White Paper

# Recent Advances In X-ray Inspection for Electronics Manufacturing

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Technology with Passion

# RECENT ADVANCES IN X-RAY INSPECTION FOR ELECTRONICS MANUFACTURING

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## ABSTRACT

Taking x-ray images goes back over 100 years.  Since then, there have been numerous advances in terms of x-ray tube and x-ray detector technology and these have been increasingly applied into helping with the manufacturing of electronic components and assemblies, as well as in their failure analysis.

Most recently, this has been rapidly driven by the continued reduction in board, device and feature size and the movement to using newer, lower density materials within the structures, such as copper wire replacing gold wire as the interconnection material of choice within components. In order to meet these challenges and those in the future, there have been a number of recent key improvements to the vital components within x-ray systems. In particular, there is a new x-ray tube type that permits high magnification inspection at improved resolution, yet retains high tube power under these conditions, allowing good x-ray flux for inspection of the smallest features.

There is also the availability of new and improved x-ray detectors (both image intensifiers and Digital Flat Panels) that are now specifically designed for electronics applications, rather than hand-me-downs from the needs of the medical market, which are able to take best advantage of these tube developments.

The choice of available technologies, however, means selecting the tube/detector combination, which is optimum for a particular electronics inspection application, is no longer so clear-cut. For example, one configuration may provide certain benefits that are applicable for one area of electronics inspection, whilst being less valid for others. This paper

will review the various x-ray tube and detector types that are available and explain the implications of these choices for electronics inspection in terms of what they provide for inspection regarding image resolution, magnification, tube power, detector pixel size and the effects of detector radiation damage, amongst others.

It will also suggest optimum configurations for the main electronics inspection tasks required today. The increasing use of copper bond wires to replace the gold wire used for many years is one example where the type of flat panel technology can have a significant effect on the resultant images.

Key words: X-ray, electronics, assembly, technology.

## INTRODUCTION

Historically the technology used to X-Ray Printed Circuit Board Assemblies was borrowed from medical applications, mainly the X-Ray of body parts looking for fractures. I am sure you will understand the many differences between these two applications and therefore the challenges faced by our industry in adapting equipment designed for totally different purposes.

This resulted in systems that were not optimised for the inspection of printed circuit board assemblies, especially those demanding technologies that we see today. X-Ray tubes were unable to provide sufficient magnification, power or the ability to see small features. Detectors were also lacking in key features to provide the detailed information to allow an accurate image to be presented onto the screen.

Software was also very rudimentary and a very skilled operator was needed to produce meaningful results from these systems.

However, in recent years some X-Ray manufacturers have focussed on improving all three of the key areas above and have continuously improved over this time. So today they are able to deliver a product that is optimised for the latest technology and also for the advances that we are currently seeing within microelectronics. Some high-end systems have the ability to image Through Silicon Vias (TSV's) and Copper Pillars that are found in ever decreasing sizes in advanced semi-conductor packages.

## ADVANCES IN TUBE TECHNOLOGY

This paper will not spend time on the basics of X-Ray theory as this has been covered in many papers. So I will focus only on the various technologies available.

Sealed Tubes were the original X-Ray sources and were developed over 100 years ago, they have little to recommend them as a radiation source for electronics, but work well in the medical field. Their main issues are within the design that does not allow the sample to get closer than about 15mm from the target. This has a dramatic effect on the available magnification as the closer a sample gets to the target the larger the image becomes. This target or anode is sealed for life inside the tube; it therefore starts to degrade as soon as the tube is used. This has a limiting effect on the usable lifetime because as the target degrades the image on the screen also degrades. Whilst this technology lasts many years within medical applications the tube lifetime in electronics is dramatically reduced leading to tube replacements every few years.

Open Tube technology was developed over fifty years ago and remained unchanged for many years. Recently, however, many improvements have been made in this technology. The main advantages of the Open Tube are that it used a Transmissive target; this allows the focal spot of the tube to be placed very much closer to the sample than a sealed tube will allow. Effectively this distance is now only limited by the thickness of the X-Ray window. This means that the geometric magnification for a system using an open tube is much greater than with a sealed tube. In addition to this the focal spot can be reduced in size, which improves the tubes resolution therefore improving the system's ability to see small features. Another advantage of the Transmissive target is that when an area becomes worn a new portion can easily replace it.

Another technology advance of the Open Tube is the addition of a replaceable filament; except for this consumable part it means that the tube has an almost unlimited lifetime. In recent years this technology has advanced significantly in many areas. The use of sophisticated software to monitor and control tube output (TXI) has led to a very stable and repeatable onscreen image and a dramatic extension in filament life.

