adding x-ray inspection to the in-circuit test also dramatically reduced field failures (from 20 PPM(c) to 3 PPM(c)), as shown in Figure 4. X-ray inspection identifies faults, such as insufficient solder, that can result in a marginal solder joint. If this solder joint makes electrical contact during both in-circuit and functional tests, the functional product ships to the end customer. After physical stress on the product (such as shipping), this marginal solder joint could become an open circuit, resulting in an end customer failure. Eliminating many of these faults at x-ray inspection results in the overall lower field returns on these products.

Case study #1 demonstrated that adding x-ray inspection to in-circuit test during the manufacturing process:

- Improved first pass functional test yield, reducing PPM(c) by almost half (from 387 to 218)
- Decreased end customer failures by almost an order of magnitude (from 20 PPM(c) to 3 PPM(c))
- Virtually eliminated board defects due to shorts, insufficient solder, opens, no solder and non-wetted pins, while greatly reducing coplanarity defects.

While this study shows functional test yield improvements (i.e. higher fault coverage), it was executed on a series of small, low complexity boards. Larger, more complex boards better demonstrate the power of this test strategy's improved fault coverage.

Case Study #2

A Contract Manufacturer (CM) performed the second case study [2]. This CM produces many large, highly complex boards. Their reasons for performing this case study were:

- Their customers continue to demand ultra-high reliability with tight schedules and budgets.
- High node count is driving fixture cost and weight up, lead time out, and reliability down.
- Product complexity of this magnitude results in lower test yields, reducing test throughput.
- Future assemblies will go beyond the node-count limits of the current in-circuit test system.

Table 4 describes the evaluated board and tests.

Table 4 – Case Study #2 Evaluated Board Size and Case Study Tests

Number of Components	2,240, including: 1,705 Discrete Analog Devices 137 Resistor Packages 148 Digital ICs (27 with Boundary-Scan)
Number of Solder Joints	24,223
Number of Electrical Nodes	5,659
Simplified In-Circuit Probe Reduction	54% (from 5,659 nodes to 2,602 nodes)
X-Ray Inspection	New
Full In-Circuit Test	Production-Tuned
Simplified In-Circuit Test	New

This case study compared a fully-probed in-circuit test on a conventional high node count test system with a combined x-ray/in-circuit test strategy, using the simplified in-circuit (i.e. lower probe count) test. In addition, the manual visual inspection performed on this board with the full in-circuit test was removed, as the x-ray inspection replaced it's fault detection. The full in-circuit test had been in use and tuned to the production process prior to this study. Both the x-ray inspection and simplified in-circuit test were new to the production process at the time of this study. The evaluation was performed on 25 to 150 boards, depending on the parameter measured.

