Automated X-ray Inspection Strategies for High Volume Resource-Constrained Production Environments

Abstract

When manufacturers implement automated inspection systems that can detect subtle anomalies in the shape of a solder joint, there is a tendency for process indicators to fail inspection and be reported as defects. Data from a test vehicle experiment demonstrates the limitations of inspection machines when programmers subjectively define acceptance criteria. If engineers do not distinguish between defects and process indicators when performing test effectiveness studies, misleading conclusions can result. For example, the Test Effectiveness (TE) of ICT in a 100% node access environment can be reported as 41% or 78% depending on the defect definition that is used. The classification of process indicators as defects in a test effectiveness study can be used to support an “inspect everything, repair everything” approach. While this strategy may be desirable for some segments of the electronics industry that build very high complexity boards, a more reasoned approach to test and inspection is required for the vast majority of manufacturers that have constrained resources and capital expenditure budgets. The Production Test Effectiveness (PTE) metric is indicative of the economic advantage of a test strategy in these constrained environments. Case study data on high complexity double-sided boards with real production failures demonstrates that the TE of two different test strategies can be identical at 97% while their PTEs are 97% and 32%; this represents a three-fold difference in the total cost of ownership.

Introduction

Automated inspection systems are an important part of test strategies for modern PCBAs. Numerous publications in the test engineering community have documented the benefits of automated inspection[1] methods for finding structural defects on PCBAs[2]. It is well understood that test strategies that make use of automated inspection and in-circuit test techniques in an integrated manner provide benefits to electronics manufacturers[3 & 4]. A production test effectiveness study is a useful tool in evaluating the performance benefits available in these types of test strategies. A methodology and case study of a production test effectiveness study is presented.

Electronics manufacturers face a technological discontinuity in standards for post reflow automated inspection systems that inspect solder joints[1] and should carefully consider the limitations of these systems before beginning a test effectiveness study (the discussion in this paper does not apply to pre-reflow AOI systems - see endnote 1). The capabilities of modern AXI and AOI systems at finding structural flaws in placement and soldering processes far outperform the ability of human visual inspectors that have been the ‘mainstay’ in the manufacture of electronics for the last 30 years. When manufacturers implement automated inspection systems that can detect small changes in the volume or shape of a solder joint, there is a tendency to identify many subtle anomalies in the assembly process as failures that are not truly defects. This can lead to the implementation of non-value added inspection, unnecessary costs and sub-optimal production efficiencies. A more reasoned approach to test and inspection is required as compared to “inspect everything, repair everything”.

Limitations of Automated Inspection Systems

AOI and AXI systems that inspect solder joints post reflow[1] help manufacturers overcome challenges resulting from a loss of electrical and visual test access. Improved reproducibility is another common reason cited for the implementation of automated inspection systems. Machines deliver nearly identical results on repeated inspections of the same board, far surpassing the capabilities of human inspectors. When it comes to standards of acceptability, however, both automated inspection systems and human inspectors use subjective criteria to determine what is defective.

Human inspectors are “calibrated” to their own interpretation of a standard like IPC610 or JSTD001; inspection results will vary from one person to the next depending on each inspector’s view of the standard through their own lens. Similarly, an

amit.verma@teradyne.com

automated inspection programmer subjectively defines thresholds or pass/fail limits on machine measurements. The programmer uses simple statistical rules to fail “outlier” solder joints and defines acceptance criteria using heuristic methods (trial and error methods that make statistical assumptions about large populations). The machine is taught which solder joints are acceptable based upon the programmer’s interpretation of how the measurements correlate to the IPC610 standard. As more boards are tested, the inspection thresholds are refined and “tuned” over time. Although this procedure is an improvement over the human inspection technique, automated inspection systems deliver results that are based upon the subjective interpretations of the programmers. The same board tested on programs written by different people will deliver conflicting results.

AOI and AXI systems do not currently inspect solder joints according to traceable standards or models that correlate to IPC610. Until these machines can perform inspections according to an accepted standard, rather than subjective criteria derived from programmer interpretations, electronics manufacturers will not fully adopt the technologies and will continue to struggle with false failures, false accepts and high support costs. To address these problems, the NEMI (National Electronics Manufacturing Initiative) Test Strategy Project[5] began a Test Vehicle Analysis Experiment in June 2001. Recently, the 10 member companies concluded a preliminary study[6] that lays a good foundation for a solder joint acceptability model for automated inspection machines.

Test Vehicle Analysis Experiment

A screen print stencil was constructed to deposit different volumes of solder paste on consecutive pins of each package on a test vehicle board. Solder volume changes were created by varying the aperture length and width on consecutive pins on a stencil with uniform thickness. In this way, the paste volume on a QFP44 might vary gradually from 10% of nominal on pin 1 to 200% of nominal on pin 44 of the same package. Similar paste volume variation was induced on each and every package type on the test vehicle. The solder paste volume of each pad was measured post screen-print by a volumetric paste inspection system. After component placement and solder reflow, AOI and AXI machines inspected the test vehicle boards. The AOI and AXI machine measurements of each and every pin were correlated via X-Y scatter plot against the solder paste volume deposited on those same pins post screen print. Charts were constructed for each package type. The following package types were included in the experiment: PBGA256, CSP128, CSP44, BGA48, RESNET, TSOP48, QFP240, QFP256, VSOP48, 0201, 0402, 0603, 0805, and 1206.

[Figures 1 and 2 have been removed for reasons of confidentiality. These were the scatter plot charts described in the preceding paragraph. One chart was for transmission AXI and the other for laminography AXI. These charts are restricted to members of the Test Strategy Project Team until April 1 2004. Presentations to non-participant companies are permitted but hard or soft copies cannot be left behind. Contact amit.verma@teradyne.com, to get receive a presentation of this data. The charts demonstrate that thresholds on automated inspection systems are defined subjectively using trial and error methods. The charts also demonstrate that transmission x-ray systems can operate at 3-times faster test speed than cross-section laminography machines.]

