TRADEOFFS BETWEEN TRANSMISSION AND CROSS-SECTION AXI IN COMPLEMENTARY TEST ENVIRONMENTS

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Abstract

AXI (Automated X-ray Inspection) is growing in acceptance as both an alternative and complementary test methodology because of the benefits it provides manufacturers in meeting test challenges resulting from:

- Continued product miniaturization amid increased product functionality
- Increased Time to market and time to volume pressures
- Growth in outsourcing and contract manufacturing

Some of the issues that engineers should consider in formulating an AXI strategy are the tradeoffs between transmission and cross-section AXI. It is intuitive to believe that double-sided circuit boards require cross-section AXI because in transmission AXI some proportion of solder joints will overlap one-another – resulting in lost test access. In drawing this conclusion however, engineers may unknowingly be making other tradeoffs that impact the total value or payback of their AXI solution by an amount greater than the loss in access due to overlapping solder joints. These tradeoffs should be considered even more carefully in environments where AXI is complemented with ICT (in-circuit test) since loss of transmission AXI access on some areas of double-sided boards can be complemented with ICT access (or flying probe test) in those same areas.

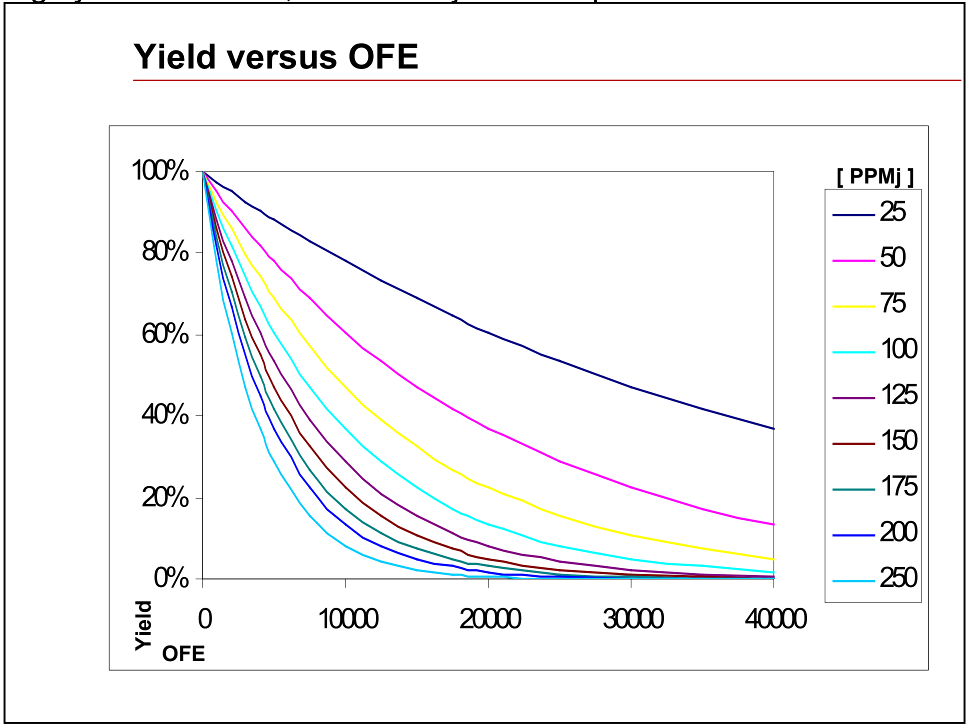
Any automated inspection methodology is based on image processing fundamentals at its core. Transmission and cross-section imaging have technological differences that translate into varying manufacturing performance levels for test coverage, false failure rates and system throughput. Engineers should understand the nature of these differences and weigh their impact in conjunction with issues of test access in determining the optimum AXI test strategy. This paper will discuss the impact of fundamentals like image resolution and contrast, “field of view” and measurement repeatability on the total value of an AXI solution in a complementary test environment.

The Need For Test Strategies That Include AXI

Increased Product Complexity and Miniaturization

There is a general trend in electronics toward increased I/O, increased product complexity, increased product miniaturization and increased product functionality; as a result, the number of solder joints present on circuit boards is rapidly increasing. Today it is not uncommon to encounter circuit boards with solder joint counts that exceed 20,000. Concurrently, assembly process complexity is also increasing; boards often undergo double sided SMT assembly, manual assembly, wave solder, press fit and mechanical assembly stages. Even though manufacturers are striving to improve their process capabilities (defect rates), they are finding it difficult to keep the number of defects per board on a declining trend because of the increased number of opportunities for error (OFE) and increased process complexity (number of assembly stages mixed together on the same product).