Figure 5 - Case Study #2: Yield Measurements

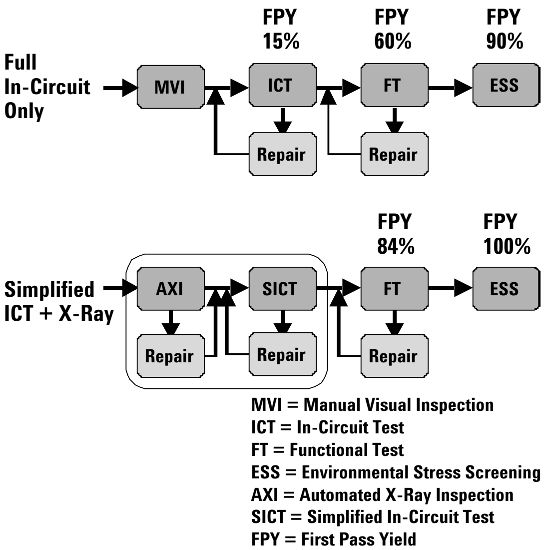


Figure 6 - Case Study #2: Measurement Test and Repair Times per Board

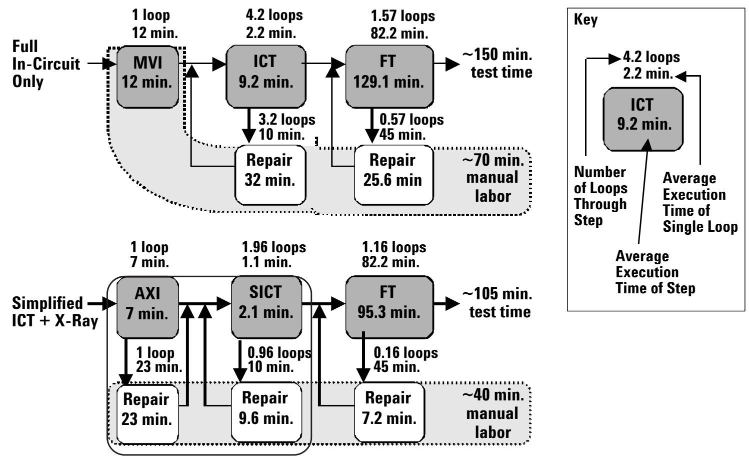


Figure 5 shows the results of this case study. Adding x-ray inspection, while reducing in-circuit test probing, increased first pass yield at functional test from 60% to 84%. While the 60% yield at functional test may appear low, this is because the size and component count of the board afford many more defect opportunities. This actually compares favorably to the first case study's yield. Comparing this data to PPM(c), 60% would correspond to an estimated 179 PPM(c), as follows:

(0.4 failures/board) / (2240 components/board) = 0.000179 failures/component

Similarly, the 84% functional test yield corresponds to an estimated 71 PPM(c), as follows:

(0.16 failures/board) / (2240 components/board) = 0.000071 failures/component

As with the first case study, this evaluation removed virtually all solder defects from the functional test failures when using x-ray inspection and simplified in-circuit test.

Implementing this test strategy also removed all test failures at environmental stress screening (ESS). This suggests that it may be possible to remove ESS when implementing the combined x-ray inspection and simplified in-circuit test strategy.

In addition to test yields, this study monitored test and repair times per board, as shown in figure 6. The test time for each step included any retest required on each board for that step. For example, the conventional high node count in-circuit test time averaged 2.2 minutes per execution. In this study, the evaluated boards entered this repair loop an average of 3.2 times. This resulted in an average of 4.2 tests on the in-circuit test system. Therefore the average test time for this test step was 9.2 minutes (2.2 minutes per execution X 4.2 loops).

This study measured an average test time savings of 45 minutes per board, and a 30 minute reduction in manual labor.

Reducing fixture probe count was also a prime motivation for this evaluation. Table 5 shows the results. In addition to the reduced probes, cost, weight, and build time, one difference noted dealt with fixture shorts. Because of the large number of test probes (over 5659) and the twisted pair wiring used in the traditional long-wire fixture, pressure from the wires forced small wire-wrap tails to intermittently contact other fixture probes or their wire-wrap tails. Because of this, the full in-circuit test fixture had a significant problem with fixture shorts. With the simplified in-circuit test fixture (less probes and single wires instead of twisted pair), no fixture shorts were detected. The long wire fixture program also required more maintenance, as wire capacitance changed with each fixture modification.

Table 5 – Case Study #2 Fixture Comparisons

Full In-Circuit Test	Simplified In-Circuit Test
5,659 Signal Nodes	2,602 Signal Nodes (54% Probe Reduction)
Traditional Long-Wire Fixture	Short-Wire Fixture
6 Week Build Time	2 Week Build Time
$37,000	$22,000
248 Pounds	148 Pounds
Significant Fixture Shorts	No Fixture Shorts

Case study #2 demonstrated the following:

- Adding x-ray inspection, while simplifying the in-circuit test, improved functional test yield from 60% to 84%.
- Combining these two test methods also eliminated all environmental stress screening failures.
- Overall test time per board (i.e. test cell throughput) was reduced by 45 minutes (150 vs. 105 minutes).
- Manual labor was reduced by 30 minutes per board (70 vs. 40 minutes).
- In-circuit test time per board was reduced by over 7 minutes (9.2 vs. 2.1 minutes).
- In-circuit test became much more efficient, sending an average board through the repair loop 0.96 times instead of 3.2 times.
- The automated process test bottleneck was reduced by over 2 minutes (9.2 minutes at full in-circuit test vs. 7 minutes at x-ray inspection).
- Fixture probe-count, cost, weight and construction time was significantly reduced.

