RECENT ADVANCES IN THE X-RAY INSPECTION TECHNOLOGY WITH EMPHASIS ON LARGE BOARD COMPUTER TOMOGRAPHY AND AUTOMATION

Evstatin Krastev and John Tingay
Nordson DAGE
Concord, CA, USA
evstatin.krastev@nordsondage.com   john.tingay@nordsondage.com

ABSTRACT

The need to non-destructively inspect electronic components and assemblies is the main driver behind the development and advancements of the X-ray inspection technology for the electronics industry. In many cases, the only other alternative to inspect an optically hidden component or solder joints is via mechanical cross-section technique. Disadvantages of the mechanical cross sectioning include being very time and resource-consuming. Also, there are chances to miss the defects if not careful with the polishing process, or "create" defects that were not present in the original device. The main downside, of course, is that the expensive device, PCB or component is being mechanically destroyed and made useless after the sectioning.

Through the years, due to the never ending trend of miniaturization combined with vastly increased functionality, particularly with needs of mobile devices, the complexity of the electronics assemblies and components increased tremendously. Due to their advantages in performance and functionality, currently microns-size devices and multi-level architecture is becoming widely used and constantly developed, improved and further miniaturized.

The above trends are constantly presenting new and more difficult challenges for the X-Ray inspection technology. The need of sub-micron resolution and extremely high definition images is combined with the requirements of speed and of course, automation. Naturally people desire to automate the inspection process in order to optimize it and make it as efficient as possible. The hope is to reduce the number of "expensive" operators and also remove the "human error" factor during the inspection. However, the current extreme complexity of the electronics assemblies coupled with the multi-level architecture result in very complex X-Ray images exhibiting significant variations. These are easily analyzed by trained human operators. Yet, the challenges are significant to develop robust and repeatable software/hardware inspection algorithms capable of tackling the above complexity and variations.

In this paper, we discuss the above challenges together with the latest X-ray inspection developments and trends trying to address these hot issues. We cover complex real life examples and case studies involving 2D/3D Inspection, 3D Large Board Computer Tomography and Automated X-Ray Inspection.

Key words: X-ray inspection, AXI, Automated X-Ray Inspection, X-ray technology, Computer Tomography, CT, Inclined CT, Partial CT, CT without cutting, Large Board Computer Tomography.

INTRODUCTION

The 2D X-Ray inspection has become a critically important tool within the test and inspection regime of the electronics design, development and manufacturing groups. The reason is that it provides the only means of inspecting optically hidden solder joints as well as looking inside microelectronics packages in a completely non-destructive fashion. The only alternative is the mechanical cross-sectioning. While the mechanical cross-section technique is widely used for failure analysis and development purposes, it has a major disadvantage – the expensive device or printed circuit board (PCB) is being cut through and this way completely destroyed without any chance for repair. With some PCBs costing in the tens of thousands of US$ destroying the board is absolutely considered as the last available alternative.

Through the last 10 years the 2D X-ray inspection technology has registered tremendous progress in capability. Current advanced 2D X-ray inspection systems feature extremely sharp and powerful X-ray sources (X-ray tubes) with submicron feature recognition down to 0.1 micron or 100 nanometers. These are capable of keeping submicron resolution while providing extremely high X-ray power/flux -- up to 10 Watts at the X-ray target. In, addition we have enjoyed significant developments in the X-Ray detectors area, with contemporary Image Intensifier and Flat Panel types providing 2, 3, 4 and in some cases up to 12 Megapixels and 16-bit imaging (65,000 gray levels) while running at 25 frames per second without binning. All of the

above advancements jointly contribute to extremely high resolution/bandwidth X-ray images, as well as significantly increased speed and automation capabilities. Naturally the result is much improved defect detection capabilities.

Figure 1 shows an exceptionally high resolution 2D X-Ray image of a blown Au wire taken on a typical high-end X-ray system. Everyone agrees that the detail is incredible with the X-ray capability going towards the realms that have been previously reserved only to the slow and destructive, but very high-resolution electron microscopy techniques.
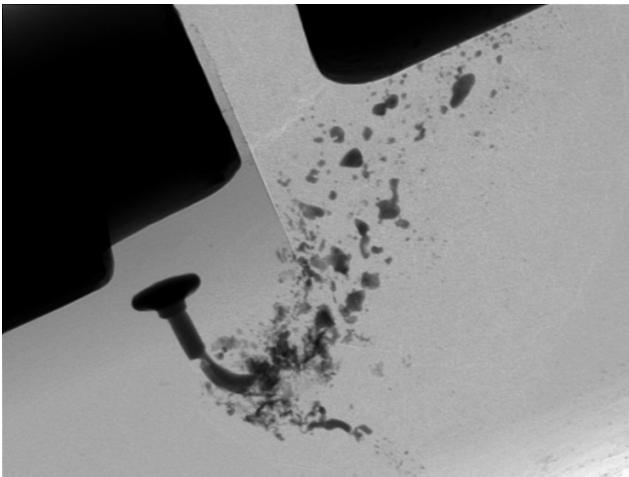

Figure 1. Extremely high resolution 2D X-ray image showing blown Au bond wire.