The IPC 7-32 Subcommittee on Automated Inspection Technologies[7] has been formed to build further upon the preliminary work completed by the NEMI Test Vehicle Experiment. The 7-32 subcommittee will thermo-cycle solder joints to failure and correlate the inspection results to IPC610 as described above. In addition, the 7-32 team may use Finite Element Modeling (FEM) techniques to provide mathematical validation to the practical reliability results. The ultimate goal of the 7-32 team is to create traceable acceptance criteria for AOI and AXI machines and translate IPC610 into a “language” that automated inspection systems can directly measure, thereby minimizing dependence on subjective criteria defined by programmers. Because current users of solder joint inspection systems are still reliant on heuristic methods, the same boards tested on programs written by different people will deliver conflicting inspection results. It is not always clear which solder joints identified by the machine are truly defective and which joints are not defective but nonetheless fail inspection as a result of misapplied acceptance thresholds due to the lack of solder joint acceptability standards for automated inspection equipment.

Defects and Process Indicators

Electronics manufacturers face a technological discontinuity in the application of automated inspection systems that is causing confusion over the definition of a “defect”. The capabilities of modern AXI and AOI systems at finding structural flaws in placement and soldering processes far outperform the ability of human visual inspectors that have been the mainstay in the manufacture of electronics for the last 30 years. The performance benefits of automated inspection have helped test engineers address challenges of increased IO density, loss of ICT access, BGA hidden solder joints and increasing board complexity. However, it is precisely these same technological advantages of automated inspection that can lead to unnecessary costs and sub-optimal production efficiencies.

When manufacturers implement automated inspection systems that can detect small changes in the volume or shape of a solder joint, there is a tendency for many subtle anomalies in the assembly process to fail inspection that are not truly defective. Furthermore, when these machines are programmed using heuristic methods subject to individual interpretation without any traceable standard of acceptability, it is easy to understand that there is a large window of interpretation surrounding the acceptability of solder joints that fail an automated inspection program. A joint with a different solder volume (that is not electrically open or shorted) may be insufficient or excessive, but is it *defective*? The technological discontinuity described has created an environment where, for example, some manufacturers may use cross-section AXI systems in production environments to identify large numbers of solder joints and components as “statistically abnormal”. There is an inclination by users to assume that these statistical abnormalities are synonymous with IPC610 non-conformance and/or that they are traceable to field reliability results, on the contrary, these may in fact be good solder joints that fail inspection due to misapplied acceptance thresholds.

The implementation of automated inspection systems can sometimes cause the perception that the number of defects produced in manufacturing is much greater than the quantity previously believed. For example, Molamphy[8] reports that prior to the introduction of cross-section AXI, 357 defects were found using in-circuit and functional test methods (335 by ICT only) in a 100% node access environment. However, after implementing AXI, 907 total defects were reported on the same group of boards. Therefore, according to Molamphy, over 550 defects were never found by ICT or functional test and the total number of defects occurring in the manufacturing environment was nearly triple the number previously reported. A large proportion of these reported defects are insufficient, excessive and voided solder joints which would pass an electrical test, but lie within the large window of interpretation previously described. This data creates a “sky is falling” mentality that every single solder joint manufactured on every single board must be inspected with AXI, and can lead to an implementation of non-value added inspection, unsustainable levels of capital spending, unnecessary increases in manufacturing cycle times, higher repair costs and reduced production efficiency. Is “inspect everything, repair everything” the use-model for inspection equipment that our industry is moving toward?

It is important to note that when the perceived number of defects found is tripled, so too is the number of invasive repair operations on the PCBA. It is believed that solder joints that undergo repair operations have lower rates of field reliability than those that have never been repaired. What is the true impact of repairing these statistical abnormalities identified by these automated inspection systems? The tripling of invasive repairs can produce more field reliability problems than they solve. It is important to note that if an automated inspection system reports a solder joint as defective and needing repair, it cannot inspect the very same solder joint location after a repair intervention – this is due principally to the fact that the inspection system does not know what truly defines an acceptable solder joint in the first place, but rather identifies anomalies in populations of measurements. This means that even after paying the reliability risk (cost) of the repair action, the user is still not certain if the solder joint meets an acceptability standard[9]. Does repairing a subtle manufacturing process anomaly improve the quality or field reliability of a product? On the contrary, the reliability risk (cost) of repairing the solder joint can outweigh any perceived benefit. The bottom-line is that engineers must be cautious in applying an arbitrary definition of a “defect” when implementing automated inspection systems and performing test effectiveness studies. *So if it isn’t broke, then don’t fix it.*

Given the limitations of automated inspection systems and their tendency to report as failures many anomalies in the assembly process that are not truly defects, a more reasoned definition of a “defect” is required before fully adopting test strategies that include automated inspection systems. The authors propose that a defect is “a non-conformance that can cause a measurable failure during the product life that must be repaired prior to shipment of the product” and a process indicator is “an undesirable outcome of the manufacturing process that should be minimized by taking corrective actions on the manufacturing process using continuous improvement (SPC) methods, but does not need to be repaired prior to product shipment”. Some examples of defects are opens and shorts, while process indicators may be insufficient solder joints, excessive solder joints, skewed devices (that still make good electrical contact) and solder voids.

It is widely accepted that insufficient solder joints (and other solder quality problems) pose a reliability risk to manufacturers. Automated inspection systems can improve the field reliability of a product by detecting these insufficient solder joints that would otherwise pass electrical test methods. A reduction in warranty failures is often used to justify the capital expense required to implement automated inspection systems. Although manufacturers should work to reduce the incidence of insufficient solder joints when field reliability is a concern, a balance between a strategy that finds & repairs every single insufficient solder joint versus one that focuses on reducing their rate of occurrence is required. As discussed previously, a strategy focused solely on finding & repairing can create a reliability risk in itself due to the reliability concerns surrounding repaired solder joints. Manufacturing engineers improve the quality and reliability of their products by reducing the initial incidence of defects. When the defect rate is reduced, we improve quality and reliability and reduce costs. Product quality is not improved by asking a repair operator to fix every single insufficient, excessive and voided solder joint on a printed circuit board with a soldering iron (or by removing and re-attaching components). Rather, quality is improved through a balanced approach of finding & repairing these joints and also by noting the rates of occurrence of these types of non-conformances, identifying the root cause and taking corrective actions on the manufacturing process to reduce their rate of occurrence on the next board manufactured. If this continuous improvement activity is sustained over time, manufacturing teams deliver higher quality, higher reliability products to their customers at lower cost.