The chart below shows that even manufacturers that attain “world-class” quality levels of 100ppm structural defect rate per solder joint (on average) are guaranteed (near) single digit yields when 20,000 solder joints are present.



As “first-pass” yields approach the single digits, Engineering communities have to pay more attention to the “structural” fault spectrum. Manufacturers are recognizing as true the old adage that “70% to 80% of all defects are structural, not electrical in nature”. This trend is causing engineers to consider automated inspection equipment that is capable of detecting structural failures as part of their broader test strategy. Also note that the density and complexity of today’s electronics assemblies are rendering human visual inspection methods ineffective.

The increased component density of today’s electronics assemblies is reducing the level of physical access (board real estate) available for bed of nails testing (ICT). This reduced ICT access translates into reduced test coverage at ICT, thereby driving the adoption of alternate test methodologies like AXI to provide complementary test coverage.

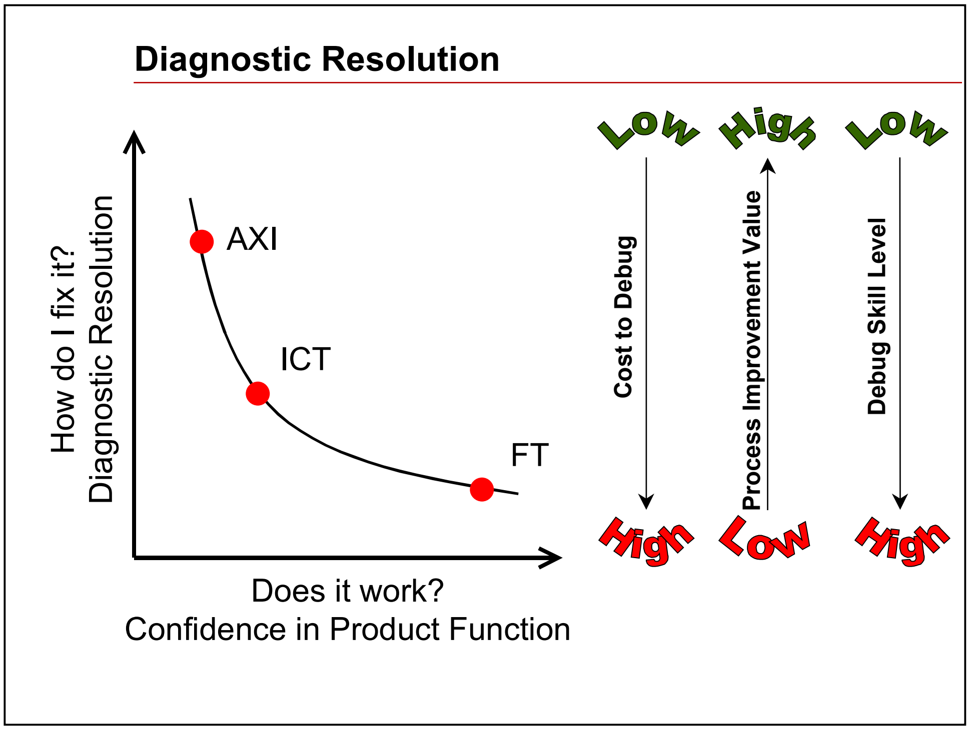
Time To Market Pressures

As product life cycles approach a magnitude in the order of 1 year, time to market becomes a key focus area for today’s electronics OEMs. The faster they move from design to prototype to production, the higher their market-share, revenues and profits. Manufacturers are looking for alternative test strategies that reduce test development time and facilitate a fast yet effective new product introduction cycle by providing a high level of fault coverage and diagnostic resolution at these early stages of product development. Non-contact test methods like AXI that exhibit high levels of fault coverage and fast test development without the requirement for expensive and long delivery-time fixtures are highly desirable for NPI (New Product Introduction).

Time To Volume Pressures

Companies that satisfy consumer demand for innovative products early in their life cycle win both market share and profits. Ramping production volumes in a more cost competitive environment requires effective detection and containment of defects at source, root cause identification, corrective action and ultimately better process capability. Manufacturers need test solutions like AXI that find defects closer to source with excellent diagnostic resolution for immediate debug and repair. Inspection methods like AXI that provide parametric data for continuous process measurement, improvement and control will help to deliver better yields over time. High levels of diagnostic resolution minimize WIP and RIP, ensure fast debug and repair, and facilitate short product cycle times and high volume manufacturing.

No single test technique provides all answers to all problems; each has its own strengths and weaknesses should be evaluated as a possible solution within the overall test plan. Although methods like automated inspection are capable of finding defects closer to source for quick debug and repair, they do not ensure confidence in product function, as do ICT digital tests and functional test methods. Utilizing a distributed test approach with the optimum level of complementary and redundant [overlapping] fault coverage to deliver the quality levels and production efficiencies dictated by the end-user application will characterize a successful test strategy.