Despite all these remarkable performance achievements, why is 2D X-ray not the only X-ray technique employed by modern electronics research, development and production? The reason for this is that the 2D X-ray image becomes very complex for multi layered assemblies and devices due to the nature of the X-rays to penetrate through the whole object. Thus having multi-layered devices involving stacked dies, TSVs, multi-level bumping and other 3D geometries poses significant challenges to the operator while trying to analyze the images. This is illustrated on Figure 2 -- 2D X-ray image of a stacked die device. It is obviously quite difficult to examine the multi-level bond wires structure looking for shorted wires using just the 2D X-ray image.

Similar to the medical fields, the microelectronics industry embraced the 3D X-ray Computer Tomography (µCT) in order to tackle projects like this one. This was facilitated by the significant advances in the 2D X-ray technology as described above as well as the constant developments in the computer technology giving us extremely high performing computing stations at a very reasonable price.
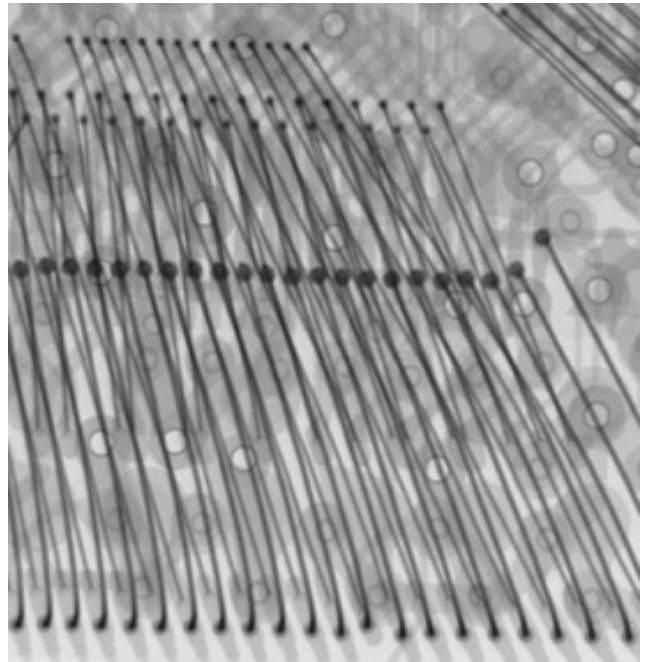

Figure 2. 2D X-ray image of a stacked device. Due to image complexity it is difficult to check for shorted bond wires.

The 3D µCT technique is capable of non-destructively producing virtual cross sections, also called e-sections, at any plane of the device in question. Figure 3 shows a couple of µCT e-sections of a similar stacked device. By changing the e-section plane angle and location we are able to examine thoroughly the condition of the stacked bond wires and look for shorts.
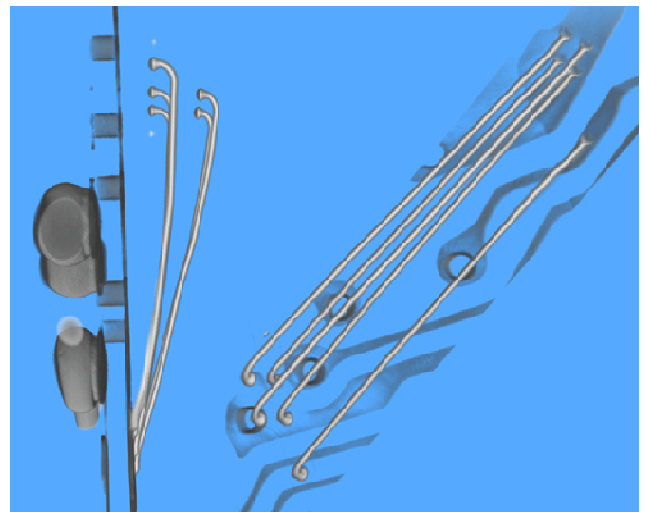

Figure3. 3D µCT e-sections of stacked device. The bond wires are easily examined by changing the e-section plane orientation