More sophisticated vacuum pumping systems have produced a higher vacuum inside the tube that further extends filament life and maintains a small focal spot size at high power. This allows smaller features to be seen at higher power, often needed for demanding applications. These pumps together with an improved internal tube design allow faster restarts after filament changes. The filament itself has also been improved and this further extends its life and aids the ability to see small features at higher power.

Another improvement has been the increase in tube power. With the advent of IGBT's higher power is needed to allow the joints within more dense materials to be analysed properly.  Also, as devices get smaller and smaller the removal of heat becomes a larger problem and this can lead to the use of thick copper heat sinks which also present challenges to some systems as the x-ray beam has to penetrate the copper in order to see the quality of the joints below.

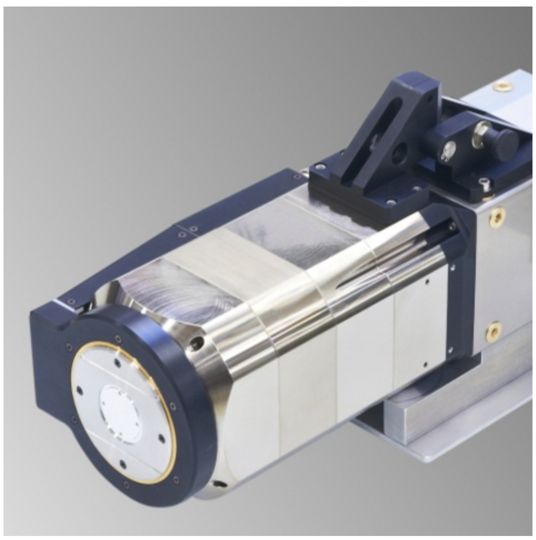

**Figure 1.** Advanced technology open tube

## ADVANCES IN DETECTOR TECHNOLOGY

It is not possible to view X-Rays directly but it is necessary to have the x-rays affect some intermediate medium, which can then be used to provide an image that is transferred onto the monitor.

Originally this was done using x-ray sensitive film.  The older ones amongst us will remember carrying these in brown envelopes to be viewed on a light box in hospital. However the overhead cost, use of wet chemistry and the time needed for developing the film means that it is no longer used for medical applications and was not transposed into the electronics industry.

The detectors used in x-ray inspection systems have been those that replaced the use of film in the medical industry.  Again, this is because the much larger demands of the medical market meant that these detectors were sold at a relatively low price that the smaller electronics market benefited from.  However, these products were not optimised for the needs of the electronics market.  The original detection source was analogue and referred to as an Image Intensifier.  Inside the II visible photons are converted into electrons, amplified by an electron tube, then converted on a phosphorus screen back to photons.  A CCD camera then images them and the results presented to the operator on a monitor.

The image produced is grey scale and varies in density due to the amount of x-rays absorbed through different parts of the sample being analysed. So where a lot of radiation passes through the sample it produces a bright area on the screen corresponding to a low-density material e.g. fibreglass or aluminium. Where more x-rays are absorbed by the sample, darker areas are produced on the screen; this corresponds to more dense material e.g. lead or tin. The resolution of this image is determined by the pixel elements within the detector, the speed with which this image is acquired is based on the acquisition speed of the detector expressed in frames per second (FPS). Analogue II systems typically had an image size of 0.3 million pixels and would struggle to display some of today's high technology.

As lenses are used within Image Intensifiers there can also be issues with 'fish eye' type distortion on the images produced. The later image intensifiers have a digital CCD that improved the image quality somewhat; they also used software to try to overcome image distortion.

A later detector technology involved the use of Flat Panel Devices (FPD). This dramatically improves the image quality as there are no lenses and no image distortion and the imaging is done direct onto an amorphous silicon substrate. By reading the charge level at each node this can be displayed as a brightness level and so an image can be produced. The higher the charge at the node the brighter the response and this again relates to a less dense material on the sample at that position The number of pixels in the area array determines the maximum image size presented to the operator whilst the resolution of the image is determined by the size of those pixels.

The natural acquisition speed of these panels can vary and they also have the ability to run in what is called 'binning mode' which speeds up the acquisition rate by up to four times. However, this is done at the expense of some image quality. Early flat panels were again taken from the medical industry where their use was much less demanding. Let us say five or six pictures every five minutes whereas within electronics they were producing ten images per second, 600 images per minute, 3000 images every five minutes. This dramatic increase in use resulted in a short lifetime for these early panels within the electronics industry.

