

The Why, Where, What, How, and When of Automated X-ray Inspection

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ABSTRACT

Use of automated X-ray inspection (AXI) for printed circuit board inspection is rapidly growing, especially on high-density, complex boards. X-ray images of solder joints can be analyzed automatically to detect structural defects, such as insufficient solder, voiding, shorts, opens, and other defects – that typically make up 80% to 90% of the total defects on an assembled circuit board. How do the different AXI technologies work? What are the appropriate uses of 2D versus 3D X-ray? Where in the manufacturing process should AXI be placed for maximum effect? And, not least, how can AXI be used to improve the manufacturing process?

THE NEED FOR BETTER TEST

For many years, the de facto test process for production of printed circuit board assemblies (PCBAs) included manual visual inspection (MVI) after soldering followed by an electrical test such as in-circuit test (ICT) at the end of the assembly process to isolate any defects that occurred during manufacturing. A final functional test was then run to verify that the product worked as required before it was integrated into the final product. This process was sufficient until the advent of surface mount technology (SMT). SMT allowed quantum advances in circuit density over through-hole technology (THT) due to much smaller packages with smaller leads. Once they were comfortable with single-sided SMT, designers began placing components on both sides of the PCBAs to obtain the most functionality in the smallest possible package. As this was happening, production rates increased for consumer products, such as cell phones, and the large complex boards used in servers, routers, and telecom equipment grew larger and more complex. Yields at functional test dropped, and large numbers of skilled technicians were needed for troubleshooting. It became clear that a new test method was needed to find manufacturing defects.

Looking at a table of defects commonly found in on PCBAs during assembly, it is obvious that most are not electrical defects, but "structural" defects.

Defect Type	Approximate Occurrence Rate	Defect Class	Solder Related
Open	25%	Structural	Yes
Insufficient	18%	Structural	Yes
Short	13%	Structural	Yes
Missing Electrical Comp.	12%	Structural	No
Misaligned	8%	Structural	Yes
Defective Electrical Comp.	8%	Electrical	No
Wrong Component	5%	Electrical	No
Excess Solder	3%	Structural	Yes
Missing Non-electrical Comp.	2%	Structural	Yes
Wrong Orientation	2%	Electrical	No
Defective Non-electrical Comp.	2%	Structural	No
Extra	2%	Electrical	Yes

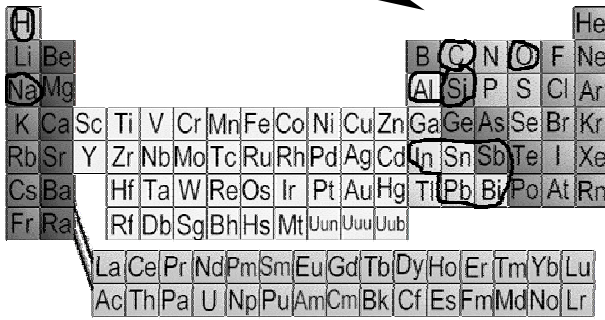
Figure 1¹

Although electrical test is effective at finding many structural defects, such as shorts and missing components, a structural test would be a better fit to the types of defects occurring in manufacturing.

WHY X-RAY INSPECTION?

There are many forms of structural test and inspection in industrial use: X-ray, optical, ultrasonic, thermal imaging, etc. As seen in Table 1, many of the defects are related to the soldering process. X-ray has a unique advantage over other structural test technologies: Materials absorb X-rays proportional to their atomic weight. Materials made of heavier elements absorb more X-rays and are easily imaged, while materials made of lighter elements are more transparent to X-rays. Solders used in electronic assembly are made of heavy elements, such as tin, bismuth, silver, indium, and lead. Most other materials used in electronics are made of lighter elements, such as carbon, aluminum, oxygen, hydrogen, silicon, sodium, and copper.

Periodic Table of the Elements
Figure 2



X-rays therefore have a unique advantage for generating images of solder joints: the solder shows up extremely well, while most packages, the PC board substrate, silicon ICs, and component leads, become barely visible. This makes analysis of the solder joints straightforward. A bonus comes from the transmissive nature of X-ray imaging. Unlike visible light used in Automated Optical Inspection (AOI), X-rays are not reflected to make an image but go through the board and form an image on a detector on the other side. This "X-ray vision," like Superman's, allows hidden features to be examined: BGAs and other array-style packages, the heels of solder joints on fine pitch packages, and the internal characteristics of the solder joints themselves.