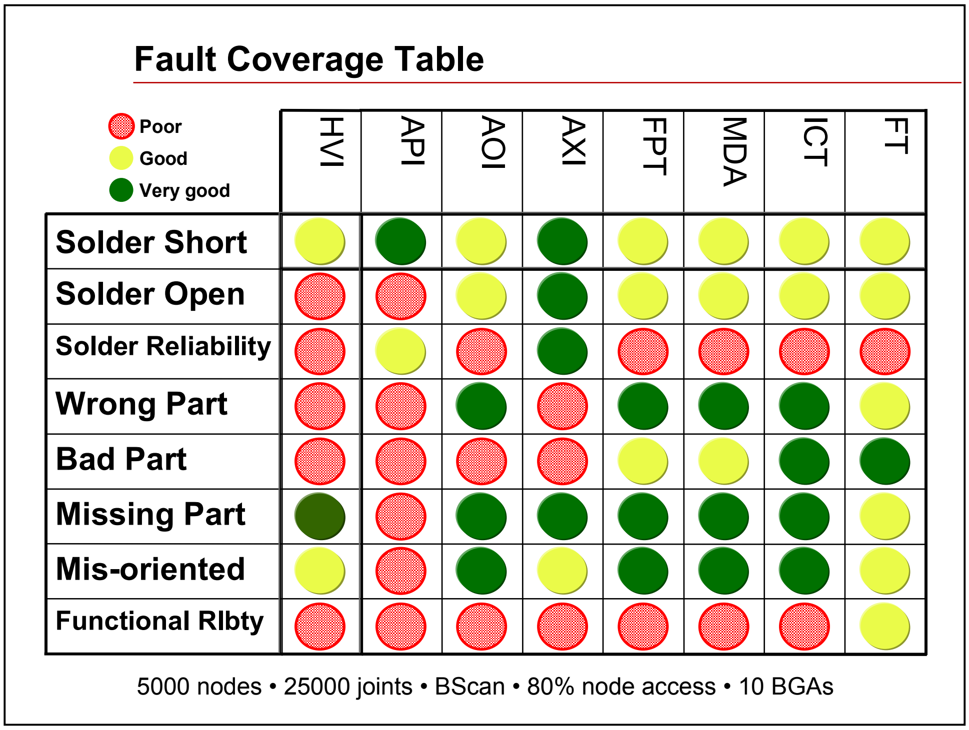
Growth Of The CEMS Business Model

The continued growth in outsourcing and CEMS (contract electronics manufacturing services) is driving the adoption of automated inspection methods like AXI. This new business model separates the manufacturing function in a way that enables OEMs to hold their contract manufacturer responsible/accountable for manufacturing assembly defects. Ensuring solder reliability and products free of assembly defects is clearly the core competency of CEMS providers. OEMs are looking for test methods like AXI to ensure their CEMS partners ship products that are 100% free of assembly defects. In this way, both CMs and OEMs are embracing test technologies like AXI to more clearly delineate responsibility of the structural fault spectrum. AXI is an effective way to verify structural product quality and reliability as the product moves from one stage in the supply chain to the next (from the CM to the OEM). In this way, automated inspection technologies are facilitating the adoption of the CEMS business model.

Manufacturers worldwide are facing shortages of skilled labor and the trend toward CEMS has meant an increased reliance on temporary workers. Manufacturers are looking for test solutions that help to relieve these labor market pressures. Many products, especially those of high complexity, spend a significant amount of time in queue waiting for scarce ICT and FT (functional test) debug skills. Electronics manufacturers are looking for alternative test strategies that can help overcome these resource constraints and achieve more continuous flow manufacturing, higher inventory turns, and reduced WIP. AXI test methods provide “ease-of-use” solutions that reduce the time required to train test development and debug operators by turning the task of development and debug into solder joint acceptability determination – a core competency of CEMS providers. ICT and FT development and debug on the other hand, require extensive product domain knowledge and circuit analysis skills – both these skill sets are heavily constrained (as compared to general soldering knowledge) within the new CEMS business model.

A Complementary Test Strategy

The discussion above highlights just a few of many reasons why manufacturers are embracing new complementary test strategies that include AXI. No single test methodology is the “cure-all” for all test challenges; a distributed test strategy that addresses the right balance of competing factors like diagnostic resolution, fault coverage, test access, fast test development time, high uptime, overall cost savings and throughput will most often deliver the optimal test strategy.



