Digital Image Processing:
Automated X-Ray Inspection in Electronics Manufacturing

Matthew D. Boardman, #B00068260
Faculty of Computer Science, Dalhousie University

October 14, 2004

Abstract

In this paper, we examine two dimensional transmission and three dimensional laminography, as implemented in two Automated X-Ray Inspection (AXI) industrial machines used for inspection of Surface Mount Technology (SMT) solder joint connections in electronics manufacturing: the Teradyne XStation and Agilent 5DX. Factors affecting x-ray image quality, such as the size of the focal spot, the x-ray source spectrum and energy absorption in the target material are described. This report is also available at [http://www.cs.dal.ca/ ∼boardman].

1 Introduction

In the mid- to late- 1990's, the world demand for computer and networking technology exceeded the capacity of many electronics manufacturers to supply products to their customers. IBM, Hewlett-Packard (HP), Sun, Cisco, Nortel and many other high technology companies turned to Electronics Manufacturing Services (EMS) providers, such as Solectron and Sanmina-SCI, to outsource or expand their manufacturing capacity. Other EMS providers such as Celestica International, Jabil Circuit and Flextronics came into existence and expanded quickly as competition grew. By the end of 2000, Celestica International, a Canadian company originally created in 1994 from a single manufacturing plant in Toronto, Ontario owned by IBM Canada Ltd., had grown to a publicly-traded international corporation with revenues approaching US $10 billion, as a result of aggressive expansion [6].

Although world demand for high technology products was greatly reduced in 2001 and the subsequent period of economic uncertainty, these five EMS providers continue to provide design and manufacturing services to their customers. The two major electronics manufacturing technologies employed by these companies are Surface Mount Technology (SMT), in which the connectors for electronic components are soldered directly to copper pads on the circuit board, and Pin Through Hole (PTH), in which the wires from electronic components are soldered through pre-drilled holes, or vias, in the circuit board.

An example of a typical SMT manufacturing line is shown in Figure 1. Electronic components such as computer chips, capacitors and resistors, and consumables such as solder paste are drawn from a materials warehouse and brought to the kitting area in preparation for a build of a batch of products. Circuit boards then move through the manufacturing line continuously, moving from each piece of equipment to the next automatically in an inline process flow. Solder paste is applied to the board by the screener, and components are placed by high speed chip shooters such as the Panasonic MV150 or high precision placement machines such as Universal's GSM. Finally the solder paste is melted into liquid solder by the reflow oven and then cooled to cement the components in place.

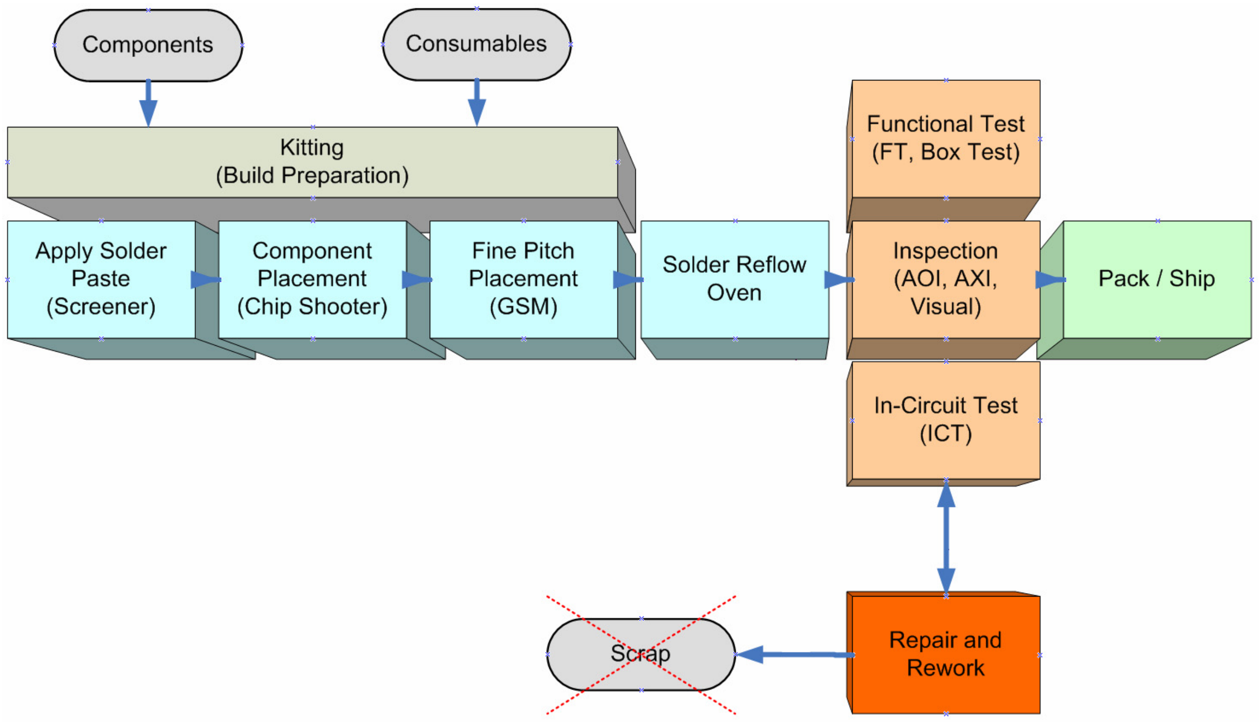


Figure 1: Representation of a typical SMT line used in electronics manufacturing, including several testing methodologies: AOI/AXI, Functional, and ICT.