OBSTACLES TO ACCEPTANCE

So X-rays appear to be the best fit for inspecting or testing solder joints on PCBAs. Why isn't X-ray the dominant inspection or test solution in SMT manufacturing? X-ray technology is not inexpensive to implement. The imaging system is complex and must be shielded. Components like specialized X-ray sources and detectors are not generally available off the shelf, like the components used in AOI systems: video cameras, visible light sources, and frame grabbers. Automatic analysis of the X-ray images requires a lot of computing power, which has only become economically available in the last few years. So it has taken several years for X-ray to become a practical test technology for the PCBA industry. In spite of the large strides made in X-ray system technology, they are not as fast as many AOI systems and are generally more costly. There has also been a sense of mystery and danger associated with use of X-ray in a production environment. This has largely been overcome by education and extreme attention to safety by the manufacturers of modern X-ray systems.

WHERE SHOULD X-RAY BE USED?
Visually Hidden Defects

One of X-ray's advantages is the ability to find hidden defects. Boards with defects not optically visible are an obvious fit: products with many BGAs, CGAs, CSPs, or components under RF shields. Increasing numbers of boards fall into this category with the increasing popularity of array-style packaging. Many cell phones and wireless communication products are placing RF shields over unsoldered components at pick and place, using the reflow process to solder them to the board. X-ray inspection is the best way to isolate soldering defects obscured by the shields.

Complex Boards

It is common now to see boards with several thousand components and well over 30,000 solder joints. Manual visual inspection (MVI) of even the visible features on boards of this size and complexity is impractical. However, boards this large will have dismal turn-on rates at ICT and functional test even when built in robust assembly processes: the large number of opportunities for defects ensures that. The following formula approximates the turn-on rate (Yield) based on number of opportunities to make a defect (n), and the defect rate of the process (dpmo-defects per million opportunities).

Boards with 20,000 solder joints and an excellent solder joint defect rate of only 50 dpmo will have turn-on rate of only about 37%.

The table in Figure 3 shows the comparative effectiveness of different test technologies at

$$Yield = [1 - (dpmo / 10^6)]^n$$

isolating defects on PCBAs.

Figure 3

Defect	Approx. Occurrence Rate (R)	AXI Eff. (Ex)	AXI Net Eff. (R*Ex)	ICT Eff. (EI)	ICT Net Eff. (R*EI)
Open	25%	95%	24%	85%	21%
Insufficient	18%	80%	14%	0%	0%
Short	13%	99%	13%	99%	13%
Missing Electrical Component	12%	99%	12%	85%	10%
Misaligned	8%	80%	6%	0%	0%
Defective Electrical Component	8%	0%	0%	80%	6%
Wrong Component	5%	10%	1%	80%	4%
Excess Solder	3%	99%	3%	0%	0%
Missing Non-electrical Component	2%	0%	0%	0%	0%
Wrong Orientation	2%	10%	0%	80%	2%
Defective Non-electrical Component	2%	0%	0%	0%	0%
Extra	2%	80%	2%	80%	2%

Using ICT only on the example board catches about 56% of the defects. This will result in a large number of boards in a "bonepile" after functional test needing skilled technical diagnosis to allow repair and shipment. When using a combination of AXI and ICT, about 96% of the defects are found and fixed and the bonepile doesn't grow to an unmanageable size.

High Reliability and Harsh Environments

Boards used in aerospace or other high reliability applications are a good fit for AXI since it evaluates the quality of the solder joints, not just their presence or absence. Similarly, products used in harsh environments are well suited to X-ray inspection. Large thermal and mechanical stresses on the board while in use cause marginal joints to fail. An example is the under-hood environment in automobiles. It is brutal, and failure of an engine or braking control system can be catastrophic. Boards are not unusually complex and are often single sided.

WHAT ARE THE VARIOUS X-RAY TECHNOLOGIES?

X-ray is now accepted as one of the best methods of isolating structural defects on PCBAs. But what X-ray inspection and test technologies are available now and where do they give PCBA manufacturers the most value?