The 3D µCT model is produced at several stages. The first one is to acquire a set of high resolution 2D X-ray images at multiple angles around the sample, while keeping track of the geometrical positioning at the highest possible accuracy

level. Typical µCT set-up used in the electronics industry is shown in Figure 4. The sample is suspended between the X-ray source and the detector. 2D images are taken at multiple angles by rotating the sample. The computer control system is working in conjunction with the precise mechanical manipulator to ensure as accurate geometrical positioning as practically feasible.
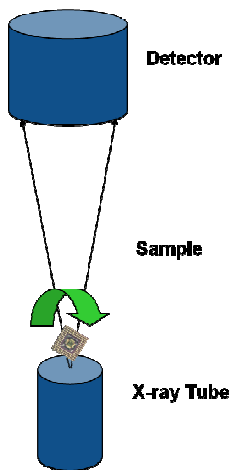

Figure 4. Typical µCT set-up used in the electronics industry. The sample is suspended between the X-ray source and detector. 2D images are taken at multiple angles by rotating the sample. After that, the set of 2D X-ray images, each containing several megapixels of information, is processed using complicated mathematical algorithms during a step called CT reconstruction. The final result is the µCT model that is a representation of the sample within a 3-dimensional density array that can be virtually sliced and diced within a specialized computer viewer in order to provide the required e-section analysis. Obviously a set containing larger number of 2D images will result in better and more detailed µCT model at the cost of longer acquisition/reconstruction time. With the continuing increase in the computing speed capabilities of current, cost effective, off the shelf CPUs and GPUs, this reconstruction step is now achievable in seconds or minutes rather than hours, as was the case only a short time ago.

Large Board CT

Due to never ending trend of miniaturization within the microelectronics industry, current requirement for a µCT system resolution, are in the micron range. In order to achieve this type of resolution we need to start with very high magnification/resolution 2D X-ray images. From basic Physical principles, this is only achievable when the sample is kept very close to the X-ray source (see Figure 4). This is where the practical maximum size limitation for a microelectronics CT system comes from. This is about the size of a credit card and the sample must be much smaller (mm sized) in order to achieve ultimate resolution. There is no problem placing a much larger sample between the X-ray

source and detector, however the resolution of the resulting CT model will be poor to be considered useful from the microelectronics point of view (Figure 5).
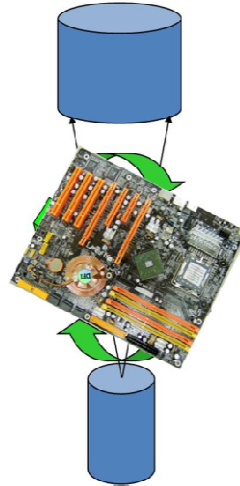

Figure 5. µCT limitations for larger samples

Thus, in order to produce an analytically useful µCT model of a device within the PCB shown on Figure 5, one needs to cut around the device thus destroying the expensive and valuable PCB assembly. This is done sometimes, however we like to keep it as a last resort.

Trying to address the above limitation of the µCT, the industry has come up in recent years with a technique called Large Board CT, Partial CT (PCT), or limited angle CT. The basic principle is illustrated on Figure 6.
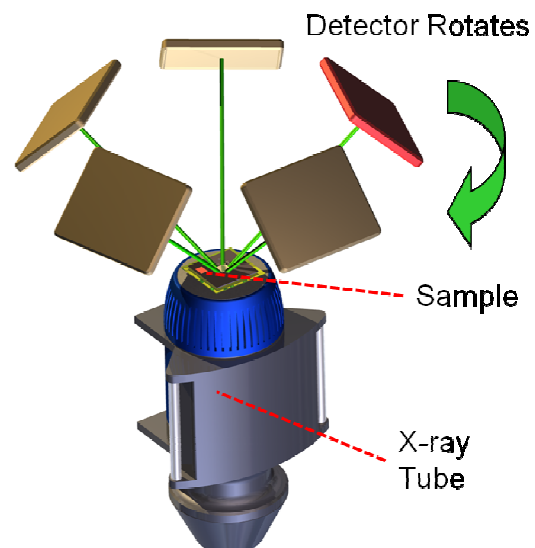

Figure 6. Basic principle of Large Board CT also called limited angle CT or PCT.

The idea is that the sample is kept flat very close to the X-ray source, thus the inspection system is able to produce very high magnification/resolution 2D X-ray images. The detector is moved around the object of interest at an oblique angle. The principle of best possible movement accuracy is of crucial importance similarly to the μCT technique.