Fault Coverage Table

🔴 Poor
🟡 Good
🟢 Very good

	HVI	API	AOI	AXI	FPT	MDA	ICT	FT
Solder Short	🟡	🟢	🟡	🟢	🟡	🟡	🟡	🟡
Solder Open	🔴	🔴	🟡	🟢	🟡	🟡	🟡	🟡
Solder Reliability	🔴	🟡	🔴	🟢	🔴	🔴	🔴	🔴
Wrong Part	🔴	🔴	🟢	🔴	🟢	🟢	🟢	🟡
Bad Part	🔴	🔴	🔴	🔴	🟡	🟡	🟢	🟢
Missing Part	🟢	🔴	🟢	🟢	🟢	🟢	🟢	🟡
Mis-oriented	🟡	🔴	🟢	🟡	🟢	🟢	🟢	🟡
Functional Rlbty	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟡

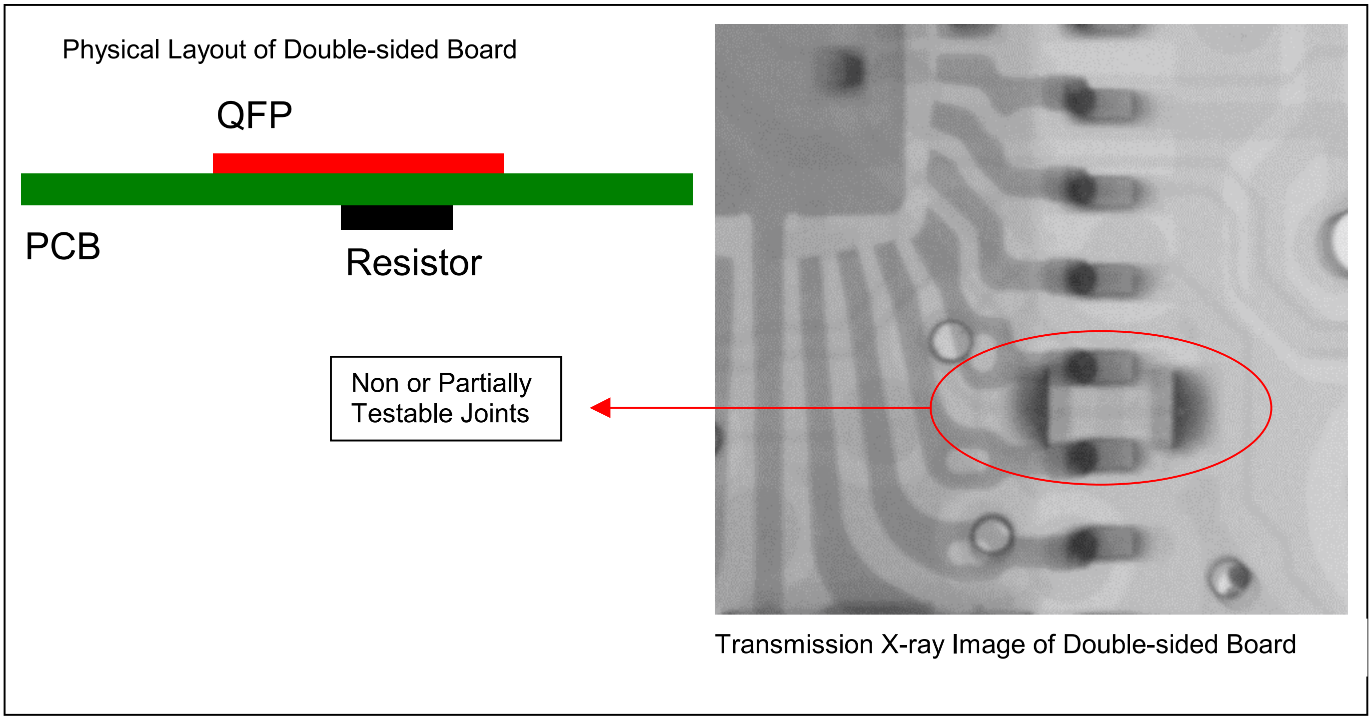
5000 nodes • 25000 joints • BScan • 80% node access • 10 BGAs

HVI – Human Visual Inspection
API – Automated Paste Inspection
AOI – Automated Optical Inspection
AXI – Automated X-ray Inspection
FPT – Flying Probe Test
MDA – Manufacturing Defect Analyzer
ICT – In Circuit Test
FT – Functional Test

AXI Test Access

Transmission AXI Test Access

Transmission AXI (sometimes referred to as 2D AXI) consists generically of an x-ray source and detector/camera assembly. The PC board surface is positioned in-between these 2 components (at a position 90 degrees to x-ray beam) and the resultant image is composed of all objects in the path of the x-ray beam. In Transmission AXI, solder joints on the topside of the board are imaged simultaneously with solder joints on the bottomside.