Manual X-ray Inspection

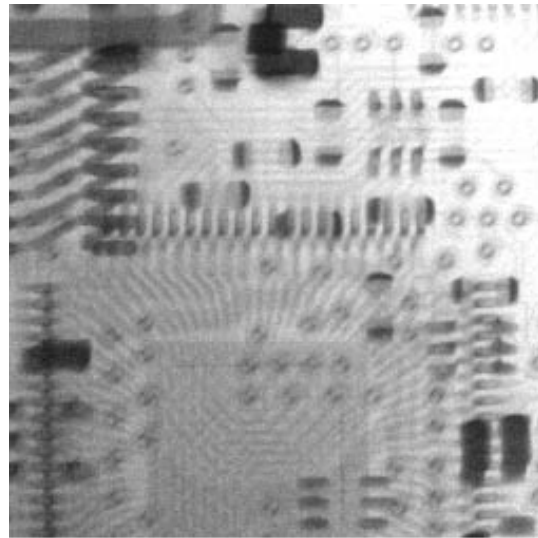
Although much more expensive than conventional MVI, manual X-ray inspection is similar: It uses the eyes and brain of the operator as the image processor and decision-maker. Like MVI, this is slow and boring in a production environment resulting in inconsistent results and is better suited to a failure analysis environment. The operator doing failure analysis usually has considerable expertise in X-ray image interpretation, and normally there is a limited number of defects to analyze. Most manual X-ray systems are transmission systems.

2D or Transmission X-ray Inspection

"2D" (two-dimensional) X-ray is another name for conventional transmission X-ray technology. X-rays are generated at a fixed point source, pass through the PCBA, and form an image on a detector. Most medical and dental X-rays are transmission systems and use photographic film as the detector. In manufacturing, an electronic detector creates the image, converts it into a digital image and transfers it to a computer where analysis of the image takes place. As in a medical X-ray, everything between the source and the detector is in focus. This works well if you are looking at a broken bone or a single sided PCBA that has only one layer of solder joints. On double-sided boards with a high density of solder joints on both sides of the board, the image gets very confusing, as shown in Figure 4.

Figure 4 2D Transmission Image

Solder joints from the top and bottom sides of the board overlap, shading each other and making analysis almost impossible. 2D X-ray test is best suited to single-sided boards and is



often used in automotive applications where high reliability is needed from single-sided boards that operate in a harsh environment. Many 2D X-ray inspection systems are in production use worldwide, usually on single-sided PCBAs.

The Need for 3D X-ray

Engineers usually design double-sided boards due to performance or space requirements of their end products. These requirements often result in poor electrical test access due to high density. This increased density and complexity are being seen in boards of ever increasing size; many as large as 18"x24". X-ray technology is a double-edged sword: It allows imaging of hidden features, but also includes everything between the X-ray source and detector in the image. It is clear that the solder joint information for each side of a double-sided board must be separated to be used effectively. For the purpose of this paper, "3D" means that clear images of single layers (or slices) of the board are generated and used for test.

3D Digital Tomosynthesis

Digital tomosynthesis creates a pseudo-3D image by reconstructing multiple transmission images taken from different angles.

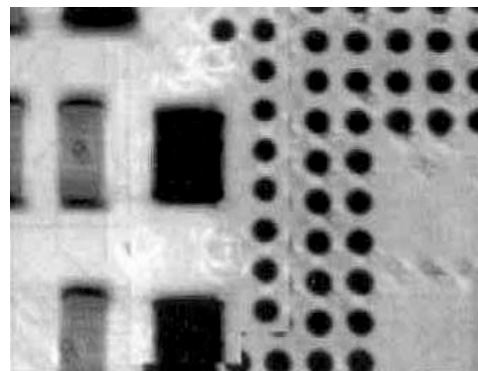


Figure 5 3D Tomosynthetic Image

The reconstruction of each slice is done computationally and requires a lot of computer power. Integrating an infinite number of images would give the clearest, truest slice images. Unfortunately, the amount of computation increases greatly as the number of images used in the integration increases. Practicality limits the number of images used in each reconstruction due to the throughput needs of a production system. The cost of reducing the number of images used results in the formation of phantom features or "artifacts" in the slice images that are a source of error in the analysis of the slice image. With today's throughput requirements of PCBA production, digital tomosynthesis is challenged to keep up. Implementation of digital tomosynthesis is still very limited in production environments but continues to be a promising technology as computers become faster and less costly.

Combining 2D and 3D Tomosynthesis

A novel approach is being offered that combines the speed of 2D transmission with the capability of 3D tomosynthesis. Many of the solder joints on double-sided boards are not shaded by joints on the other side of the board when viewed with 2D transmission.

In this combination technology, joints without shading are inspected with the faster 2D X-ray, and 3D digital tomosynthesis is used on the joints that are shaded from the other side of the board. This would seem to be a good approach, applying the strong points of each technology. Both the 2D and 3D imaging are done in one pass in the same system.