Figure 7 represents an example of head in pillow (HIP or HOP) defect imaged using Large Board CT on a large 16"x16" PCB in a completely non-destructive manner. Using e-sections at various plane orientations makes it very easy to come up with an unquestionable evidence of the defect.
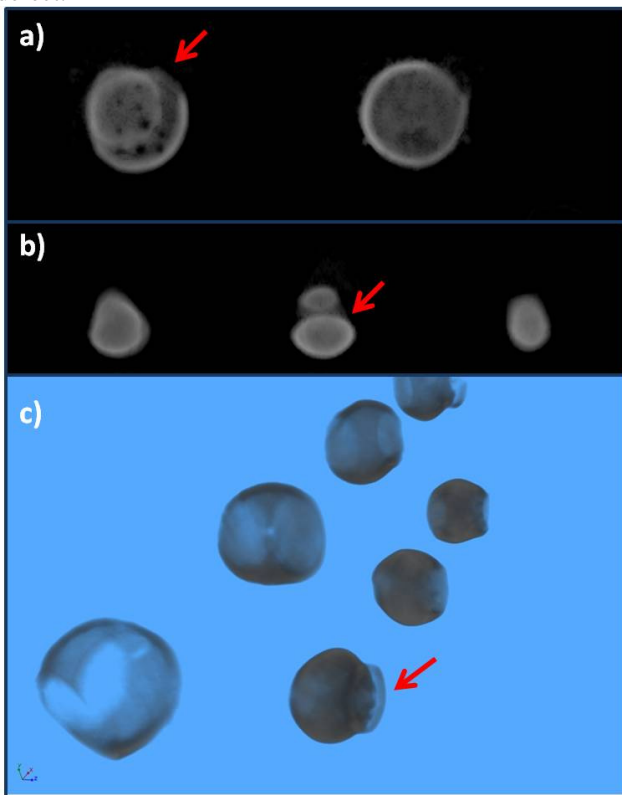

Figure 7. HIP/HOP defect imaged using PCT on a very large 16"x16" PCB. a) virtual cross section (e-section) in the horizontal plane of the pad area, b) e-section in a vertical plane, and c) 3D rendering overview.

Automation
Automating the X-Ray inspection process has always been on the top priority wish-list of any microelectronics manufacturer. The idea of pressing the "magic" button and as a result the X-ray inspection system independently comes up with a detailed list of all defects while eliminating the possibility of "human-related" errors is definitely very tempting. However, in reality it has proved to be a significant challenge to be accomplished practically. This is due, to large extent, to the high complexity of the X-ray image. Visible light inspection (like AOI) provides information only from the object surface through reflection. In contrast, the X-ray image furnishes information of the whole volume despite being only a "gray-level" image. This

is because the X-rays travel through the whole body of the object before being registered by the detector. In order to simplify the image that is being analyzed very fast on the go, limited angle CT techniques are being employed in the contemporary automated X-ray inspection (AXI) systems. However, due to the need for speed, the image quality and consequently the defect detection and false call rates are not on par with the requirements of the microelectronics manufacturers.

Based on the above we envision good opportunities in the AXI field for performance improvement resulting in better speed and defect detection capability. This could be accomplished through improvements in both the hardware and software realms. As an example, we will discuss the case of CAD driven automation for irregular BGAs and micro-bump patterns later in the paper.

Large Board CT (PCT) evaluation of Interfacial BGA voiding and comparison with 2D results
Calculation of voiding percentage is a standard quality assurance procedure within the testing regime of the microelectronics/PCB manufacturers. Figure 8 shows a 2D X-ray image revealing the voiding within a corner section of a BGA device. The large void in the central joint (orange arrow) is definitely a problem as it is over the 25 % criteria as per IPC-A-610. This large of a voiding present is a serious concern requiring immediate process review and improvements.

However, the smaller voids, as indicated by red arrow, could be an equally alarming indicator for a reflow process that needs improvement, despite that they might pass the IPC-A-610 criteria. The problem in this case comes from the fact that these voids are predominantly concentrated at the joint interface, thus making the joint less reliable and prone to interface failures in the field, particularly the fatigue failures typical of the use case of mobile devices.
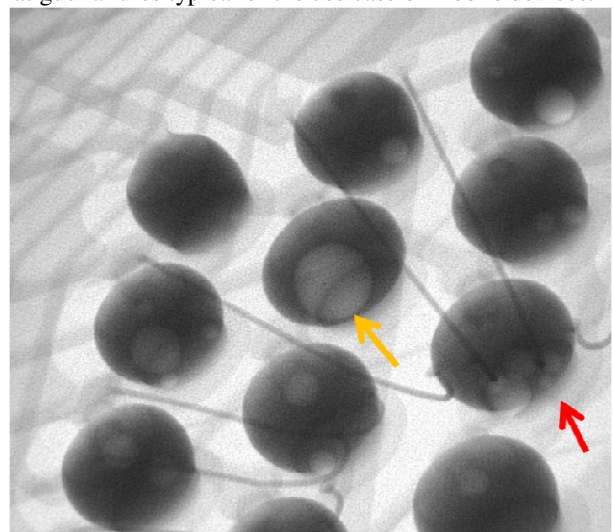