Case Study #3

A CM and their OEM jointly performed the next case study. Their goals were to:

- Gain an experience in a combined x-ray/in-circuit test environment
- Select the best test strategy from among three

Figure 7 illustrates the 3 test strategies being evaluated. This case study compared the current test strategy (full in-circuit test) with a full combined test strategy (x-ray inspection followed by full in-circuit test) and a simplified combined test strategy (x-ray inspection followed by simplified in-circuit test).

Figure 7 - Case Study #3: Evaluated Test Strategies

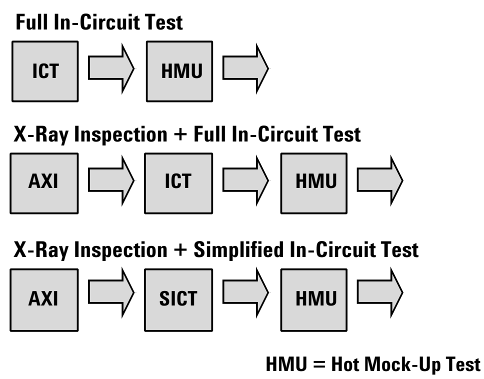


Table 6 describes the evaluated board and tests.

Table 6 – Case Study #3 Evaluated Board Size and Case Study Tests

Number of Components	2,523
Number of Solder Joints	14,000
Number of Electrical Nodes	3,955
Simplified In-Circuit Probe Reduction	43.2% (from 3,955 nodes to 2,248 nodes)
X-Ray Inspection	New
Full In-Circuit Test	Production-Tuned
Simplified In-Circuit Test	Production-Tuned

This case study evaluated 30 boards. To maximize board faults, all upstream manual visual inspection steps were removed for these boards. All boards were tested with all 3 strategies. To accomplish this, the boards were tested as follows:

- Boards were tested with x-ray inspection.
- Faults were noted, but not repaired.
- Boards were tested twice, with both full and simplified in-circuit tests.
- Faults were only repaired to continue in-circuit testing (e.g. after running both in-circuit tests, shorts failures were repaired, then boards were tested again with both in-circuit tests, etc.).
- After hot mock-up unit (HMU) functional testing, all faults were evaluated, repaired, and re-tested with the hot mock-up.

Both the full and simplified in-circuit tests had been in use and tuned to the production process prior to this study. Since this study used the same in-circuit test system for both full and simplified in-circuit testing, the production-tuned tests from the full in-circuit test were copied to the simplified in-circuit test and modified for probe removal. The x-ray inspection was new to the production process at the time of this study.

The study detected the following faults at each testing stage:

- Total defects on sample boards – 277
- Defects detected by x-ray inspection/simplified in-circuit combination – 271 (97.8%)
- Defects detected by only x-ray inspection – 245 (88.4%)
- Defects detected by only full in-circuit – 110 (39.7%)
- Defects detected by only simplified in-circuit – 97 (35.0%)

This case study detected 13 more faults with the full in-circuit test (110) than with the simplified in-circuit test (97). All of them occurred on nodes for which probes were removed. X-ray inspection detected all 13 faults.

Figure 8 illustrates these results. All 277 faults were verified by the CM and the OEM representative, and identified as true defects. The percentages for each test step represent the percentage of known faults detected by each test step. For example, the full in-circuit test detected 110 of the 277 known faults, which is effectively 40% fault detection. Without x-ray inspection, 158 faults (over half) would have escaped the test process. These faults would not normally be detected by electrical tests (in-circuit or functional). Figures 9 through11 illustrate some of these defects.