Completed circuit boards are then tested using one or more of three main test methods: Functional Testing (FT), which tests the functionality of each board using a simulated environment similar to the one in which the boards will finally be used; In-Circuit Testing (ICT), in which particular circuit paths are tested for continuity using a flying probe; and visual inspection either by human beings, or by automated systems such as Automated Optical Inspection (AOI) and Automated X-Ray Inspection (AXI). The high complexity and increasing density of modern electronics frequently necessitates a complex testing strategy, and automated inspection systems such as AXI are increasingly a part of such strategies. In this paper, we examine two machines used for AXI in electronics manufacturing for inline SMT and PTH technologies: the Agilent 5DX and the Teradyne XStation, shown in Figure 2.

2 Two Dimensional AXI

Two dimensional AXI, or Transmission AXI, is similar to optical photography except that no lenses are used as focussing elements, since the glass in such lenses would absorb a large part of the x-ray spectrum[9]. The x-ray source illuminates the target circuit board, which casts a “shadow” on a digital x-ray detection plate as shown in Figure 3(a).

An example of an transmission x-ray image in comparison to a similar optical image is shown in Figure 4. Since solder is often composed of lead (Pb) or other dense metals, the x-ray spectrum cannot easily penetrate the solder joints on a circuit board, and these solder joints therefore show as dark areas on the x-ray image. Similarly, the fibreglass (FR-5) circuit boards allow x-rays to pass through easily, so these areas appear much lighter in the x-ray image. Interestingly, several x-ray imaging systems makers, including Agilent [1] and Oy Ajat [11], but not Teradyne [13], show the inverse of these intensities to the user, presumably since it makes more intuitive sense that metal areas should be shiny and white. Examples of the images captured by the Agilent and Teradyne machines as shown to the

(a) Agilent 5DX: Laminography AXI. (b) Teradyne XStation: Transmission AXI.

Figure 2: Two industrial machines for automated SMT testing using x-ray technology, the Agilent 5DX [1] and Teradyne XStation [14].

machine operator can be see in Figure 8.

3 Three Dimensional AXI

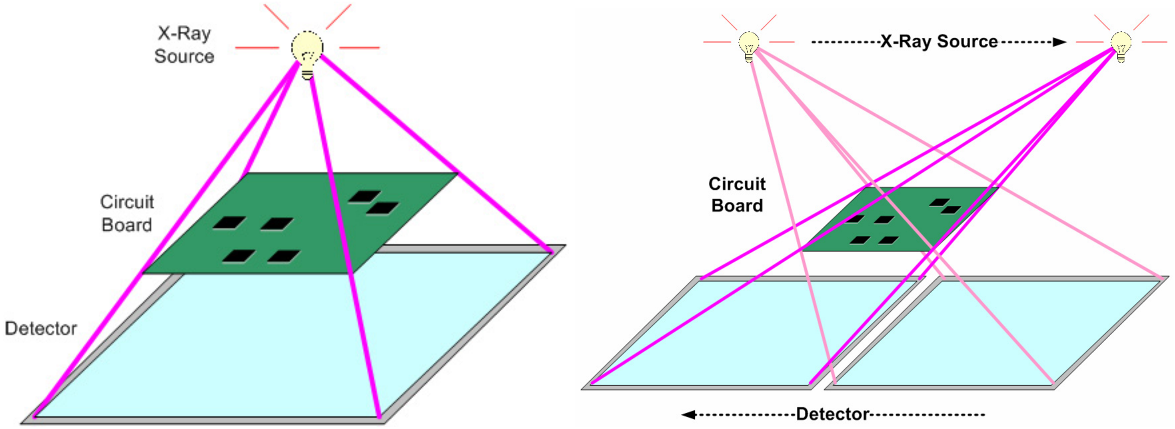
Three dimensional AXI, or Tomography AXI, takes a cross section or “slice” at a specified height just above the surface of the circuit board. There are two implementations in industrial tomography: laminography and tomosynthesis[7].

Laminography is based on relative motion of the x-ray source and detector, moved relative to each other in order to intentionally cause motion blur in any features of the target which are above or below the slice, causing those features to disappear in the resulting image. This is the more common implementation for electronics manufacturing tomography AXI. This concept is shown in Figure 3(b).