Figure 8. Oblique 2D X-ray image showing volume and interfacial voiding

One of the important strengths of the Large Board CT is that the operator can easily chose the location of the slice (e-section) where the voiding calculation is performed. Thus we can easily obtain accurate data for the interfacial voiding percentage that is not available using just 2D X-ray analysis. Naturally, we decided to do a study and compare total voiding percentage as per 2D imaging data vs. interfacial voiding percentage as calculated using Large Board CT data. The goal was to determine the correlation level and find out if the total voiding percentage calculation as per IPC-A-610 gives us an adequate representation of the interfacial voiding. Figure 9 is a typical void calculation taken at a 2D top-down view as per IPC-A-610 of a corner area of a BGA device. Figure 10 is a voiding calculation of the same area, but performed at an e-section located at the BGA joints interface.
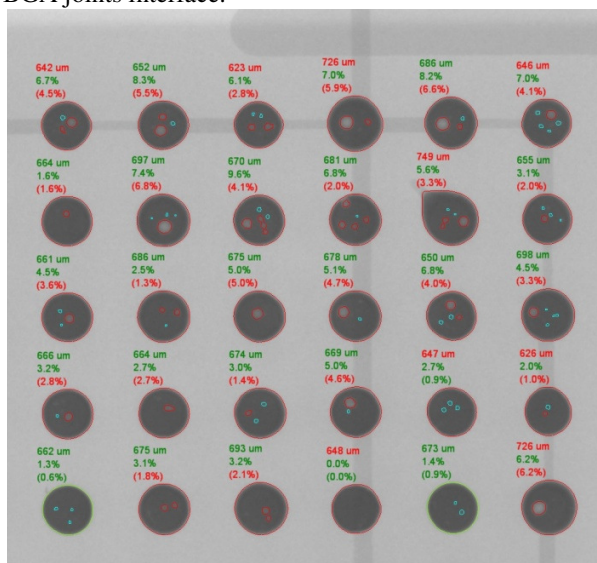

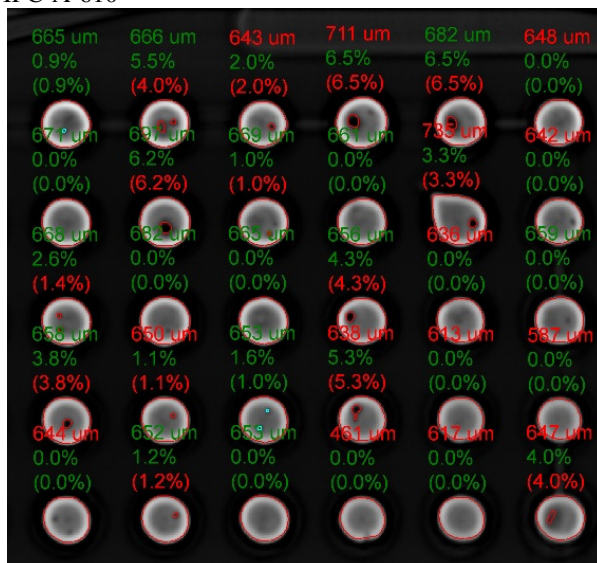**Figure 9.** 2D voiding calculation of a BGA device as per IPC-A-610

Figure 10. Voiding calculation performed using Large Bard CT e-section

It is obvious from the images that the voiding calculations using the two methods provide quite different results. The data is also summarized in Table1 comparing the voiding calculation by the two methods at each pin location.

Pin Number	Large Board CT Interfacial Void (%)	2D Total Void (%)
A1	0.9	6.7
A2	5.5	8.3
A3	2.0	6.1
A4	6.5	7.0
A5	6.5	8.2
A6	0.0	7.0
B1	0.0	1.6
B2	6.2	7.4
B3	1.0	9.6
B4	0.0	6.8
B5	3.3	5.6
B6	0.0	3.1
C1	2.6	4.5
C2	0.0	2.5
C3	0.0	5.0
C4	4.3	5.1
C5	0.0	6.8
C6	0.0	4.5
D1	3.8	3.2
D2	1.1	2.7
D3	1.6	3.0
D4	5.3	5.0
D5	0.0	2.7
D6	0.0	2.0
E1	0.0	1.3
E2	1.2	3.1
E3	0.0	3.2
E4	0.0	0.0
E5	0.0	1.4
E6	4.0	6.2

Table 1. Void percentage calculation comparing total voiding as per 2D data and interfacial voiding as per Large Board CT data

In some cases it can be observed that the % voiding of the interface can be higher than the 2D total voiding %, this is because the area of the interface is smaller than the maximum projected 2D area of the ball, so voiding just occurring at the interface will give a greater % voiding.