Recent technology advances within the flat panel arena have seen substantial increases in life expectancy. Also improvements in image stability, both by design of the panel and the use of monitoring and controlling software. Pixel sizes have also decreased which allows even smaller features to be seen on screen. Another issue with early panels were areas of dead pixels; these were caused by weaknesses in the manufacturing capability of this technology. These have largely been overcome and areas of dead pixels are no longer an issue.

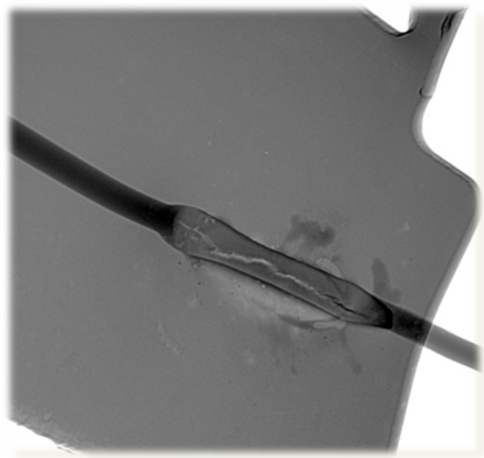

**Figure 2.** Image from High end Digital Flat Panel

## SOFTWARE

Early systems were very limited in software, requiring a very skilled operator, often with a high level of programming skills; these early systems were really designed for use in laboratories not on the production floor.

As you will all be aware computer technology is moving at a tremendous pace and this allows the deskilling of the system operation. Opening up the use of these systems to technicians and production line operators. This computing power has also allowed the use of sophisticated algorithms, which means that some inspection tasks can be automated, taking decisions away from the operator. These tasks include void measurement, wire sweep calculation, checking for shorts and missing balls etc. This can speed up the use of the system and also produce reliable data for SPC and factory management systems. Sophisticated Graphic User Interfaces are now standard on many systems and these offer many easy to use functions including simple step and repeat inspection programming and the use of a library of reference or golden inspection images for comparison leading to easier decision making.

The two biggest areas that have advanced however are ease of use and image enhancement. Many systems can now be controlled with a few clicks of a mouse; indeed some systems key software features can be activated by a single click. This 1-click mentality also has a dramatic effect on throughput and ease of operation. The more sophisticated machines have a 'photo shop' type suite of filters that can be used to enhance the image allowing the operator to see potential faults more clearly. Contrast stretch and other fine-tuning controls also make it easier to view the more challenging images of today's advanced technology.

Recent advances have gone further with the development of special filters that with one click dramatically enhance the image and make the task of the operator even easier. These sophisticated filter systems have been specifically designed to enhance difficult images. State of the art Graphics Cards, a technology driven by the games industry have also lead to huge improvements in image quality and processing speed.