If engineers understand that test strategies must address both defects and process indicators, they can better plan for challenges that will arise during production. For example, SPC methods should make use of process indicator data to address the root cause of defects before they actually occur. This continuous improvement methodology has been an elusive goal of many AXI installations. The problem is that many of these installations are offline because the inspection speed of the system is too slow and boards are batch processed through the cross-section X-ray system. A continuous improvement strategy is most effective when feedback to the SMT line occurs in real-time using in-line inspection techniques like AOI. If the inspection system is offline and boards are batch processed, time sensitive information loses its value and many corrective actions can never be taken. If the inspection machine is in-line, actionable information can lead to reduced defect rates, lower DPMO[10], higher delivered quality and improved field reliability. In-line inspection creates an integrated assembly and test process – when the two operations occur simultaneously in real time, "quality becomes everyone's job" and manufacturing teams solve problems more effectively. The challenge with in-line inspection is inspection speed. In the past, few AXI systems could keep pace with modern SMT lines. Today, however, transmission AXI systems[11 & 15] perform at test speeds equivalent to AOI systems. Therefore both AXI and AOI systems perform at inspection speeds that match the beat rate of the fastest production lines in the industry.

The Production Test Effectiveness Metric

Test effectiveness studies are useful in determining the capability of inspection and test equipment at finding defects on a population of PCBAs. Test effectiveness experiments are generally performed under very controlled conditions, by dedicating focused resources and long periods of time to carefully document exactly how many failures are found by each machine in a test strategy. Engineers have a responsibility to consider constraints in real-world production environments before implementing test effectiveness experiment results. In the manufacturing environment we have constrained human resources, constrained capital expenditure budgets and constrained factory floor space. Engineers must consider the impact of these limitations before implementing experimental conclusions in production.

"Production Test Effectiveness" (PTE) is a measure of the defect coverage of a test strategy in a manufacturing environment with constrained resources. The PTE is a measure of the defect coverage of the test strategy when using fixed capital expense, fixed human resource and a fixed amount of floor space. These constraints are fixed because real world production environments do not have the unlimited resources that might be available under experimental conditions. Production Test Effectiveness is calculated by multiplying the percentage of total defects found with the relative throughput of the test strategy. Production Test Effectiveness is an important metric in volume manufacturing because these environments *are* constrained and a test strategy with 1/3 the throughput of another would require triple the resources, triple the floor space and triple the capital expense to implement.

Production Test Effectiveness (PTE) = (% of total defects found) x (relative throughput)

Note that the relative throughput is normalized to 1. If, for example, test strategy *A* provided three times faster test speed than *B (at the same outlay of resources)*, then the relative throughput of *A* would be "1" while that of *B* would be "1/3". If *A* provided three times faster test speed than *B* at ½ the outlay of resources (capital cost, floor space, support), then the relative throughput of B would be "1/6".

PTE is contrasted with Test Effectiveness (TE), which is simply the percentage of total defects found by the test strategy during the experiment (regardless of the resources required to implement the strategy).

Test Effectiveness = (% of total defects found)

As described in the discussion that follows, both TE and PTE reveal important attributes of product test strategies. A high PTE value indicates the cost effectiveness or economic advantage of a test strategy whereas a high TE value indicates effectiveness regardless of cost/constraints.

Test Effectiveness Case Study Background

The NEMI Test Strategy Project[12] conducted an investigation into the defect coverage of ICT, AXI and combined ICT and AXI test strategies in reduced access environments[13]. Two forms of automated X-ray inspection were investigated: transmission and cross-section[14]. Cross-section AXI inspects discrete slices of solder joints independently and therefore removes solder information from above and below the slice in each image; by contrast, transmission AXI inspects the entire solder joint volume in each image[15]. Each technique has strengths and weaknesses.

The primary benefit of cross-section AXI is that it exhibits the greatest solder joint test access. The primary disadvantage is slow inspection speed relative to transmission AXI. Figures 1 and 2 above demonstrate that the transmission AXI technique exhibits the same solder joint measurement discrimination at a field of view (FOV) that is more than 5-times the area of the cross-section technique (1 square inch vs. 0.16 square inches). Similar results were observed on all package types listed in the Test Vehicle Analysis Experiment. This means that transmission AXI systems can inspect many more joints in each field of view while providing equivalent defect coverage on accessible joints. The result is that transmission AXI systems exhibit 3-times faster test speed than cross-section AXI systems at the same resource level (capital expense, support, floor space). Therefore the weighted throughput for the PTE calculation is ‘1/3’ for cross-section AXI and ‘1’ for transmission AXI (note: transmission AXI operates at the same test speed as ICT and it is assumed the user is already using ICT, hence ICT has little impact on the weighted throughput figure).

The disadvantage of transmission AXI systems is that some subset of solder joints on double-sided boards is non-accessible due to overlap. Transmission AXI test access is board-dependent but is typically in the range of 70% to 95% for double sided boards that are between [4”x4” in dimension and have approximately 1500 joints] to boards that are [15”x12” and have 14000 joints] (boards that fit within these bands of dimension and joint count will typically exhibit between 70% to 95% solder joint test access). The premise of a combined test strategy is that strengths in one test platform are leveraged against weaknesses in another. If joints are not tested at ICT, they may be tested at AXI and vice versa. Solder joints not tested at transmission AXI can often be tested at ICT without negative impact on the total test coverage; results can vary depending upon DFT methods used during the PCB design and introduction cycle[2]. Software tools are available to aid manufacturers in this regard[10].