In order to find out if there is a correlation between the two void measurement methods, we plotted the data as shown on

Graph 1 and calculated the coefficient of determination R^2. Values of R^2 close to 1 indicate a strong correlation, while values close to 0 indicate very weak or no correlation.
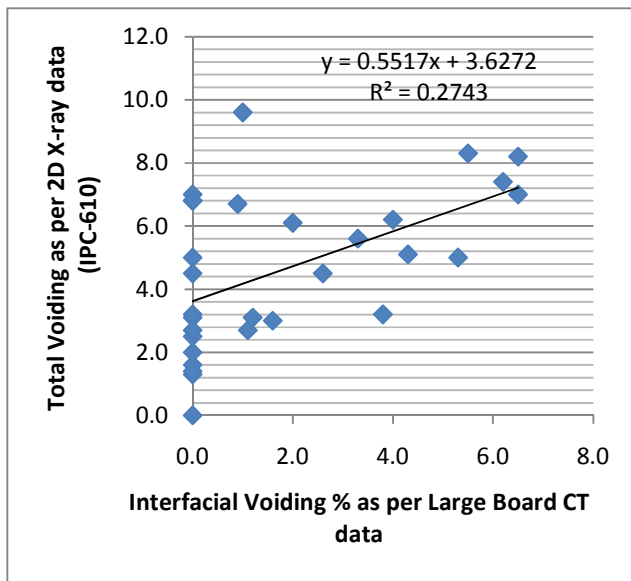
Graph 1. Total Voiding vs. Interfacial Voiding BGA device- Area **A**

Obviously the correlation is weak ($R^2 =0.27$) thus telling us that the 2D total voiding calculation % does not give us a good indication of what is going on at the joint interfacial level.

In order to double check our finding above, we tested a different area of the BGA device as plotted on Graph 2.
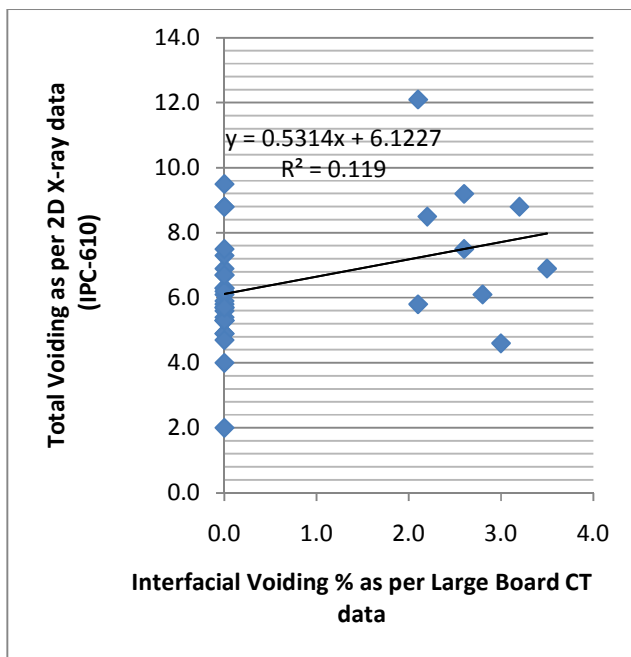
Graph 2. Total Voiding vs. Interfacial Voiding of BGA device – Area **B**

Again, as expected, we found a very poor correlation with coefficient of determination $R^2 = 0.119$. This confirms our earlier findings that in this case, total voiding percentage determined by 2D X-ray images, as per IPC-A-610, is not a good indication of the voiding levels at the joint interfaces. Therefore the most accurate nondestructive method to analyze the interfacial voiding of a BGA device is by employing Large Board CT technique –using the virtual cross sections also called e-sections.

CAD-driven Automation for Irregular BGA devices and bumps

Achieving high levels of automation during the X-ray inspection is a very high priority concern for the microelectronics and PCB manufacturers. As discussed earlier, there are many challenges when trying to automate the X-ray inspection of complex multi layered devices and PCBs. Below, we would like to discuss our approach for automation of irregular bumped devices. These types of devices are becoming very widespread especially when high density interconnect is required. We used conventional high resolution 2D X-ray imaging for the examples shown, however, the results are also valid for e-slices produced by Large Board CT.

Regular bumped devices as the one shown in Figures 9 and 10 are relatively easily handled by the X-ray inspection system when setting up an automation inspection routine. Usually the software automatically identifies the locations, pitch and diameters of the BGA balls or bumps and compares these to a database containing standard sizes and patterns.