Tomosynthesis is also referred to as the limited angles technique[7], and has been in use since the late 1980s. It is more commonly use in industrial Computerized Axial Tomography (CAT) x-ray machines used for medical imaging, where the goal is to create a three dimensional model of a rounded target such as human being, by combining many cross sectional slices through the target, rather than creating a two dimensional image of a single slice through a relatively flat target such as a circuit board.

One of the factors affecting the quality of a 3D AXI image is the size of the “focal spot,” or thickness of the slice. For example, the slice height is on the order of 1 mm in the University of Texas machine whose spectrum we examine in the next section[8], whereas the Agilent 5DX claims a slice height as small as 5 microns[1].

Some examples of slice heights recommended by [12] to effectively measure the quality of solder joints used in electronics manufacturing are shown in Figure 5. Ball Grid Array (BGA) connectors are commonly used to attach semiconductors with a large number of input/output pins, such as computer processors. In this case, three slices are used to measure the width of the solder ball, the volume of solder present in the upper solder joint to the packaging, and the volume of solder present in the lower solder joint to the copper pads on the circuit board. J-Lead connectors, where pin leads are bent underneath the plastic packaging, are commonly used for semiconductors with parallel connections such as DRAM memory. In this case, two slices are used to measure not only the volume of solder connecting to the



(a) Transmission.

(b) Laminography.

Figure 3: Two dimensional transmission AXI and three dimensional laminography AXI. Dotted lines show motion during laminography image capture, in order to intentionally blur those features which are not within the target slice height. Images redrawn based on [7].

copper pad on the circuit board, but also to detect the presence and orientation of the component.

4 X-Ray Spectrum

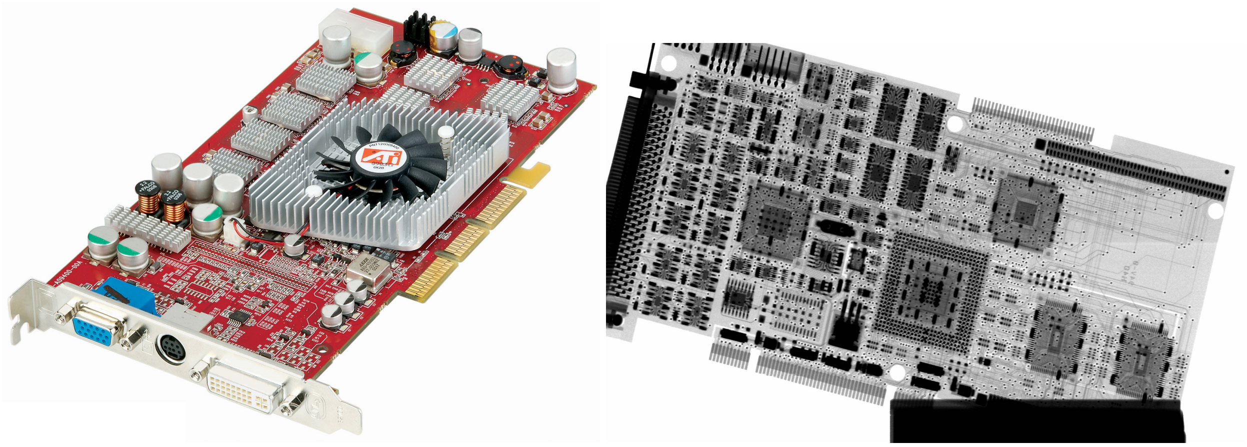
A theoretical example of an x-ray spectrum is shown in Figure 6. This spectral model is based on a 420 kV x-ray source at the University of Texas CT Facility, which uses a 0.8 mm high resolution focal spot and a 1.8 mm high power focal spot[8].

In addition to the continuous spectra from 20–410 keV caused by synchrotron radiation or *Bremsstrahlung*[8], the result of radiation emitted from charged particles[5], K-Series peaks can be seen in the 57–59 and 67–69 keV range[8], and are a result of the tungsten (W) detector used in this case: tungsten has K-level emission lines at 59.3 keV, 58.0 keV and 67.2 keV [2].

It is also worth noting that the intensity of the x-ray sources used in industrial applications such as electronics manufacturing are generally greater than those used in medical applications[8]. The shorter wavelengths in this x-ray spectrum is in the range referred to as “hard” x-rays with wavelengths on the order of 0.01 nm, whereas visible light has wavelengths of 400–700 nm[9]. This is so that the x-rays can partially penetrate the small volumes of lead in the solder joints. The only known radiation type currently defined with shorter wavelengths is gamma radiation, and in fact part of the example spectrum in Figure 6, in which the mean energy of the source is 114 keV, can be considered to be gamma radiation, which is generally considered to be energies in excess of 100 keV[9].