Figure 8 - Case Study #3: Fault Detection Results

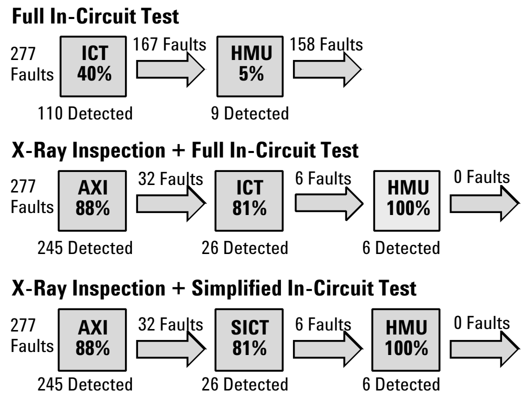


Figure 9 - Extra and Missing Device Faults

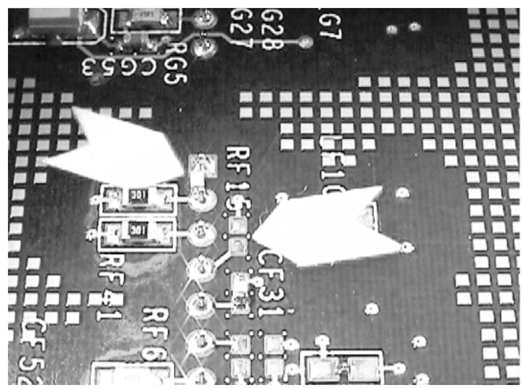


Figure 10 - Missing Device Fault

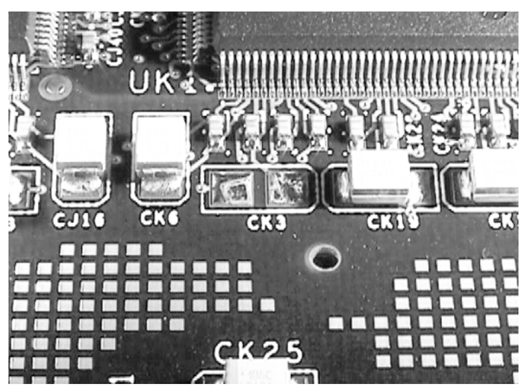
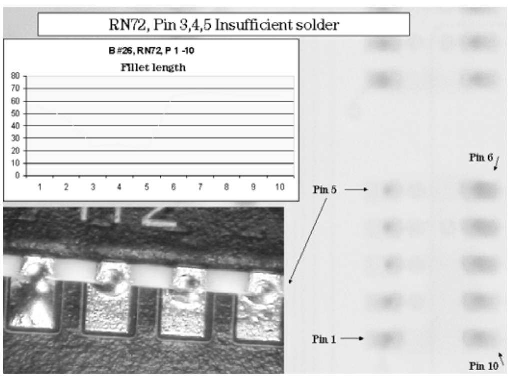


Figure 9 shows both a missing resistor and an extra device. All 3 test steps (x-ray inspection, full in-circuit and simplified in-circuit) detected the missing resistor. Extra devices, however, were detected differently. If the extra device was a resistor, both the full in-circuit and simplified in-circuit tests detected its presence with a resistance measurement. X-ray inspection, however, was the only test technique that detected the extra device if it was a capacitor. The tantalum material in capacitors is very opaque to x-rays, making their presence easy to detect.

Other board faults included missing by-pass capacitors (shown in Figure 10 (CK3)). Only x-ray inspection was able to detect these faults. With numerous capacitors in parallel, electrical tests can not identify circuits where one or two small-valued capacitors are missing. X-ray inspection, however, looks at the physical placement of each device, independent of its value.

Figure 11 - Insufficient Solder Fillet Fault



Another fault detected only by x-ray inspection, illustrated in Figure 11, was insufficient solder. These solder joints can make good electrical contact during in-circuit and functional tests, but could open after board vibration, such as shipping to the end customer. This figure shows the physical picture of these defects, along with the corresponding x-ray inspection image and resulting system measurement of the fillet length.

Case study #3 showed that by adding x-ray inspection and using simplified in-circuit test:

- No defect escaped the test process, compared to full in-circuit test.
- The number of defects captured increased significantly, from 110 (40%) to 271 (98%).
- The simplified in-circuit test reduced fixture test points by 43.2%.
- By finding faults earlier in the process, yields and throughput improved at subsequent test stages.
- With the current test process, there is a risk of shipping products with faults.