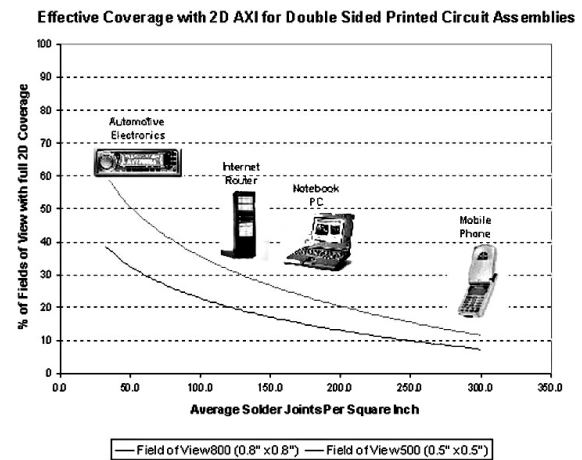
Fields of View

Driven by the size and cost of X-ray detectors, limitations in system resolution, and the large quantity of data present in each image, all automated X-ray systems divide the board under test into smaller parts for imaging and analysis. In most systems, the size of these "fields of view" ranges from about 0.3-inch to 1.0-inch square. The theory behind the combination 2D/3D systems is that a large percentage of solder joints are not shaded and can therefore be inspected in 2D mode. However, since the board must be divided into views, the presence of any shaded joints in a view requires that the entire view be inspected in 3D mode. This greatly increases the percentage of the board that must be inspected in the slower 3D tomosynthesis mode. The higher the density of solder joints on the board, the higher the likelihood that any view will require 3D inspection due to shading.

Figure 6 illustrates the percent of views that can be inspected in 2D-transmission mode for several typical products. Results for two different sized fields of view were calculated from real production board CAD data.

Figure 6

It is apparent that for high-density double-sided boards there will not be much of a throughput advantage in using 2D/3D combinational testing compared to using 100% 3D tomosynthesis.



3D Laminography

In 3D laminography, the X-ray source and the detector move in a circular pattern, synchronized but 180 degrees out of phase. The X-ray image is integrated around an entire revolution, digitized, and sent to the computer. In the image, only the features in one plane of the board are in focus.

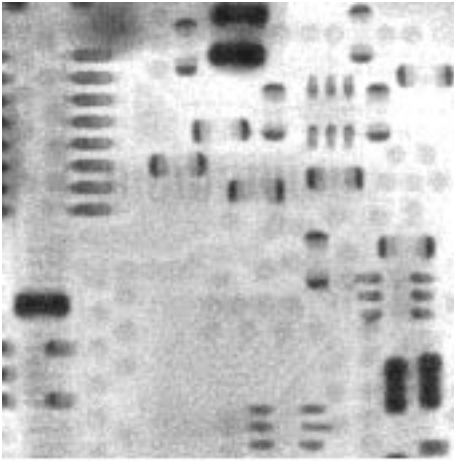


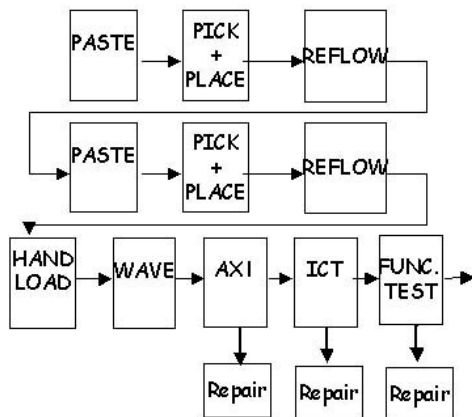
Figure 7 3D Laminographic Image

Solder joints and anything else not in the plane of focus are sufficiently blurred out across the image to allow independent analysis of the joints in the plane of focus. By precisely moving the board up and down (in the Z-axis), images of joints on each side of the board can be independently generated for test. Since the image of each side of the board is physically generated by the imaging system and not as a result of tomosynthetic computation, laminography is much faster than digital tomosynthesis. In a laminographic system, the ability to focus on a single slice of the board also requires the system to know where that desired slice is located in the Z-axis. Laminographic systems must measure the precise Z-axis position of the top and bottom of the board. Typically this is done on each board at the beginning of the test cycle with a laser or optical system that is an integral part of the system. Although this has a negative effect on throughput, overall production rates of laminographic systems are considerably faster than for existing 3D digital tomosynthesis systems. At present, there are several hundred 3D X-ray laminography systems in use in PCBA manufacturing worldwide.