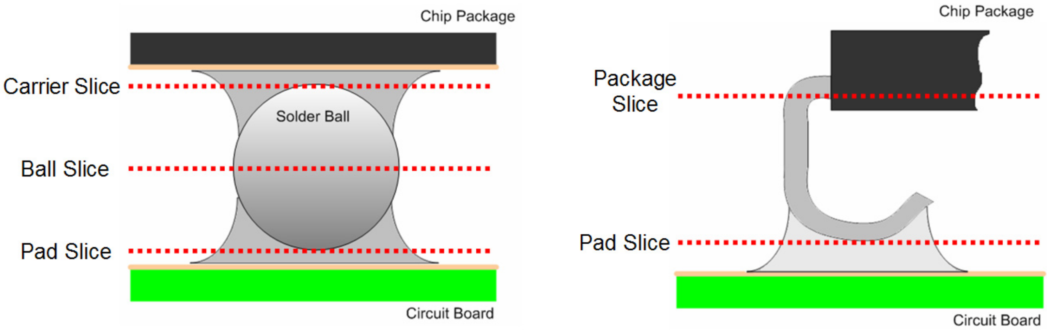
5 Beer’s Law for Energy Absorption

Beer’s Law describes the energy loss due to absorption and scattering as the electromagnetic energy from an x-ray source pass through homogeneous materials[8]. By extending Beer’s Law over a series of homogeneous materials, the following decay function describes the energy received by the x-ray detector, integrated over the range of frequencies



(a) ATI Radeon$^{\text{TM}}$9800 Pro 256MB.   (b) X-Ray image of similar card.

Figure 4: Optical [3] and x-ray [11] images of a PCI computer card, manufactured using primarily SMT manufacturing processes. X-Ray images have inversed gray scale from original source [11] in order to show uncorrected image.



(a) Ball Grid Array (BGA) Connector.   (b) J-Lead Connector.

Figure 5: Examples of slices used for defect detection in cross-sectional tomography. Images redrawn based on [12].

in the source spectrum [8]:

$$I = \int I_0(E) \mathrm{e}^{\sum_i (-\mu_i(E) x_i)} \mathrm{d}E \tag{1}$$

where $I_0(E)$ describes the x-ray source spectrum, and for each material i, x_i is the thickness of the material and $\mu_i(E)$ is the linear attenuation coefficient [8] for the material, which describes the rate at which the material absorbs and scatters x-ray energy at the particular frequency E.

In industrial applications, however, rather than integrate the material scattering and absorption rates over the entire x-ray source spectrum, the mean intensity of the spectrum is generally used. If we make this simplification to Beer's Law above, and substitute some common materials used in the manufacturing process of circuit boards, as seen in Figure 7, we see the following decay function:

$$I = I_0 \, \mathrm{e}^{-\mu_{Cu} x_{Cu}} \, \mathrm{e}^{-\mu_{Fibreglass} x_{Fibreglass}} \, \mathrm{e}^{-\mu_{Pb} x_{Pb}} \, \mathrm{e}^{-\mu_{Si} x_{Si}} \, \mathrm{e}^{-\mu_{Plastic} x_{Plastic}} \tag{2}$$

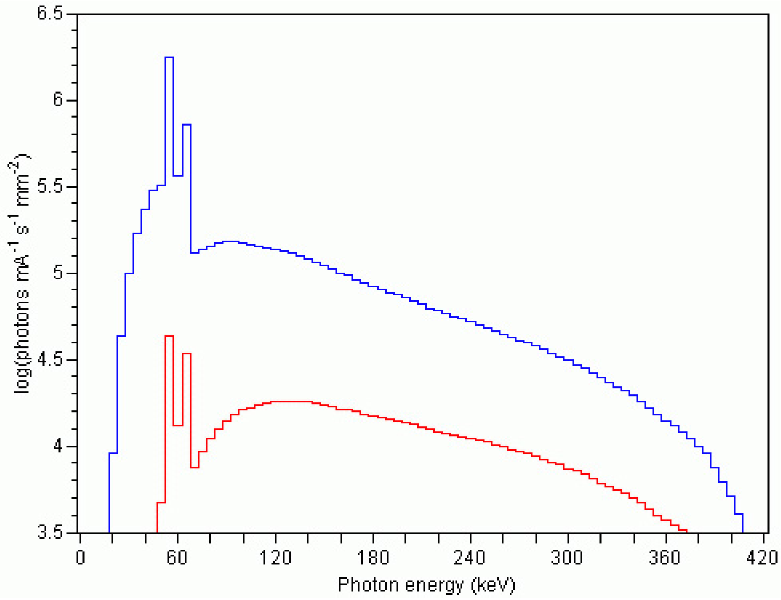


Figure 6: Example of a theoretical x-ray spectrum from the University of Texas, from a 420 kV source with tungsten target[8]. The upper (blue) line represents the source spectrum, and the lower (red) line represents the spectrum that would be detected through 5 cm quartz. Theoretical detector includes 3mm aluminium.

where I_0 is the mean intensity of the x-ray source at the mean frequency. This approximation is appropriate in x-ray laminography for electronics manufacturing due to the high number of artifacts created as a result of the process itself, which must be compensated for during image capture[8].