Physical Layout of Double-sided Board

Transmission X-ray Image of Double-sided Board

Although topside and bottomside solder joints appear simultaneously within the same x-ray image, topside and bottomside solder joints are clearly distinguishable from one another by machine CAD data and image processing software. For this reason, both topside and bottomside solder joints are independently and correctly inspected by a transmission AXI system.

Only when topside and bottomside solder joints obscure and overlap (touch) one another do the solder joints become “non-testable” or “partially testable”– this is referred to as a loss of “test access” in transmission AXI terminology.

Note that only those solder joints that are obscured by other solder joints on the opposite side of the board experience this loss of test access; a subset of a component’s solder joints may be rendered non-testable and the remainder rendered testable. For this reason, transmission AXI is almost always able to test a higher percentage of the components on a double-sided board than the percentage of solder joints on the board. Also note that solder joints obscured by component bodies are often rendered testable (since the bodies are transparent to the x-ray energy used). The table below shows some examples of the level of test access provided by transmission AXI on some double-sided PCB assemblies.

	Dimensions [inches]	*Total # of Components*	*Total # of Joints*	*% Component Access*	*% Joint Access*
Board1	16.5x7.5	1664	8869	95%	67%
Board2	12x10	1503	12945	86%	83%
Board3	14x11	963	6753	69%	58%

When double-sided boards are inspected in a 2-pass transmission AXI process, the level of access increases since nearly 100% of solder joints in the 1st pass are accessible; the 2nd pass has the same level of access as before. Although this inspection methodology increases board handling overhead by introducing a 2nd inspection stage (one after bottomside assembly, another after topside assembly) it may be desirable in some specialized circumstances due to the improved immediacy of feedback to the manufacturing line and the benefits of transmission AXI (relative to cross-section AXI) discussed later in this paper. The table below shows the level of test access provided by 2-pass transmission AXI on the same assemblies displayed in the 1st table above. Note that only those solder joints not inspected in the 1st pass would be inspected in the 2nd pass, rendering the total test time nearly the same as a 1-pass process on a double sided board[i].

	1st Pass % Component Access	*1st Pass % Joint Access*	*2nd Pass % Component Access*	*2nd Pass % Joint Access*	Total % Component Access	Total % Joint Access
Board1	62%	44%	36%	39%	98%	83%
Board2	71%	29%	23%	62%	94%	91%
Board3	44%	38%	31%	34%	75%	72%

Note: 1st pass and 2nd pass percent statistics were calculated based on total number components and joints on the board, not the number components and joints on each of the respective sides of the board.

Cross-section AXI Test Access

Cross-section AXI (sometimes referred to as 3D AXI) will always exhibit maximum test access on double-sided circuit boards (relative to transmission AXI). Since cross-section AXI has the ability to image topside and bottomside components independently, obscuration of solder joints (as in transmission AXI) is less of an issue. There are two types of cross-section AXI:

- Digital Tomosynthesis
- Laminography

Although cross-section AXI will always maximize the level of test access (relative to transmission AXI on a double-sided board), this does not mean that test access is 100%. There exist numerous circumstances where device shading and lack of board real estate for surface map points[ii] render Laminography unable to inspect a subset of the components and solder joints on a board. Digital tomosynthesis would generally exhibit greater test access than laminography due to its non-requirement for surface map points and its ability to completely remove shading effects from devices on the opposite side of the board.

What Level Of AXI Test Access Is Required?

It is intuitive to believe that double-sided circuit boards require cross-section AXI because in transmission AXI some proportion of solder joints will overlap one-another – resulting in lost test access. Is the maximum access provided by cross-section AXI required in every AXI test strategy however? The requirement to perform automated x-ray inspection of every single solder joint on a PC board is certainly a 'new' philosophy if not completely unfounded and without historical precedence. Electronics manufacturers have invested millions of dollars and decades of knowledge and continuous improvement efforts in establishing manufacturing teams, procedures and equipment that deliver products of high quality and high reliability. To think that one must inspect every single solder joint on a PC board with AXI (in all cases) to ensure product quality and reliability would certainly cast doubt on the level of collective knowledge and expertise acquired by the industry over many years of SMT and wave soldering experience.

Any test stage in the manufacturing assembly process serves two broad purposes:

- First to contain defects produced by previous stages and prevent them from escaping downstream
- Secondly to provide feedback and process measurement data to address root cause corrective action and facilitate continuous improvement

Let us discuss these objectives in the context of AXI test access, transmission AXI and cross-section AXI.