However irregular patterns of varying shapes as shown in Figure 11 are becoming increasingly popular with the microelectronics manufacturers.
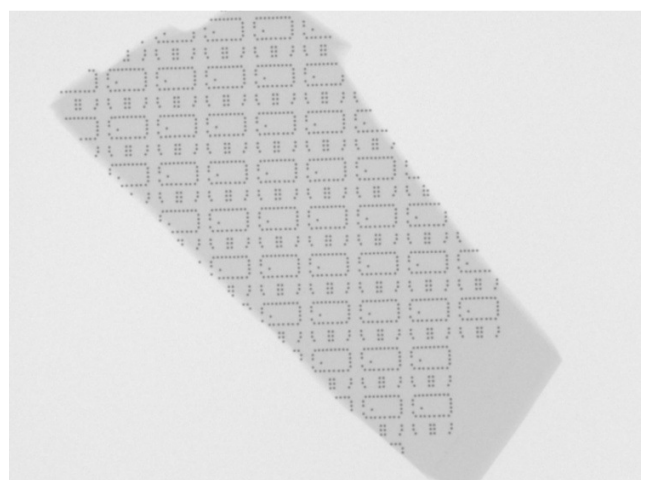

Figure 11. Wafer piece with a irregular bump pattern

The standard automatic algorithms within the X-ray inspection system "expect" a regular and standard pattern and could often have a problem dealing with the irregular and highly customized patterns as shown in Figure 12. In this case, it is obvious that the standard regular pattern algorithm was able to identify the balls, however there is some mismatch within the pitch as the software is attempting to fit this irregular pattern to a regular one available in the database.
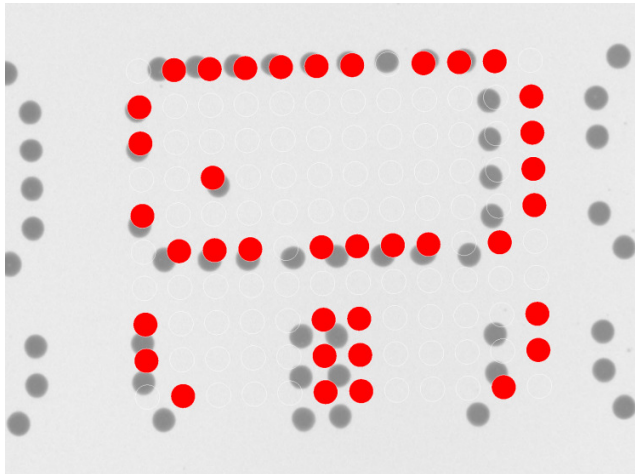

Figure 12. Standard algorithms designed for regular patterned BGAs and bump devices usually have problems with highly customized irregular bump patterns.

As these irregular patterns are not standardized and there are very large variations out in the field, the best approach for automation of the X-ray inspection in this case is to use CAD data in order to "teach" the inspection locations within the inspection routine. There are two approaches here. The first one is to use the CAD data provided by the electronics manufacturer. In many cases, this data could not be made available or it is very complex. The second approach, is to generate our own CAD data within the software that is unique for the particular irregular pattern device. This approach is very flexible. The results are very simple and reliable CAD files that reflect only the needed information for the automatic X-ray inspection.
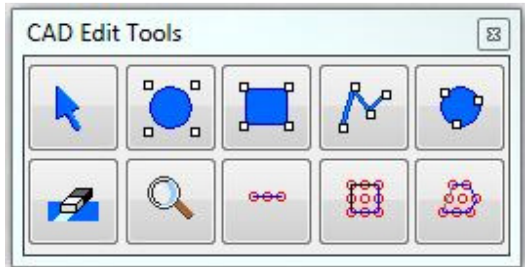

Figure 13. Internal CAD generation editor tools

As shown in Figure 13 the X-ray inspection automation software is equipped with an internal set of CAD tools that make the generation of the CAD file extremely easy and

straightforward. Using these generic shapes, the operator creates a simple overlay on the X-ray image displayed on the screen. Using this info the CAD pattern is promptly generated by the software and ready to be used as shown in Figure 14.
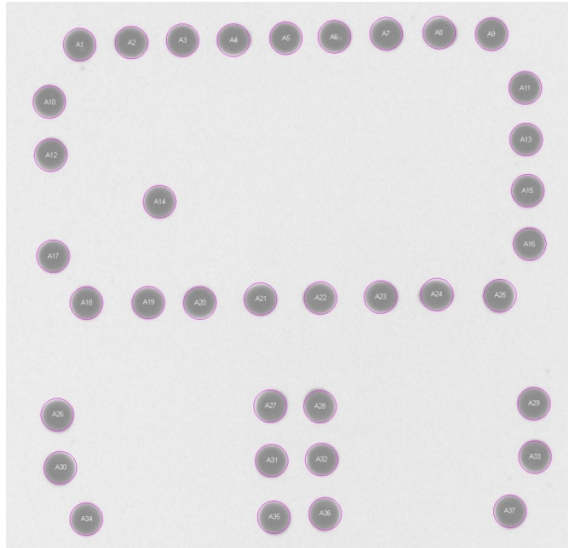

Figure 14. Irregular pattern bumped device – test locations identified using CAD generation tools.