Two board types (see below) were included in the test effectiveness experiment and inspected using AXI and ICT machines. The failures found by each machine were carefully noted (solder joints were not repaired after AXI so that it could be determined if ICT would find the same failure). The data was analyzed to determine the failures that would be found using different types of combinational AXI and ICT strategies. A detailed description of the experiment methodology can be found at the footnoted web address[16].

	Board Type 1	Board Type 2
Total # of Boards in Experiment	15	30
# of Nets per Board	9,292	3,955
# of Joints per Board	33,325	14,346
Transmission AXI Test Access	39%	67%
Board Complexity	Very High Complexity / Double Sided	High Complexity/ Double Sided

amit.verma@teradyne.com

	/ Double Sided	Double Sided
# of Total Failures (defects + process indicators)	252	277

The failures on each board type are described by the figures below:

Figure 4 – Number of Failures on Board Type 1 by Failure Type

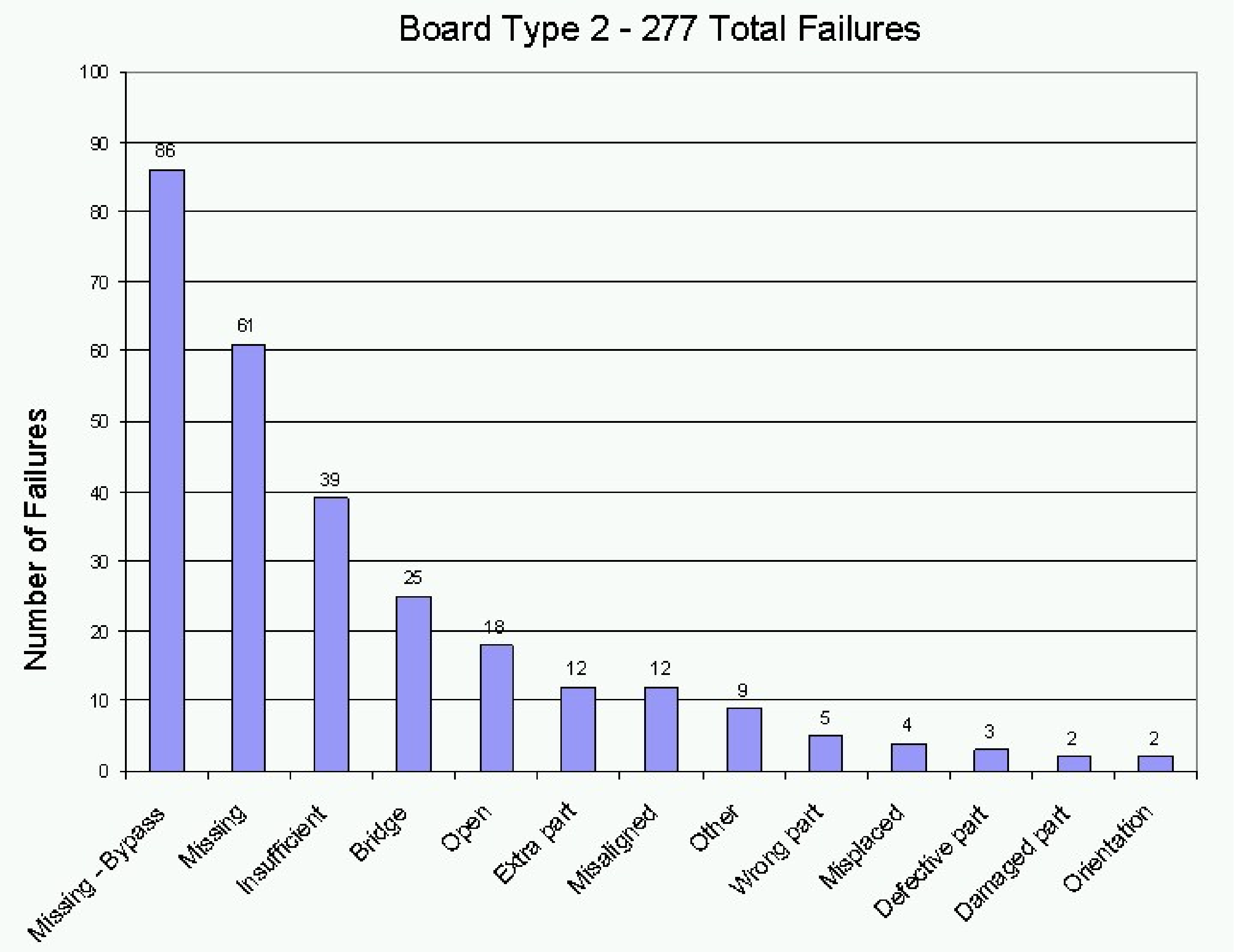


Figure 5 – Number of Failures on Board Type 2 by Failure Type

Test Effectiveness Study Results

The case study results are presented in the context of the definitions of defects and process indicators discussed previously. Without careful consideration of what constitutes a defect, engineers can arrive at misleading conclusions about the benefits of different test strategies during a test effectiveness study. It is evident that that AOI and AXI systems do not inspect solder joints using accepted industry models and that we have technological discontinuity with inspection standards. Programmers define threshold limits based upon imprecise interpretations of standards like IPC610. The IPC 7-32 committee on Automated Inspection Technologies is working to create traceable acceptance criteria and translate IPC610 into a “language” that automated inspection systems can directly measure. Because automated inspection systems have the capability to measure many subtle anomalies in the assembly process, there is a propensity to report many solder joints as defects that are truly process indicators. If engineers can distinguish between defects and process indicators when performing test effectiveness studies, they can better identify test strategies that will improve customer satisfaction and deliver competitive advantage at lower cost.