Regarding the containment of defects: no test stage will ever perform with 100% test access and 100% fault coverage[iii] to deliver perfect test performance. The value of a test stage in containing defects is determined instead by its ability to deliver the right balance of throughput, diagnostic resolution, overall cost savings, defect detection, test access, low support levels, fast test development time, high uptime and a multitude of other factors specific to any given manufacturer. It would be incorrect to assume that the optimum balance of these factors occurs at a point where the level of test access is simply maximized. Transmission AXI has inherent technological benefits (discussed later in this paper) that provide levels of performance that are superior to cross-section AXI in regard to fault coverage, test development time, uptime, diagnostic resolution, throughput and overall cost savings. In perhaps every aspect other than test access, transmission AXI exhibits performance levels that are superior to cross-section AXI.

Certainly there exist those applications where AXI test access must be maximized but even these cases should be carefully considered in the context of a complementary test strategy where multiple test stages are designed to provide an intelligent balance of overlapping and complementary fault coverage. Those same solder joints that are rendered non-testable by either transmission or cross-section AXI could be tested downstream at ICT for example. In this way, the use of complementary test strategies can mitigate issues of lost access at one test stage with minimal impact on product quality and manufacturing efficiencies. The use of DFT (design-for-test) software can further simplify and automate this distribution of complementary tests at test stages like AXI and ICT.

Regarding the feedback of process measurement data to address root cause corrective action and facilitate continuous improvement: the vast majority of engineering effort in this area is centered upon the analysis of trends and of variation from board to board, time to time, machine to machine, joint to joint or component to component etc. These types of analyses are based on principles of statistics; these principles ensure that a reasonable sampling strategy of the AXI process measurement data is all that is required to bring to light any causes of variation inherent in the manufacturing process. The level of test access provided by transmission AXI to components, joints and the different package types on the board should be sufficient for most any engineering study or process control strategy. For this reason, it can be argued that the level of test access provided by either transmission or cross-section AXI is sufficient to meet the requirements of process feedback, control and continuous improvement.

Reduced ICT Bed of Nails Access

Many electronics manufacturers are adopting complementary AXI/ICT test strategies to mitigate impacts of lost ICT test coverage due to loss of physical access and board real estate for test pads. In these types of test strategies, it is desirable to reduce the total number of nails required within the ICT fixture in order to reduce the total board real estate required for test pads. Both transmission and cross-section AXI strategies can significantly reduce the number of nails required at ICT; although the nail reduction provided by cross-section AXI will be greater than that provided by transmission. The use of DFT software can simplify the distribution of complementary tests between AXI and ICT to reduce total nail count.

Technology Differences between Transmission and Cross-section AXI

We have discussed tradeoffs and issues for consideration surrounding the level test access provided by transmission and cross-section AXI. Let us now focus on some of the differences that impact the “performance” of these technologies in the manufacturing environment. Any automated inspection methodology is based on image processing fundamentals at its core. Transmission and cross-section imaging have technological differences that translate into varying manufacturing performance levels for fault coverage, false failure rates, system throughput, support levels and total return on investment (ROI). Engineers should understand the nature of these differences and weigh their impact in conjunction with issues of test access in determining the optimum AXI test strategy.