Once we have the CAD template in place, the procedure is very straightforward. The machine automatically moves to the desired test locations and performs the calculations. An example of this is shown in Figure 15, including bump diameters, total voiding and larges individual void.
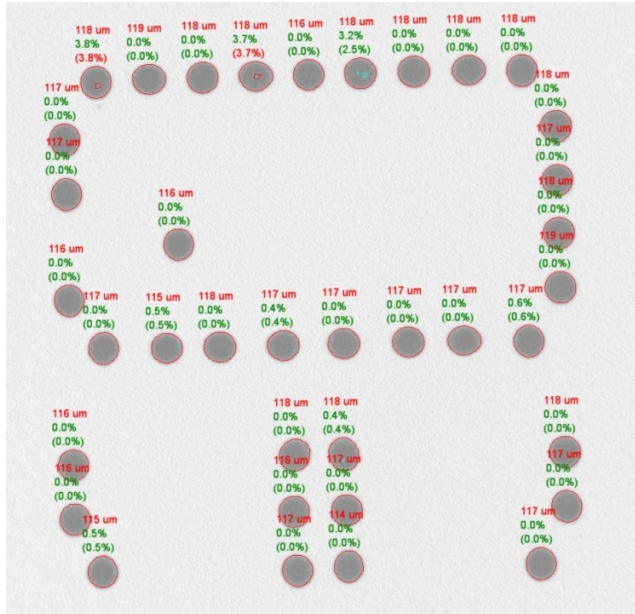

Figure 15. Automatic X-ray inspection of irregular pattern devices. Automatic calculations of bump diameter, total voiding and largest individual void.

To summarize, a simple CAD generation methodology has been presented above that facilitates and streamlines the automation of X-ray inspection of irregular bumped devices.

CONCLUSIONS

In this paper, we discussed in detail the increasing challenges to the advanced X-ray inspection for the microelectronics industry due to miniaturization and the need of automation. As an illustration, we presented a couple of case studies.

First of all, we utilized Large Board CT for studying interfacial voiding of BGA devices. The quality of the joints at the interfaces is crucial for the BGA device reliability and field performance. The Large Board CT technique permits us to non-destructively create virtual cross sections (e-sections) at any plane of the devices of interest. Based on our study, we concluded the total voiding calculation using 2D X-ray images as per IPC-A-610 has a very poor correlation with the voiding calculations at the joint interfaces calculated using e-sections. This tells us that the 2D X-ray total voiding calculation does not provide a good representation of the joint interface condition. Therefore, the best way to non-destructively study the interfacial area is using Large Board CT.

Further, we described our simple and effective method of CAD driven X-ray inspection automation for irregular bumped devices, including CAD data generation within the automation software. This technique is invaluable when the original CAD data is not available or there is a need of simplification or modification in order to streamline the automatic X-ray inspection.

REFERENCES

[1] 'Modern 2d / 3d X-ray Inspection - Emphasis on BGA, QFN, 3d Packages, and Counterfeit Components', Evstatin Krastev & D. Bernard, Pan Pacific Symposium Conference Proceedings 2010, available through the SMTA bookshop

[2] '3D Board level X-ray inspection via limited angle computer tomography', Evstatin Krastev, D. Bernard, Dragos Golubovic, *SMTA International Conference, Orlando, Florida, October 14 – 28, 2012*

[3] 'Computerized Tomography Meets the Challenges of IC Package Inspection', Evstatin Krastev, Chip Scale Review, October 2007

[4] 'Non-Destructive Techniques For Identifying Defect In BGA Joints: TDR, 2DX, And Cross-Section/SEM Comparison', Zhen (Jane) Feng, Ph.D., Juan Carlos Gonzalez, Sea Tang, Murad Kurwa, and Evstatin Krastev, Ph.D., SMTAI 2008

[5] 'Modern 2D X-ray Tackles BGA Defects', Zhen (Jane) Feng, Jayapaul Basani, & Murad Kurwa, Flextronics International; David Bernard & Evstatin Krastev, Dage Precision Industries, SMT magazine 2008

[6] 'A Practical Guide to X-ray Inspection Criteria & Common Defect Analysis', D. Bernard & B. Willis, Dage Publications 2006, available through the SMTA bookshop

[7] 2D/3D X-Ray Inspection: Process Control & Development Tool, Zhen (Jane) Feng, Tho Vu, Michael Xie, David Geiger, Murad Kurwa, Zohair Mehkri, and Evstatin Krastev, SMTAI 2013