Case Study #4

A CM and their OEM also jointly performed the final case study. Their goals were to:

- Compare fault coverage of the current test strategy (automatic optical inspection/full in-circuit test) with the combined x-ray inspection/simplified in-circuit test strategy
- Gain an understanding of the combined x-ray inspection/simplified in-circuit test environment
- Better understand the strengths and weaknesses of the various test and inspection points

Table 7 describes the evaluated board and tests.

Table 7 – Case Study #4 Evaluated Board Size and Case Study Tests

Number of Components	3,291, including: 3,224 SMT 67 Through-Hole
Number of Solder Joints	32,106
Number of Accessible Electrical Nodes	7,500
Simplified In-Circuit Probe Reduction	60% (from 7,500 nodes to 3,000 nodes)
X-Ray Inspection	New
Full In-Circuit Test	New
Simplified In-Circuit Test	New

Figure 12 shows the two evaluated test strategies. The full in-circuit test strategy includes an Automatic Optical Inspection (AOI) between the SMT and wave solder processes. This test step was removed when adding the full x-ray inspection. This test strategy also uses x-ray inspection only on Ball Grid Array (BGA) packages. The combined test strategy replaced the BGA x-ray inspection with a full x-ray inspection, a superset of this test. All test steps (x-ray inspection, full in-circuit test and simplified in-circuit test) were new to the production process at the time of this study. Just under 20 boards were evaluated for this case study.

Figure 12 - Case Study #4: Evaluated Test Strategies

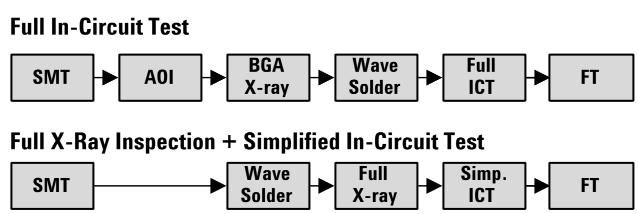


Figure 13 illustrates the results of this evaluation. Follow-up functional test stages detected additional faults on the sample boards. A third evaluation was also performed, adding an AOI test step to the combined x-ray inspection/simplified in-circuit test strategy. After evaluating all known board defects, the overall test effectiveness of these various test strategies are:

- Full In-Circuit Test & AOI = 51% (124 escapes into functional test)
- Full X-Ray Inspection & Simplified In-Circuit Test = 92% (20 escapes into functional test)
- Full X-Ray Inspection, Simplified In-Circuit Test & AOI = 97% (8 escapes into functional test)

Figure 13 - Case Study #4: Defective Detection Results

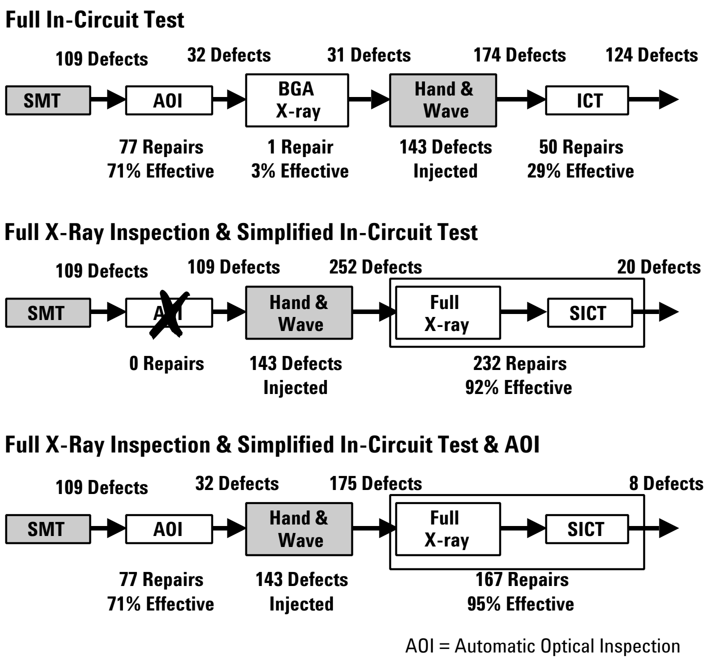


Table 8 summarizes the defects detected and not detected with each test strategy. While the combined x-ray inspection/simplified in-circuit test strategy detected significantly more defects, there were a few cases where the detected fault was better isolated with the full in-circuit test.