It is also important to consider any materials present in the detector. For example, in the source spectrum in Figure 6, 3 mm of aluminium is present in the detector plate.

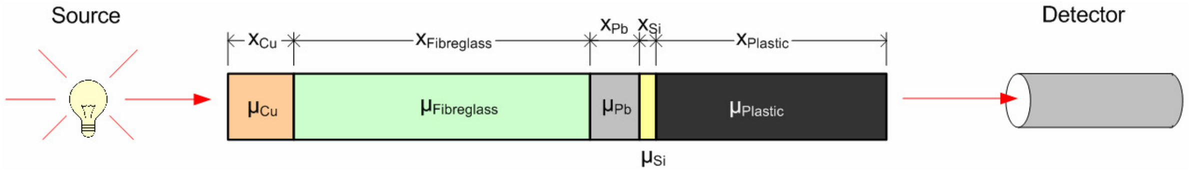


Figure 7: An example of x-ray energy absorption through materials present in SMT circuit boards.

6 Defects Detected by AXI

In AXI testing for the electronics industry, we are primarily concerned with the volume of solder at each solder joint location, and the presence and orientation of each required component. Some photographic examples of such defects are shown in Figure 10 [4].

Figure 10(a) shows an example of a missing component. In this case, it appears that the component was placed with an incorrect orientation (upright, or “tombstoned”) and then subsequently knocked off the board during the placement of other components.

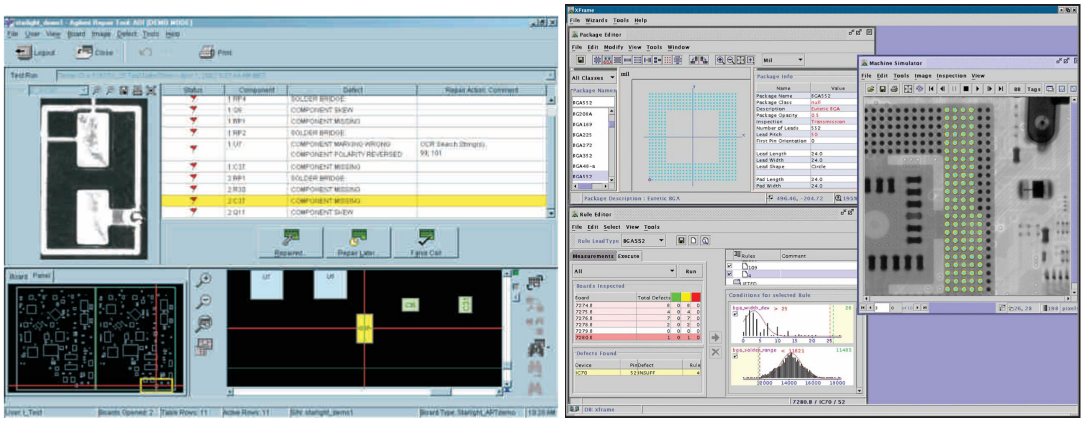
Figures 10(b) and 10(e) show examples of insufficient solder in SMT and PTH processes respectively. Figure 10(c) could also be an example of insufficient solder, since the volume for some connections does not seem to be sufficient to reach the connector, or it may be an example of a misplaced or deformed connector block.

Figure 10(d) shows an example of debris, in this case an extra discrete component (a capacitor), causing bridging between fine-pitch connections.

7 Software for AXI Machines

Once the machine has captured an x-ray image through either transmission (2D) or laminography (3D), this image must be used to identify defects at solder joint locations. There are several methods for this, and the exact methods used in the Agilent and Teradyne machines are protected by each company respectively, however we can speculate on some of the techniques that may be used, based on screen images of the provided software.

Examples of a screen which may be shown to operators of the Agilent and Teradyne machines are shown in Figure 8. The Agilent 5DX software shows a magnified laminography image of a missing component, with the gray-scale intensities reversed, as identified by CAD drawings of the board input by the AXI operator. The Teradyne XFrame^{TM}software shows a magnification transmission image of a BGA connection, and has identified the solder balls as having an insufficient volume of solder. The statistical profile used in making this determination can be seen in the bottom centre of Figure 8(b).



Status	Component	Defect	Repair Action Comment
▼	1:RP4	SOLDER BRIDGE	
▼	1:Q6	COMPONENT SKEW	
▼	1:RP1	COMPONENT MISSING	
▼	1:RP2	SOLDER BRIDGE	
▼	1:U7	COMPONENT MARKING WRONG COMPONENT POLARITY REVERSED	OCR Search String(s): 99; 101
▼	1:C37	COMPONENT MISSING	
▼	2:RP1	SOLDER BRIDGE	
▼	2:R30	COMPONENT MISSING	
▼	2:C37	COMPONENT MISSING	
▼	2:Q11	COMPONENT SKEW	

(a) Agilent software.