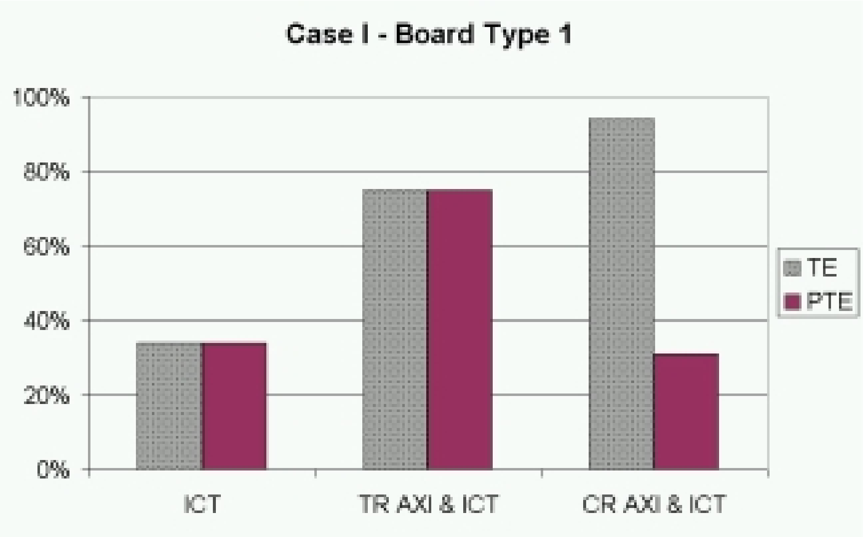
Note – All ICT figures in all sections below are at 100% node access to the board. Probe reduction can be achieved without changing defect coverage by removing probes where redundant coverage is provided at AXI or with techniques like boundary scan. More information on probe removal methods analyzed in the experiment can be found at the footnoted web address.[17]

Case I: Detection of Failures

If all defects and process indicators are considered together as failures, the ICT effectiveness figures that result are counter-intuitive to the known capabilities of ICT in 100% node access environments. The very low TE of the ICT-only strategy demonstrates the logical disconnect and technological discontinuity in inspection standards discussed previously.

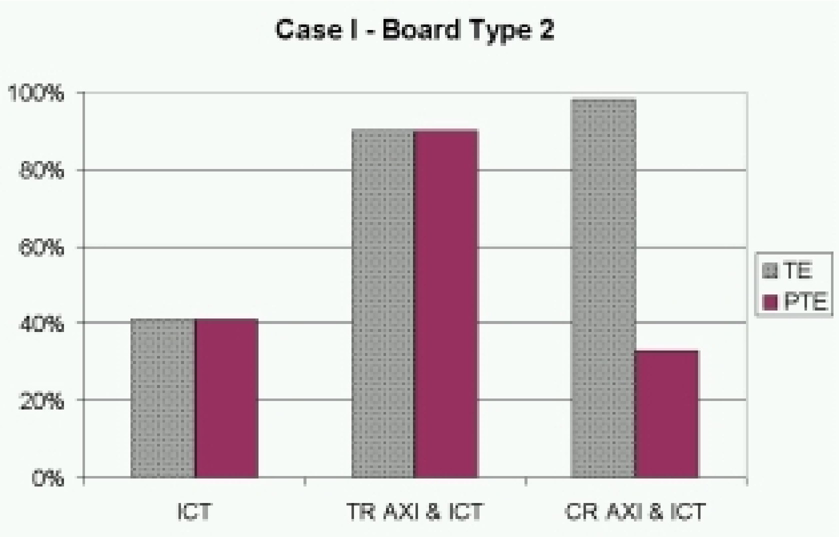
Case I, Board Type 1 – 252 total failures over 15 boards

- ICT Only	34% TE	34% PTE
- Transmission AXI & ICT	75% TE	75% PTE
- Cross-section AXI & ICT	94% TE	31% PTE



Case I, Board Type 2 – 277 total failures over 30 boards

- ICT Only	41% TE	41% PTE
- Transmission AXI & ICT	90% TE	90% PTE
- Cross-section AXI & ICT	98% TE	33% PTE



The ICT-only TE numbers seem to support the “sky is falling” mentality; it is obvious that ICT is not finding a very large number of the failures that are being found with AXI. Clearly the definition being used for a failure in this case encompasses the many types of subtle failures that are electrically good (i.e. not open and not shorted) that only automated inspection methods can find. Does every one of these types of failures need to be found and repaired? As discussed previously, repairing each and every insufficient, excessive and voided solder joint with a soldering iron (or by removing and re-attaching components) does NOT improve the delivered quality of the product. Also note the much lower PTE of the cross-section AXI strategy – manufacturers must consider whether the expenditures required to find every insufficient, excessive and voided solder joint are worth the very high costs of implementation. It is interesting to note that the PTE of cross-section AXI is lower than the PTE of the ICT-only strategy, primarily due to the relatively slow inspection speed of cross-section AXI. Cross-section AXI systems are on average 3 times slower than modern SMT lines. Is the cost of making the assembly process a “slave” to the test process worth the perceived improvement in delivered quality? The fact that the ICT-only PTE is higher than the cross-section AXI/ICT PTE may explain why there is low adoption of cross-section AXI in the vast majority of electronics product segments that have cost and throughput constraints. Clearly the PTE of the transmission AXI strategy is high.

The key observations from this data set are:

- The low TE of ICT in 100% access environments is counter-intuitive to the vast majority of manufacturers in the industry and demonstrates the logical disconnect and technological discontinuity of defect definitions and inspection standards in some test effectiveness studies.
- The TE of ICT for boards 1 and 2 seems to correlate with the TE reported by Molamphy (335 / 907= 37%), this validates the broad definition of failures (that includes subtle process anomalies) previously discussed.
- The TE of the transmission and cross-section AXI strategies are both much greater than the TE of the ICT-only strategy.
- The PTE of the cross-section AXI strategy is lower than the PTE of the ICT-only strategy – this may explain why there is low adoption of cross-section AXI in the vast majority of electronics product segments except those that make very high complexity boards in low volume
- The PTE of the transmission AXI strategy is more than double that of the cross-section AXI strategy.