Image Contrast

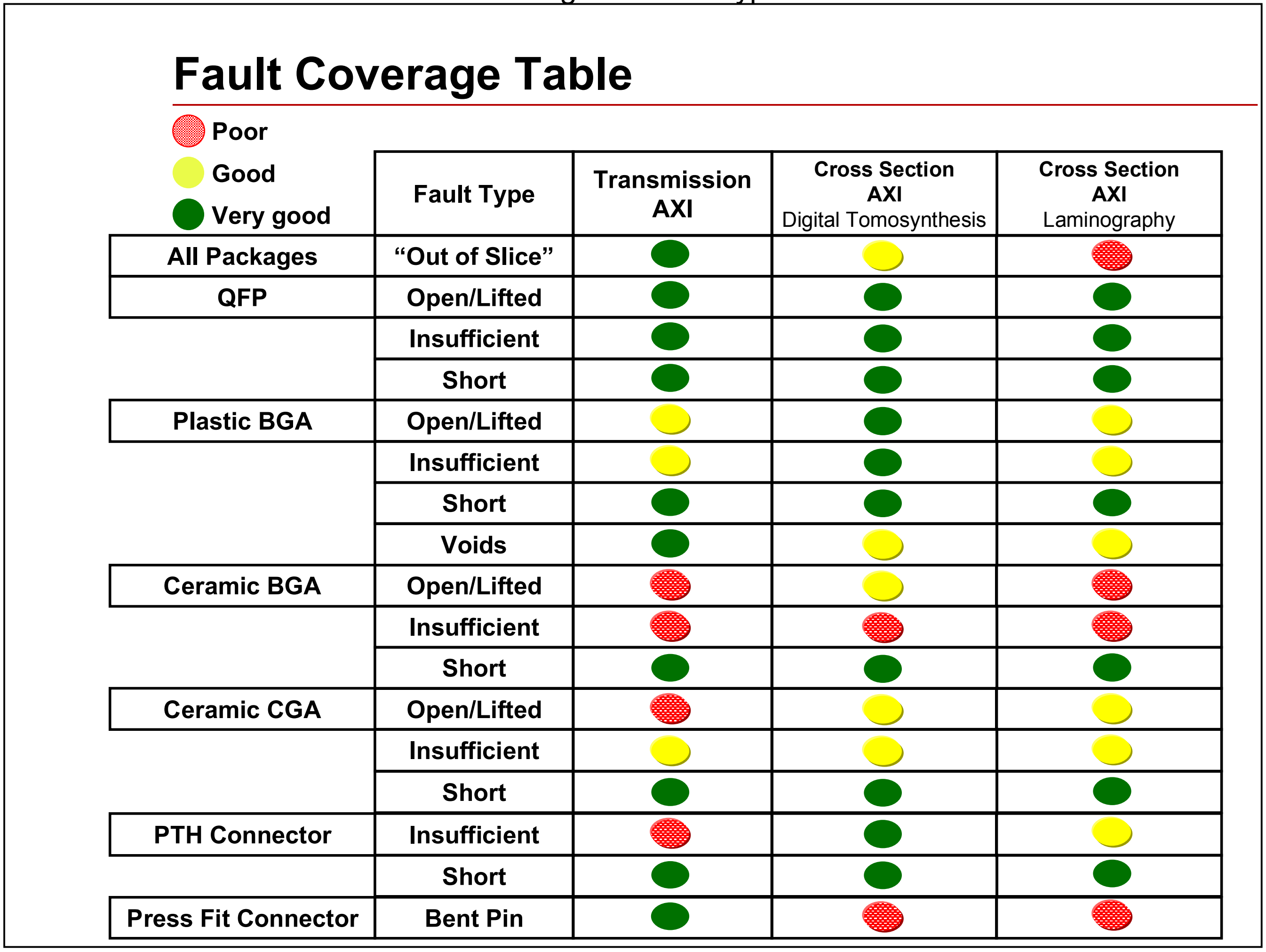
A measure of image contrast is the difference in the gray scale measurement from the region of interest (or solder joint area being inspected) to the background (or surrounding area) within an x-ray image. The higher the difference between these gray scale values, the greater the image contrast. Greater image contrast will always deliver greater edge strength and signal-to-noise ratio within the image. Image processing algorithms search for these edges within solder joints to define extents for gray scale and dimensional measurements; all AXI solder joint measurements and defect detection capabilities are based upon these gray scale and dimensional measurements. An automated inspection system will always be limited by the quality of its images, greater image quality will deliver superior inspection performance.

Transmission AXI will always deliver greater image contrast and edge strength versus cross-section AXI due to its orthogonal nature (x-ray beam angle is 90 degrees to board surface). All cross-section AXI methods will exhibit reduced contrast due to their rotational (laminography) or angular (digital tomosynthesis) image acquisition methodology. The improved contrast of transmission AXI provides manufacturers with a tool capable of delivering improved feature identification, greater measurement repeatability, higher fault detection, lower false calls and higher call accuracy versus cross-section AXI.

Fault Coverage

Transmission AXI will exhibit greater fault coverage than cross-section AXI on marginal/subtle solder defects like solder insufficient conditions due to improved image contrast. Transmission and cross-section AXI exhibit equivalent levels of coverage on most solder defects including PBGA defects; transmission AXI has been shown to be effective at detecting PBGA open and insufficient conditions based on high resolution ball diameter and edge strength measurements.

The table below shows areas of relative fault coverage strength and weakness between transmission and cross-section AXI. Note that transmission AXI has coverage on press-fit connectors and solder shorts above the cross-section slice (further up the pin for example) whereas cross-section AXI has no coverage on these types of defects.