WHEN SHOULD AXI BE USED?

In the Assembly Process

Automated X-ray inspection can be useful at many stages of the assembly process, but time and resource constraints usually limit most



products to a single pass through X-ray. It should be implemented where it will have the maximum positive effect on the process. Since automatic analysis of finished solder joints is its strength, most systems are placed after soldering processes, even though automated X-ray inspection is excellent for monitoring the solder paste deposition process.

Given a single X-ray inspection in the process, the best use is usually at the end of the final soldering process, be it either wave or reflow. All solder joints on the board are present and can be covered in a single test. Also, by waiting until the completion of all assembly processes, any defects caused by the later processes (such as damaged or missing components) will be found. The diagram in Figure 8 shows the flow for a double-sided board with 2 reflow and a selective wave process.

Figure 8 Common Process Flow

Product Lifecycle

The answer to another "when" question involves the life cycle of the product: Prototyping, early production, and volume production.

Prototyping

To minimize the time to market for new products, the ability to turn-on and troubleshoot prototype designs quickly is critical. This is particularly difficult with large, complex boards: The designer is usually confronted with an unproven circuit design on an untested board that probably contains manufacturing defects. Finding and fixing the manufacturing defects can save days or weeks in validating the design for production. Options in the prototyping phase are manual visual inspection, electrical test with a flying prober, AOI, and AXI. ICT is not a normal option due to the lead-time for fixturing and programming. The flying prober has at least the same accessibility problems as ICT and only performs shorts, opens, and analog in-circuit measurements. It is not very effective at finding most solder defects, and work invested in developing a flying probe test can not be leveraged into production: A flying prober cannot keep up with production volumes. Programs developed for AXI move with the product to production, so the investment in prototype test is not wasted.

Early Production

The value of AXI in volume production has already been discussed. Early low-volume production can also have situations uniquely answered by AXI. Many manufacturers' normal test methodology uses ICT as the predominant production test. Sometimes the ICT program or fixture is not ready when production begins. Due to its lack of fixturing and comparative ease of programming, an X-ray inspection can be

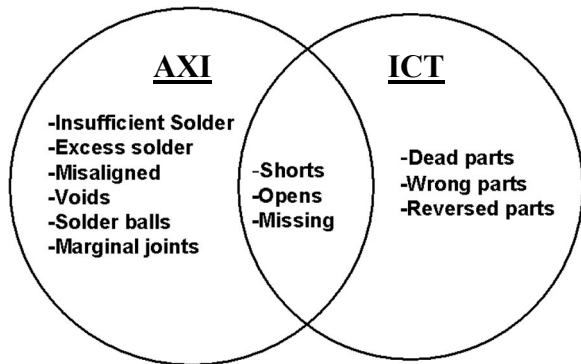
ready in a matter of hours or days and production can proceed without choking functional test with difficult-to-isolate defects.

Volume Production

When the ICT program and fixture become available and have been debugged, using both ICT and AXI as partners covers the largest defect spectrum.

Defect	Approx. Occurrence Rate	AXI Eff.	ICT Eff.	AXI + ICT EFF.
Open	25%	95%	85%	99%
Insufficient	18%	80%	0%	80%
Short	13%	99%	99%	100%
Missing Electrical Component	12%	99%	85%	100%
Misaligned	8%	80%	0%	80%
Defective Electrical Component	8%	0%	80%	80%
Wrong Component	5%	10%	80%	82%
Excess Solder	3%	99%	0%	99%
Missing Non-electrical Component	2%	0%	0%	0%
Wrong Orientation	2%	10%	80%	82%
Defective Non-electrical Component	2%	0%	0%	0%
Extra	2%	80%	80%	96%

Figures 9+10 Combined Effectiveness of AXI+ICT



The key to this effectiveness is that each technology complements the other. ICT can detect but not isolate shorts and cannot find intermittent open solder joints. AXI cannot find reversed ICs or wrong parts. Together they assure that very few defects escape downstream.

PROCESS CONTROL

Up to this point, the discussion has focused on automated X-ray inspection being used for screening defects on PCBAs. This has the most immediate and positive impact on the shipment and quality performance of a manufacturer. But while testing boards, automated X-ray inspection generates information for two additional opportunities to improve a shop's performance: attribute data (defects) and continuous (measurement) data about the solder joints.

Attribute Data

By recording defect data in a database and running periodic queries, a manufacturer can isolate and quantify manufacturing problems and take corrective action. If problems are design related, hard data can often be used to convince designers to improve future designs.