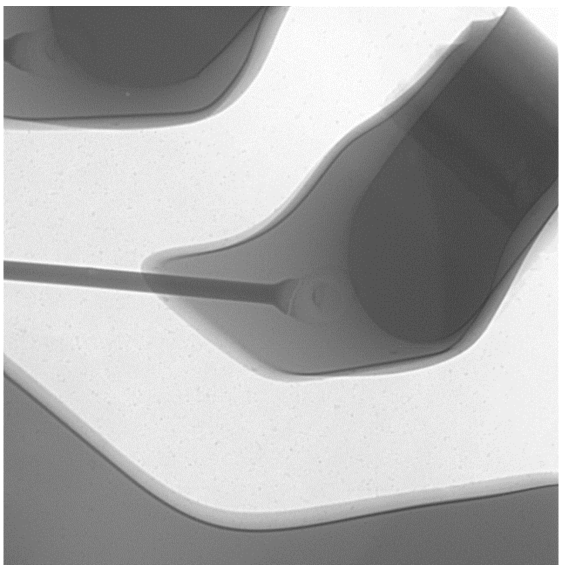

**Figure 3.** 2D image from high-end system

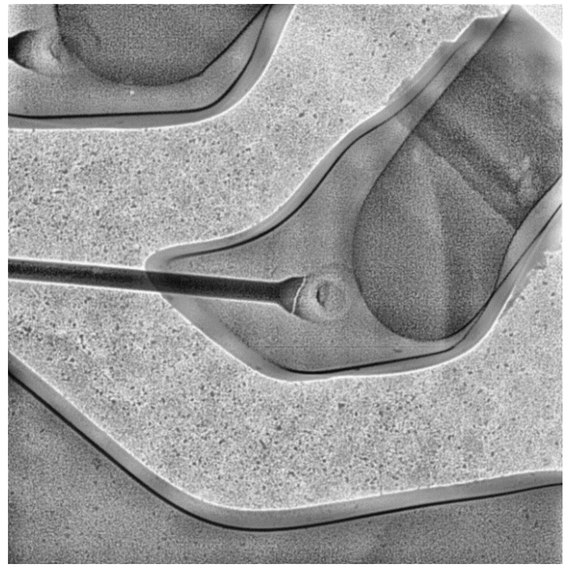

**Figure 4.** Same image digitally enhanced

## 3D INSPECTION

Traditional CT or 3D imaging involved what is technically known as the Cone Beam Technique. This meant that the sample was rotated through 360 degrees within the beam of the x-ray tube; this dramatically affected the size of the sample suitable for this technique. For realistic results the maximum sample size was that of a business card. So unless you were working with small hybrid structures or at component level this was effectively a destructive technique similar to micro sectioning. This meant that whether the result was a pass or fail the printed circuit board assembly was no longer of use. So effectively Cone Beam CT was limited to the failure analysis arena.

A recent advance in this area goes under several names; Inclined CT, Oblique CT, Partial CT and I am sure one or two others. This technique has one huge advantage over traditional CT in that it is non destructive. A region of interest on the board is selected then a number of images are taken at a fixed angle of view and these images are reconstructed to produce a series of laminography slices, allowing strategic layers within the assembly to be easily viewed and analysed. In addition to this, these slices can be output to a 3D reconstruction station where a 3D representation can be built, allowing the operator to rotate, slice and magnify the sample at will. The use of this technology greatly improves many increasingly important areas of x-ray inspection including analysis or voids on thermal pads allowing efficiency of heat transfer to be calculated.

Voiding at joint interfaces including those of balled devices can easily be measured, allowing the operator to calculate the percentage reduction in joint strength attributed to the voiding on that interface. However, the quality and accuracy of these images and results are entirely dependent on the quality of the mechanical system within the machine, the quality of the original images captured and the algorithms used to reconstruct that data and remove artefacts and noise created by their acquisition.

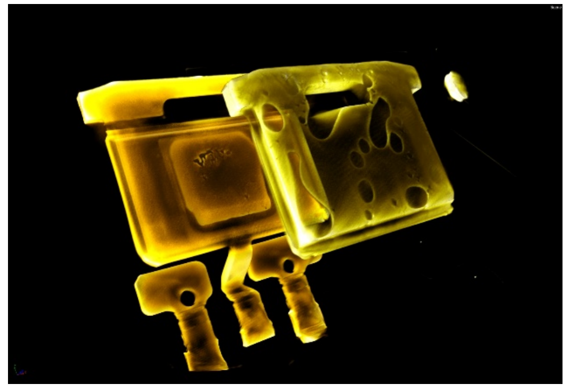

**Figure 5.** 3D reconstruction of ICT sample

## CONCLUSION

In recent years the change from using medical based components to those specifically produced for the electronics industry has led to a dramatic leap forward in the quality of the images produced by these systems.

Advances in software have also lead to the production of systems which are easier to use and give more accurate and repeatable results, computer power and the games industry have also played their part.

As the technology has advanced and the feature size has reduced exponentially some of today’s systems are able to cope with this and also what is on the component and semi-conductor road map for the next five years.

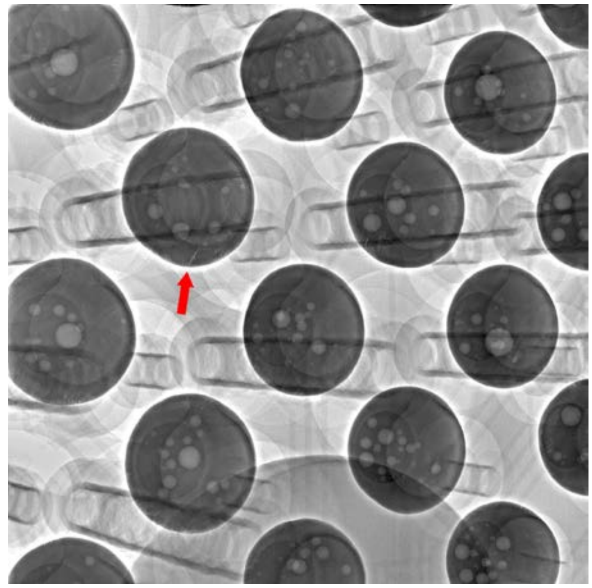

**Figure 6.** Very small crack in CSP ball, visible due to the recent technology advances.