(b) Teradyne XFrame^{TM}software.

Figure 8: Software used by Agilent[1] and Teradyne AXI machines[13].

The actual method used to identify defective solder joints may be a simple comparison to a "known good" image, as is often done in Automated Optical Inspection (AOI). Such a method would mean that the machine could "learn" over the first few products what each section of the circuit board should look like, and automatically flag any differences as defects. This is possible since the x-ray images are taken under very controlled conditions inside the machine, and would be automatically aligned using pre-drilled fixture holes in the circuit board itself. However, this could mean a high number of false failures, where the machine identifies a good solder connection as being bad, during the learning process: for example, during a prototype batch.

In two dimensional transmission AXI, the volume of the solder at each location could be determined numerically using quantization. Given a bounding box for each solder connection input by the operator through CAD drawings for example, the sum of the reversed gray-scale intensities over each pixel within this bounding box would be an indication of the total solder volume within the connection. However, such a technique may not detect a defect such as shown in Figure 10(c), in which the solder volume is sufficient however the connector itself was placed slightly above the solder and has not made an electrical connection: in two dimensional AXI, the volume of solder would be sufficient and the connector (from above) would appear to be in the correct place. To improve computational speed, the machine could compute a statistical profile of the solder volume at pre-selected locations and compare this to a theoretically ideal profile. We see an example of such as profile applied to BGA connections in Figure 8(b).

In three dimensional laminography AXI, a similar method could be utilized to calculate the cross sectional area of solder at each location, by summing the number of pixels within the bounding box in which the gray scale intensity is within a predefined range indicating the presence of solder. Similarly, the presence of a component could be detected by simply changing the search range of intensity values through that particular slice. Orientation of the component could be performed by determining the component's centroid and corner locations using standard two dimensional computational geometry.

In the case of BGA connectors, according to Agilent, the method employed is to measure the diameter of solder balls progressively through a slice and search for diameters that differ significantly from nearby neighbors[1]. Agilent claims the speed of this software comparison to be on the order of "thousands of joints per minute" [1] for the Agilent 5DX, which although extremely fast for these computations, would indicate that the speed of the machine could not keep inline with the manufacturing process for boards with a high degree of complexity and would more likely be done offline while another product is being built on the manufacturing line.

8 Effectiveness of AXI

The National Electronics Manufacturing Initiative (NEMI) recently performed an analysis of two highly complex circuit boards to determine the effectiveness of two dimensional and three dimensional AXI in comparison to AOI and ICT [4]. The study found that 3D AXI machines were able to test more joints and found a greater percentage of the total known defects than any other independent methodology, and found nearly 100% defect coverage when three dimensional AXI and ICT were both performed [4]. However, this test did not consider functionality of the completed circuit board: it was designed only to test for manufacturing related defects and did not consider component quality.

The defect coverage found by NEMI for each circuit board in both transmission (2D) and laminography (3D) is plotted in Figure 9. As can be seen, although the transmission AXI works well, the laminography AXI has nearly 100% coverage of solder locations for both boards. The complexity of these boards was approximately 14 000 connections each, and both boards were found to have approximately 200–300 solder defects by combining results from 2D AXI, 3D AXI, AOI and ICT (these boards were designed specifically for the purpose of creating manufacturing defects and were not production quality designs).

One advantage of using AXI in an inline process, where the manufactured boards are automatically loaded into the AXI machine and tested, is that the number of defects can be tracked over time. Although a particular defect may not be serious enough to affect the functionality of a product, it may be a indication of a manufacturing process that may cause more serious problems if left unchecked. This "process indicator" [4] data is useful for EMS companies to improve a product's first pass yield, which is a measure of the ratio of good products to bad without considering repair and rework. This yield can vary greatly with the complexity and size of the product being produced. For example, a typical first pass yield for small, less complex boards such as SDRAM memory products may be well above 99%, whereas larger, more complex boards such as a quad-processor network router may have a first pass yield of only 60–70%.