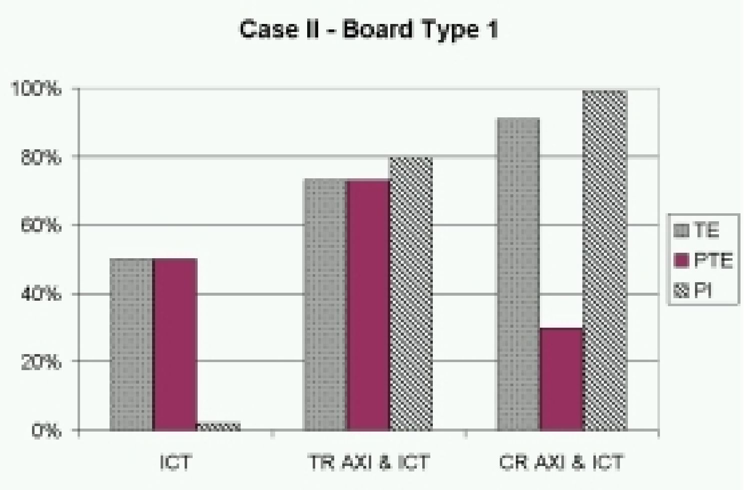
Case II: Detection of Defects and Process Indicators (Missing Bypass Capacitors are Process Indicators)

If we re-analyze the data and apply the definition of defect as *a non-conformance that can cause a measurable failure during the product life that must be repaired prior to shipment of the product* and a process indicator as *an undesirable outcome of the manufacturing process that should be minimized by taking corrective actions on the manufacturing process using continuous improvement (SPC) methods (the process indicator does not need to be repaired prior to product shipment)* on the same data set, a very different outcome results:

Note – Process indicators are categorized as missing bypass capacitors & insufficient solder joints, excessive solder joints and solder voids all of which electrically pass ICT under 100% node access conditions. The percent of process indicators found by the strategy is denoted as "% PI". All other failures are considered defects.

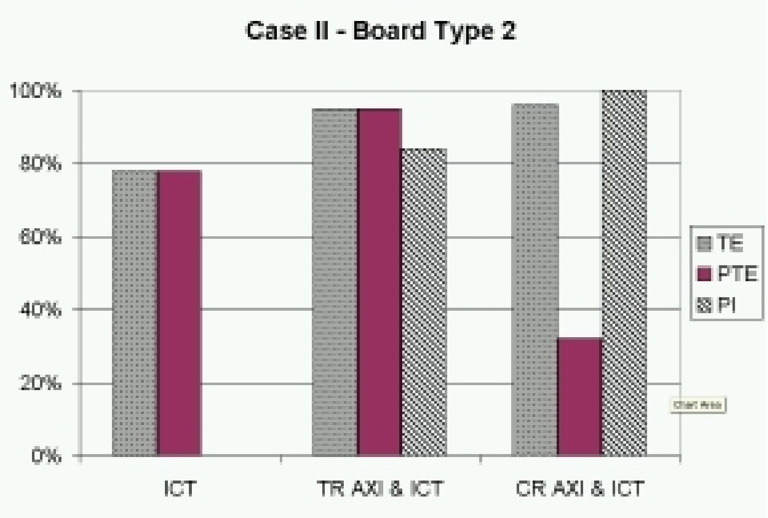
Case II, Board Type 1 – 168 total defects, 84 total process indicators (PI) over 15 boards

- ICT Only	50% TE	50% PTE	2% PI
- Transmission AXI & ICT	73% TE	73% PTE	80% PI
- Cross-section AXI & ICT	91% TE	30% PTE	99% PI



Case II, Board Type 2 – 147 total defects, 130 total process indicators (PI) over 30 boards

- ICT Only	78% TE	78% PTE	0% PI
- Transmission AXI & ICT	95% TE	95% PTE	84% PI
- Cross-section AXI & ICT	96% TE	32% PTE	100% PI



In this new data set there is a significant improvement in the TE of ICT-only strategy due to the updated defect definition. The 78% TE of ICT on the 2^{nd} board (an improvement from the 41% noted before) is more in-line with our understanding of the capabilities of ICT in 100% access environments and the generally accepted definition of defect that the vast majority of manufacturers employ. The TE of the transmission and cross-section strategies are comparable, especially for the second board. Once again, the PTE of the transmission AXI strategy is much higher than that of the cross-section AXI. Also note that while ICT rarely finds process indicators, the transmission AXI strategy detects a majority and the cross-section strategy finds close to 100%. If one agrees with the definition of process indicator stated above, a sufficient statistical sample is all that need be found. A key objective of the transmission AXI strategy is to operate at the beat rate of the manufacturing line and provide real time corrective actions to production. Quality and reliability improvements are made by reducing DPMO rates; not by repairing every insufficient solder joint. An important difference is that the cross-section AXI strategy operates at slow inspection speed with 1/3 the speed of transmission AXI, thus necessitating offline batch inspections that can make continuous improvement more difficult.

The key observations from this data set are:

- The updated definition of defect brings the TE of ICT in 100% access environments in-line with the performance experienced by the vast majority of manufacturers. This seems to validate the presence of a discontinuity in inspection standards in some test effectiveness studies.
- If Molamphy reported defects and process indicators as defined here, it seems reasonable that his data would change in a similar manner. Only by identifying defects separate from process indicators can we ascertain these performance differences.
- The TE of the transmission and cross-section AXI strategies are comparable when we use the updated definition of defect (especially for board 2). Both AXI strategies are still a significant improvement over the ICT-only strategy.
- The PTE of the cross-section AXI strategy is lower than the PTE of the ICT-only strategy.
- The PTE of the transmission AXI strategy is more than double that of the cross-section AXI strategy.
- Only a representative number of process indicators need be found to perform continuous improvement activities. Continuous improvement activities are best performed using in-line techniques.