Case study #4 showed:

- The combined x-ray inspection/simplified in-circuit test environment detected more defects than the combined AOI and full in-circuit test process (92% vs. 51%).
- Adding AOI to this test strategy further improved this yield to 97%.
- The combined x-ray inspection/simplified in-circuit test environment detected virtually all solder related defects (opens, solder bridges, solder splashes, voids, excess solder, etc.).
- Defect isolation of the x-ray inspection system was excellent, with resolution to the solder joint.
- Risk of shipping products with latent defects or difficult to detect defects (poor solder, missing capacitors. etc.) was reduced.
- X-ray inspection provides detailed information to fine-tune the manufacturing process.

During this case study it was also observed that adequate staffing should be provided for repair of x-ray inspection faults. Should the operators inadequately repair these defects, they may or may not be detected by the simplified in-circuit test.

Table 8 – Case Study #4: Defect Summary For Each Test Strategy

Test Strategy	Defects Detected	Defects Not Detected
Full ICT & AOI	All misoriented & wrong parts	124 Faults
	Most misplaced & extra parts	123 of these detected by x-ray inspection/simplified ICT
	Many missing, tombstoned & defective parts, coplanarity faults & solder bridges	Most damaged parts & marginal solder faults (solder splashes, voids, excess, etc.)
		Many intermittent solder-related opens
		Lifted leads/coplanarity defects on QFP corner pins–typically power/ground
		Many missing bypass capacitors
		Some in-circuit defects beyond the capability of the high node-count ICT equipment
Full X-Ray & Simplified ICT	All missing, misoriented & wrong parts, & solder bridges	20 Faults
	Virtually all solder opens and marginal solder faults	12 Detected by AOI–2 deformed capacitors,10 solder or device lead defects *
	Most misplaced, damaged, tombstoned & defective parts & coplanarity defects	7 Detected by full ICT–extra parts, shorts & opens *
		1 defective IC detected only by functional test

* Many of these defects could be detected by x-ray inspection or simplified in-circuit test with additional test tuning.

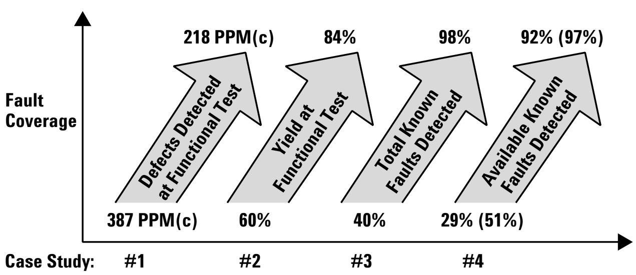
Summary

The results of these 4 case studies showed that adding x-ray inspection, while typically simplifying the in-circuit test, significantly improved fault coverage. Figure 14 summarizes this as follows:

- Case Study #1 measured almost a 2-fold decrease in PPM(c) defects at functional test.
- Case Study #2 produced a 24% improvement of incoming yield at functional test.
- Case Study #3 more than doubled the known process faults detected by the full in-circuit test alone.
- Similarly, case study #4 either doubled or tripled the available known faults detected, compared to either full in-circuit alone (from 29% to 92%) or combining these test strategies with AOI (from 51% to 97%).

While the measurements methods for each study differed, they all showed significant improvements in fault coverage.

Figure 14 - Overall Functional Test Yield Improvements When Adding X-Ray Inspection to In-Circuit Test



In addition, various case studies showed that incorporating this combined test strategy:

- Reduced failures at later test steps, such as ESS (case study #2)
- Reduced end customer returns (from defect levels of 20 PPM(c) to 3 PPM(c) – case study #1)
- Detected virtually all solder defects (case studies #1, #2 & #4)
- Improved overall test throughput (from 150 to 105 minutes – case study #2; qualitative observation – case study #3)
- Reduced manual test labor (from 70 to 40 minutes – case study #2)
- Reduced fixture cost, weight and build time (by $15,000, 100 pounds and 4 weeks, respectively – case study #2; 43.2% probe reduction – case study #3; 60 % probe reduction – case study #4)

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