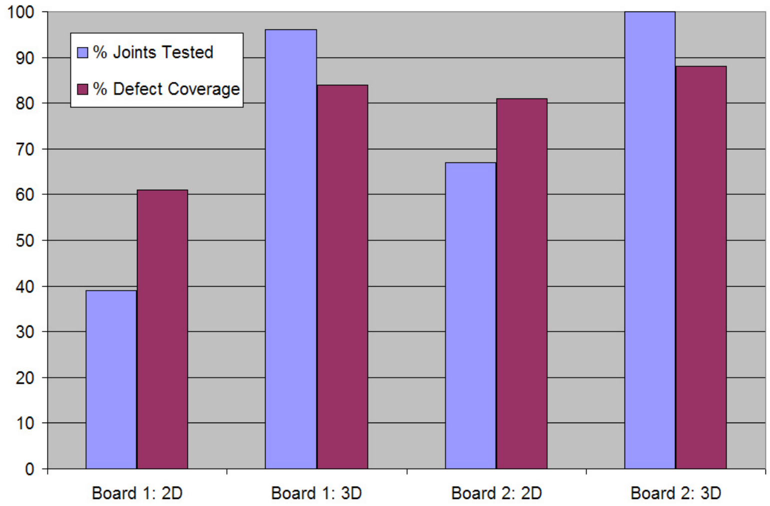


Figure 9: Results from two examples of circuit boards used by NEMI to determine test coverage of AXI machines[4]. Boards had approximately 14 000 connections each, and both were determined to have approximately 200-300 defects each, including only manufacturing related defects. Each board was tested using both 2D and 3D x-ray machines.

9 Conclusions

Although these x-ray scanning methods are not new techniques, the convergence of this technology with automated image comparison, sophisticated statistical analyses and software engineering gives a powerful new tool to electronics manufacturing process engineers. Transmission and Laminography AXI as applied to automated electronics testing in the EMS industry is a mature and effective technology. The cost of the machines can often be justified from the savings incurred from improving the overall yield by catching process defects early, with a corresponding reduction in field warranty and replacement services. In addition, process savings can be achieved in accurately diagnosing reported failures and reducing guesswork, for the purpose of offline repair and rework.

Functional testing will most likely never be replaced. However, it seems probable that the use of AXI machines will not only increase in electronics manufacturing, but that in the near future many boards may be designed with automated testing of this nature in mind: for example, future board designs may reduce or eliminate cases where components on the front side of the board coincide with components on the back side, which could cause detection errors in transmission AXI.

Potential improvements to this technology could be made by employing neural networks in the image processing algorithms to improve the speed of comparison, or fuzzy processing to accurately distinguish between defects and process indicators in order to catch potential problems earlier in the process, before there is a detrimental effect on first pass yield.

References

[1] *“Agilent 5DX Automated X-Ray Inspection Test System,”* Product Brochure, Agilent Technologies, 2003.

[2] J. A. Bearden, *“X-Ray Wavelengths,”* Review of Modern Physics, January 1967, pp. 86-99.

[3] *“Board Shot: Radeon^{TM}9800 Pro 256 MB,”* [http://atitech.com/products/radeon9800/radeon9800pro/gallery.html], ATI Technologies Inc., 2004.

[4] Board Assembly TIG, *“Test Strategy Project 1: Test Coverage Analysis,”* National Electronics Manufacturing Initiative (NEMI), March 2003.

[5] Rudolf K. Bock, *“The Particle Detector BriefBook: Internet Version,”* [http://rd11.web.cern.ch/RD11/rkb/titleD.html], European Organization for Nuclear Research (CERN), April 1998.

[6] Investor Relations, *“Historical Financials,”* Celestica International, 1998-2004.

[7] S. Gondrom, S. Schröpfer, Saarbrücken, D., *“Digital Computed Laminography and Tomosynthesis - Functional Principles and Industrial Applications,”* International Symposium on Computerized Tomography for Industrial Applications and Image Processing in Radiology, Berlin, Germany, March 15–17, 1999.

[8] Richard A. Ketcham, William D. Carlson, *“Acquisition, Optimization and Interpretation of X-Ray Computed Tomographic Imagery: Applications to the Geosciences,”* Computers & Geosciences, Vol. 27, 2001, pp. 381–400.

[9] National Aeronautics and Space Administration (NASA), *“Electromagnetic Spectrum,”* Imagine the Universe, [http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html], 1997-2004.

[10] Frank Natterer, Erik L. Ritman, *“Past and Future Directions in X-Ray Computed Tomography (CT),”* International Journal of Imaging Systems and Technology, Vol. 12, Issue 4, pp. 175–187.

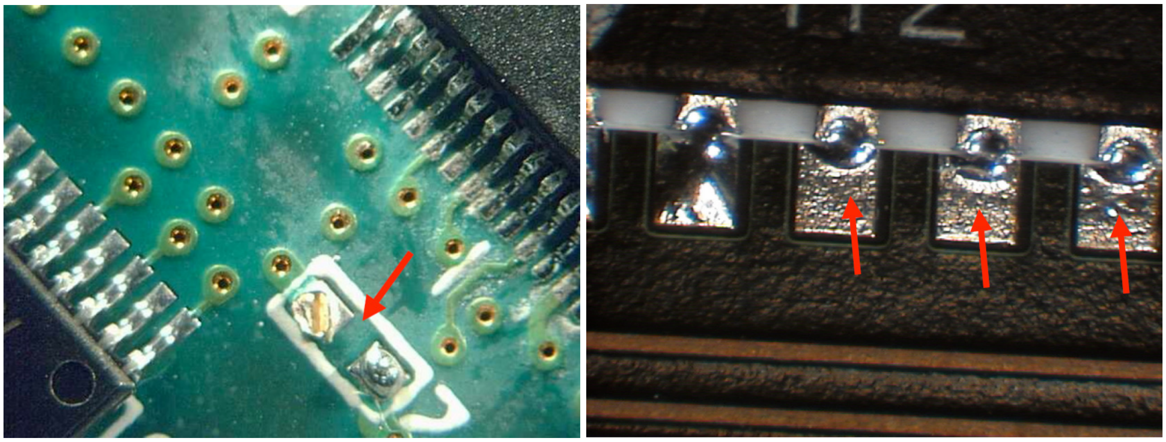
[11] *“Sample Images,”* [http://www.ajat.fi/images], Oy Ajat Ltd., 2004.