Fault Coverage Table

🔴 Poor
🟡 Good
🟢 Very good

	Fault Type	Transmission AXI	Cross Section AXI Digital Tomosynthesis	Cross Section AXI Laminography
All Packages	"Out of Slice"	🟢	🟡	🔴
QFP	Open/Lifted	🟢	🟢	🟢
	Insufficient	🟢	🟢	🟢
	Short	🟢	🟢	🟢
Plastic BGA	Open/Lifted	🟡	🟢	🟡
	Insufficient	🟡	🟢	🟡
	Short	🟢	🟢	🟢
	Voids	🟢	🟡	🟡
Ceramic BGA	Open/Lifted	🔴	🟡	🔴
	Insufficient	🔴	🔴	🔴
	Short	🟢	🟢	🟢
Ceramic CGA	Open/Lifted	🔴	🟡	🟡
	Insufficient	🟡	🟡	🟡
	Short	🟢	🟢	🟢
PTH Connector	Insufficient	🔴	🟢	🟡
	Short	🟢	🟢	🟢
Press Fit Connector	Bent Pin	🟢	🔴	🔴

Throughput

Transmission AXI provides greater image contrast and better overall image quality than cross-section AXI. Manufacturers can effectively "trade" these benefits for improved system throughput by inspecting the board at higher "fields of view" (or reduced magnification) and thereby fitting a larger board area into each and every x-ray image. This will reduce the total number of images required to inspect the board and reduce the overall test time vs. cross-section AXI which must use lower "fields of view" (or higher magnification) in order to achieve the same level of perceivable detail (resolution) within the x-ray image.

Laminography AXI requires a technique called "laser surface mapping" to define the topology of the board surface for cross-section position calibration. This technique adds additional overhead time to the test but also negatively impacts the ability of laminography to perform robust inspections at higher fields of view (reduced magnification). To significantly reduce the total inspection time, one must reduce the total number of images inspected by inspecting a larger board area within each x-ray image. Production AXI processes exhibit both board warp and board bounce[iv]. Laminography technology is limited in its ability to generate a cross-section at large fields of view (FOV) where all solder joints are "in focus". The "in focus" tolerance for fine pitch solder connections is in the range of 0.001" to 0.003". Most board manufacturers however conform to a board warp specification of 1%; this means that the board warp in the Z direction over a 1" FOV could be as high as 0.010". This amount of board warp would render a significant proportion of fine pitch solder joints in a 1" FOV "out of focus" and thereby non-inspectable or even non-accessible. This behavior reduces the fault coverage of laminography AXI, increases false call rates, increases escape rates and reduces system uptime due to frequent program interventions. Note that digital tomosynthesis AXI does not exhibit these characteristics because of the digital reconstruction techniques employed by this technology.

When Cross-section AXI is Required

If the test engineer has considered tradeoffs of transmission and cross-section AXI and decided that cross-section AXI is required, then the remaining decision is whether to use laminography or digital tomosynthesis technology in the test plan. It is not the purpose nor scope of this paper to address the relative strengths and weakness between these two cross-section AXI technologies. It is important to note however that digital tomosynthesis provides manufacturers with many of the benefits of transmission AXI. Digital tomosynthesis AXI is a hybrid technology that utilizes both transmission and cross-section imaging methods.

Conclusion

The return on investment of a test solution is dependent on a multitude of factors, some of which are specific to each application environment. The capital cost of transmission AXI is significantly lower than cross-section AXI due to the relative simplicity of the technology. Transmission AXI will generally provide savings greater than $150,000 in capital equipment costs alone over cross-section AXI using today's equipment prices. Beyond the initial capital expenditure however, engineers should be conscious of ongoing support and programming costs.

System uptime, machine electromechanical complexity, programming time, program optimization time, measurement repeatability, false failure rates and fault coverage will all contribute to the payback of the chosen test strategy over the long term. Transmission and cross-section AXI systems have technological differences that will yield performance differences for these key manufacturing metrics.

Although AXI is a highly valuable and exciting technology for electronics assembly test and inspection, many organizations approach AXI cautiously due to their relative unfamiliarity with its technological complexity and long term operating costs. All AXI users should carefully consider the impact of the technological issues and tradeoffs described on the long term payback, ease of use, fault coverage and effectiveness of their chosen test strategy.

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[i] Note that transmission AXI systems have no surface map time overhead. For a definition of 'surface map' see endnote (ii)

[ii] Laminography AXI requires laser surface map points to be positioned on the board in a regular grid pattern in order to define the top surface plane of the board for cross-sectioning. These surface map points are approximately 0.030" in diameter and require 'free' board real estate. Surface map points are not required by digital tomosynthesis. For a discussion on surface mapping, see the body of the paper under "Technology Differences".

[iii] The term “fault coverage” is defined as the effectiveness of the test stage at detecting defects and is independent of the level of test access available. For example: “…this test stage is 95% effective at detecting solder shorts on accessible solder joints…” (Fault Coverage) x (Test Access) = (Overall Test Coverage)

[iv] Board Bounce occurs within the AXI system due to movement of the board in the X, Y or Z direction.