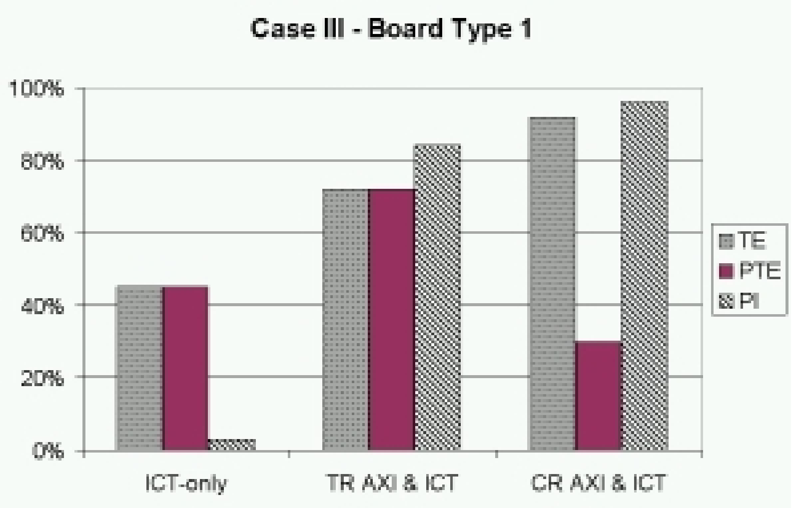
Case III: Defects (Missing Bypass Capacitors are Defects) and Process Indicators

If the data is analyzed once more to address the fact that some may consider it tenuous that bypass capacitors would be categorized as process indicators (discussed previously), another set of results is shown:

Note – Process indicators are categorized as insufficient solder joints, excessive solder joints and solder voids all of which pass ICT under 100% node access conditions. All other failures are considered <u>defects</u>.

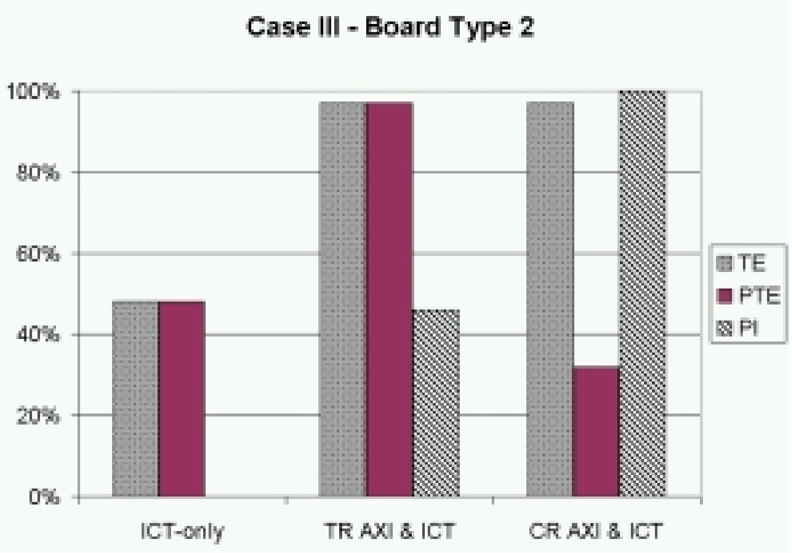
Case III, Board Type 1 – 186 total defects, 66 total process indicators over 15 boards

- ICT Only	45% TE	45% PTE	3% PI
- Transmission AXI & ICT	72% TE	72% PTE	84% PI
- Cross-section AXI & ICT	92% TE	30% PTE	96% PI



Case III, Board Type 2 – 238 total defects, 39 total process indicators over 30 boards

- ICT Only	48% TE	48% PTE	0% PI
- Transmission AXI & ICT	97% TE	97% PTE	46% PI
- Cross-section AXI & ICT	97% TE	32% PTE	100% PI



They key observations from this final data set are not appreciably different from those observations described in the previous data sets.

All 3 data sets presented above indicate the following:

- The TE of both the transmission and cross-section AXI strategies, when combined with ICT, are much higher than the TE of the ICT-only strategy – this indicates that test strategies which combine imaging methods with electrical test improve defect coverage.
- The PTE of the cross-section AXI & ICT strategy is lower than the PTE of the ICT-only strategy – this may indicate why cross-section AXI sees very low rates of adoption in the vast majority of electronics product segments that are resource constrained (except those that build very high complexity boards in low volume).
- The PTE of the transmission AXI strategy is more than double that of both the ICT-only and cross-section AXI strategies – this may indicate an opportunity for manufacturers to realize significantly improved performance using transmission AXI test strategies.
- The TE difference between the transmission and cross-section strategies on Board 1 is significantly greater than the TE difference between the strategies on Board 2. This indicates that the effectiveness of the transmission AXI strategy can be board dependent and is most advantageous for boards that are low to high complexity and less advantageous for very high complexity boards.

If one believes in the value of the TE and PTE metrics, a high TE value indicates an attractive test strategy for low volume applications regardless of cost/constraints whereas a high PTE value indicates the economic advantage or attractiveness of a test strategy for volume production environments.

Conclusions

When manufacturers implement automated inspection systems that can detect small changes in the volume or shape of a solder joint, there is a tendency for many subtle anomalies in the assembly process to fail inspection that are not truly defective. Furthermore, when these machines are programmed using heuristic methods subject to individual interpretation without any traceable standard of acceptability, it is easy to understand that there is a large window of interpretation surrounding the acceptability of solder joints that fail an automated inspection program. The IPC 7-32 committee on Automated Inspection Technologies is working to resolve this problem.