[12] Vijay Sankaran, Andrew R. Kalukin, and Russell P. Kraft, *“Improvements to X-Ray Laminography for Automated Inspection of Solder Joints,”* IEEE Transactions on Components, Packaging and Manufacturing Technology, Part C, Vol. 21, No. 2, April 1998.

[13] *“XFrame^{TM}: Integrated Software Development Environment for XStation HS^{TM}Automated X-Ray Inspection Systems,”* Product Brochure, Teradyne Inc., 2003.

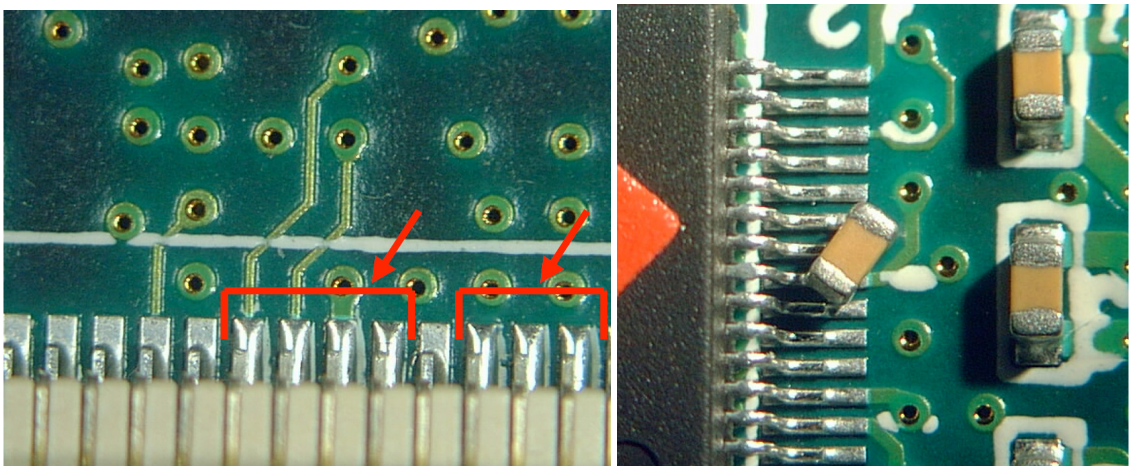
[14] *“XStation^{TM}HSTM: In-Line High-Speed Automated X-Ray Inspection (AXI) System,”* Product Brochure, Teradyne Inc., 2002.

This document was created using the LaTeX document preparation system. Image 4(a) of ATI Radeon$^{\text{TM}}$9800 Pro 256 MB is used under license and is a registered trademark of ATI Technologies Inc. in the United States and other countries. Figures 4(b) Copyright © Oy Ajat Ltd, 2002–2004. All rights reserved. All other trademarks used are properties of their respective owners.



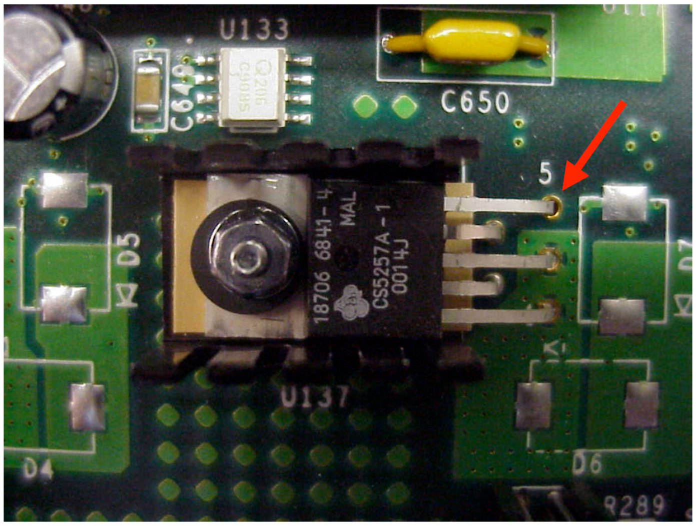
(a) Component missing (SMT).

(b) Insufficient solder (SMT).



(c) Unattached connectors (SMT).

(d) Debris (SMT).



(e) Insufficient solder (PTH).

Figure 10: Examples of defects in electronics manufacturing.[4]