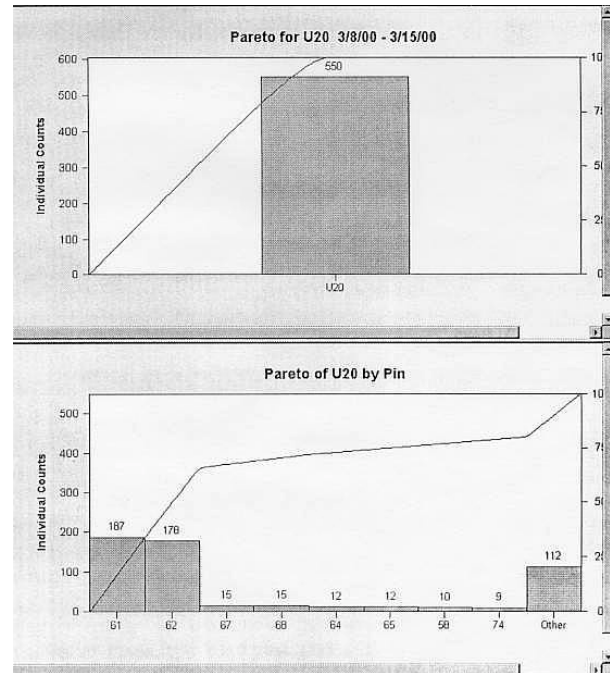


Figure 11 Defects by Pin Number on U20

The example in Figure 11 shows how attribute data can be used for solving process problems. After the manufacturer sorted defects found by AXI by board type, defect type and component reference designator. Defects on component U20, a 0.5-mm pitch QFP64 package on the top of the board, were found to be much higher than on any other part. Setting up another quick series of Pareto charts indicated that the vast majority of defects were solder bridges. The

next Pareto showed that most were on pins 61 and 62. (Figure 11.) The process engineer took this information to the solder paste-stenciling process, where a very small "dimple" was found in the stencil between the apertures for pins 61 and 62. This dimple allowed paste to be squeezed onto the board between the pins, causing a high occurrence of bridging. X-ray inspection generates detailed defect data that can lead to improved processes.

Use of defect data, in conjunction with a database tool allowing the manufacturer to track yields and isolate problems, can lead the way to improving quality and assembly yields.

Measurement Data

Measurement data from x-ray inspection of solder joints gives the manufacturer information needed to implement real-time process control.

At present, real-time process control is not commonly used in PCBA manufacturing. It is a difficult environment for real-time process control due to a large number of factors:

- There are many possible causes for most process variations.
- The correlation between specific measurement variations and their causes has not been well characterized by the industry. A large amount of work is needed to develop this characterization.
- In high mix shops, there are thousands of uncontrolled variables, such as lead material, finish, and size, the thermal characteristics of each product, and vendor-to-vendor component variations.
- The short life cycle of most products (often six months or less) and influx of new products makes characterization difficult.
- Product requirements often dictate that the board's design is not an optimum fit with the PCBA assembly processes.
- The frequent transfer of products from line-to-line and facility-to-facility.

Today, the best fit for implementation of real-time SPC in PCBA manufacturing is in high-volume production facilities, building single products over an extended period.

Unique among test technologies, AXI collects detailed solder measurement data that only now can give the industry the information it needs for successful SPC efforts. It promises to open new opportunities for major improvements in PCBA manufacturing.

SUMMARY

Automated X-ray inspection is the most effective technology for finding manufacturing defects in PCBA assembly operations. Its acceptance is increasing and it is being successfully used in production and in prototype operations on many kinds of assemblies.

2D transmission is an excellent fit for single-sided PCBAs, and 3D AXI is the best fit for high-density double-sided boards.

3D digital tomosynthesis is a very attractive technology for testing high-density double-sided boards, but still lacks the throughput required for many applications. With improved throughput its use can become widely accepted.

3D laminography is a good fit for testing high-density double-sided boards. Its higher throughput has resulted in successful production implementation at many facilities throughout the world.

Defect data is being used today to isolate and solve many problems in production, and the data generated by AXI has the potential for use in process control as SMT manufacturing processes become characterized.

When used in prototyping, all AXI technologies contribute to minimizing the time to market for new products. In production, AXI is the most effective method of finding manufacturing defects. When coupled with electrical test in a production environment, manufacturers obtain the broadest possible coverage of the PCBA defect spectrum.

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