Some test effectiveness studies have a propensity to report many solder joints as <u>defects</u> that are truly <u>process indicators</u>. The very low test effectiveness (34% & 41%) of ICT reported in these studies (@ 100% node access) is counter-intuitive to the practical experience of the vast majority of electronics manufacturers and demonstrates the logical disconnect and technological discontinuity of defect definitions and inspection standards. These types of test effectiveness studies create a “sky is falling” mentality that promotes a philosophy that every solder joint is a potential field failure until it is inspected by automated inspection methods. Is the cost of making the assembly process a “slave” to the test process worth the perceived improvement in delivered quality? Product quality is not improved by asking a repair operator to fix every single insufficient, excessive and voided solder joint on a printed circuit board with a soldering iron (or by removing and re-attaching components). A more reasoned approach to test and inspection is required rather than “inspect everything, repair everything”. In addition, product quality is best improved using in-line inspection techniques that allow real time process improvement. If engineers can distinguish between defects and process indicators when performing test effectiveness studies, they can better identify test strategies that will improve customer satisfaction and deliver competitive advantage at lower cost.

Production Test Effectiveness (PTE) is indicative of the cost effectiveness and economic advantage of a test strategy and is an important metric to evaluate in parallel with the test effectiveness (TE). Case study data on a high complexity double-sided board with real production defects demonstrates that the TE of two different test strategies can be identical at 97% while their PTEs are 97% and 32%; this represents a three-fold difference in the total cost of ownership.

Several case studies describing the TE and PTE of combined automated inspection and ICT strategies were presented; the following observations were made:

- The TE of both the transmission and cross-section AXI strategies, when combined with ICT, are much higher than the TE of the ICT-only strategy – this indicates that test strategies which combine imaging methods with electrical test improve defect coverage.
- The PTE of the cross-section AXI & ICT strategy is lower than the PTE of the ICT-only strategy – this may indicate why cross-section AXI sees very low rates of adoption in the vast majority of electronics product segments except those that build very high complexity board types in low volume (despite its high TE).
- The PTE of the transmission AXI strategy is more than double that of both the ICT-only and cross-section AXI strategies – this may indicate an opportunity for manufacturers to realize significantly improved performance using transmission AXI test strategies with a low expenditure of resources.
- The TE difference between the transmission and cross-section strategies on Board 1 is significantly greater than the TE difference between the strategies on Board 2. This indicates that the effectiveness of the transmission AXI strategy can be board dependent and is most advantageous for boards that are low to high complexity and less advantageous for very high complexity boards.

---

[1] The terms "automated inspection systems", "AOI" and "AXI" in the context of this paper refer only to post reflow solder joint inspection systems that also have some component defect coverage. The discontinuities in inspection standards discussed in the paper do not concern pre-reflow inspection systems that perform paste and/or component inspection.

[2] "Optimizing Test Strategies During PCB Design for Boards with Limited ICT Access", Verma, SEMI 2002 Conference Proceedings

[3] http://www.teradyne.com/prods/cbt/products/library/general_lib.html - Select "Designing Test Strategies for Modern PCB Assembly Web Seminar"

[4] The NEMI Test Strategy project (see endnote 5) created an economic model that can be used to quantify the financial benefits of a test strategy. Read more about this model at this web address http://www.nemi.org/newsroom/PR/2003/cost_model.html and download a free copy at this web address http://www.nemi.org/projects/TSCM/test_strat_cost_model.html.

[5] The NEMI Test Strategy Project was chaired by Amit Verma, Teradyne and David Mendez, Solectron. Ten companies participated in the project including Teradyne, Solectron, Celestica, Plexus, GSI Lumonics, Agilent, Alcatel, Intel Hewlett Packard & Delphi. A press release describing the project can be found at http://www.nemi.org/newsroom/PR/2001/PR103001.html. The team's experimental report can be downloaded at http://www.nemi.org/newsroom/apex2003/meetings_apex_2003.html .The conclusions & opinions presented in this paper are those of the author and are based upon data from the Test Vehicle Analysis Experiment; they may not represent the conclusions of the NEMI Test Strategy Team.

[6] Only team member companies are permitted copies of the Test Vehicle Analysis experiment report. Presentations of the data are permitted to other companies but hard or soft copies cannot be distributed. Papers are permitted after September 29, 2003. This restriction expires on April 1 2004. The conclusions & opinions presented in this paper are those of the author and are based upon data from the Test Vehicle Analysis Experiment; they may not represent the conclusions of the NEMI Test Strategy Team.

[7] The IPC 7-32 Subcommittee on Automated Inspection Technologies is co-chaired by Amit Verma, Teradyne and Steven Perng, Solectron. The subcommittee's work is currently in progress. To participate, please contact johnperry@ipc.org or one of the co-chairs.

[8] "Six Case Studies Show More Defects Found than Expected" by Tom Molamphy, APEX 2002 Conference Proceedings

[9] IPC Standard 7095 "Design and Assembly Process Implementation for BGAs" is currently under revision to address this conundrum. Table 19 in the 7095 standard may be revised to identify voids in BGA solder joints as "process indicators" rather than "defects" in order to reduce the reliability risk and assembly cost of repairing voids in BGA solder joints (the industry has no definitive data identifying the field reliability risk of voids in BGA solder joints).

[10] "DPMO Management Processes Reduce The Cost of PCB Assembly", Verma, APEX 2003 Conference Proceedings. Also see http://www.nemi.org/newsroom/PR/2003/NEMI_DPMO.htm

[11] "Tradeoffs Between Transmission and Cross-section AXI", Verma, Etronix 2001 Conference Proceedings. Also see endnote 15.

[12] See endnote 5

[13] "NEMI Project Investigates Test Strategies", Verma, Circuits Assembly Magazine, page 35, August 2002

[14] See endnote 11

[15] SMTA Testability Guidelines, 2002 Edition, page 31

[16] A copy of the NEMI Test Coverage Analysis team report can be found at the following web address http://www.nemi.org/newsroom/apex2003/meetings_apex_2003.html. The conclusions & opinions presented in this paper are those of the author and are based upon data from the Test Coverage Analysis Experiment; they may not represent the conclusions of the NEMI Test Strategy Team

[17] http://www.nemi.org/newsroom/apex2003/meetings_apex_2003.html.