3D Board Level X-ray Inspection via Limited Angle Computer Tomography

By David Bernard Ph.D., Dragos Golubovic Ph.D., Evstatin Krastev Ph.D. Nordson DAGE

Abstract

Computer Tomography (CT) is a powerful inspection technique used widely in the electronics industry, especially for the analysis of multi-layered devices and joint interconnections. As the resolution required to be able to inspect today's devices is in the micron range, this aspect of CT is often referred to as μCT so as to differentiate it from medical and industrial CT applications where the same level of resolution is not possible or required. The μCT technique permits different layers / slices of the device to be isolated and examined individually, so practically providing an electronic, or virtual, cross-sectioning within the sample. The benefits of an 'electronic cross-section' compared to traditional mechanical cross-sectioning are many. These include that the electronic cross-sectioning is reversible – you cannot over polish and go too far into the sample - the cutting plane can be positioned in any orientation within the 3D space of the CT model and no additional defects are introduced or existing defects concealed compared with the process of mechanically cutting, polishing and preparing the sample for a cross-section. One of the limitations of traditional μCT is that there is a restriction to the maximum sample size that can be used to produce a μCT model with reasonable speed, quality and analytical value. Usually, the maximum practical size for a regular μCT is ~ 2" x 2" (50 x 50 mm). Thus, it is not possible to use the μCT technique on a large PCB unless you are willing to cut around the device / region of interest to be examined to make it small enough for analysis, but in so doing destroying the board. In order to overcome the sample size limitation of 'full μCT', a 'limited angle' or 'partial' μCT technique has been developed and used in some X-Ray systems. This permits a 3D model to be created from devices / regions of interest anywhere within a board without the need to destroy it. This paper will explain the mechanism and differences between full μCT and the various types of limited angle μCT and compare different applications where one or the other technique is applicable, backed by real life cases and examples.

Key words: X-ray inspection, X-ray technology, Computer Tomography, CT, Inclined CT, Partial CT, CT without cutting.

Introduction

Many talented scientists have contributed to the instigation and development of the computerized tomography technique the way we know it now. In 1937, a Polish mathematician, named Stefan Kaczmarz, developed a method to find an approximate solution to a large system of linear algebraic equations, which further developed into his powerful reconstruction method the "Algebraic Reconstruction Technique (ART)". This technique was later adapted by Sir Godfrey Hounsfield as the image reconstruction mechanism for his famous invention, the first commercial CT scanner. William Oldendorf, a UCLA neurologist and senior medical investigator at the West Los Angeles Veterans Administration hospital, published a landmark paper in 1961, where he described the basic concept later used by Allan McLeod Cormack to develop the mathematics behind computerized tomography (from Wikipedia). These are some of the pioneering scientific endeavors that paved the way to the remarkable developments in the capabilities of medical diagnostic radiology in the latter half of the 20th century. Initially, this was through Computer (Aided) Tomography, which we have come to know as CAT or CT scanning, and this was subsequently followed by the other imaging techniques we also now take for granted, such as MRI and PET scanning. The needs of being able to look inside an object, without opening it up, or destroying it, and separating the different features that would otherwise overlap each other when seen in a standard 2D x-ray image, are the same for electronics inspection as they are in the medical sphere. If there is a problem with a board (or a person!) ideally we want to analyse the situation as much as possible with everything in its natural, and untouched, state before we opt, if necessary, to take more radical action to probe the fault location with more invasive techniques and, possibly, a ‘surgical’, or destructive, inspection. Once the fault location has been modified through any external action then some important information may be lost from the analysis through the modification of the location and thereby possibly obscure the root cause of the issue.

These reasons are why non-destructive 2D x-ray inspection has become, for many years, an important part of the inspection regime in electronics manufacturing both for failure analysis and process development and control. More recently, it has become even more important owing to the proliferation of devices that have optically hidden joints (such as BGAs, QFNs, POPs, MCMs, etc.) in addition to the needs of inspecting thru-hole joint quality and its assistance in identifying counterfeit components. Such 2D x-ray inspection systems can be seen as analogous to a simple 2D x-ray in the hospital, which would be used when you have a suspected broken leg, for example. The only difference from a hospital environment is that the x-ray systems used for electronics inspection require that they provide magnification of objects under test so as to allow the ever-shrinking features within electronic devices to be seen clearly. They are also generally, but not always [1], able to ignore the radiation dose to the ‘patient’. However, when you have many different, varyingly-dense objects all within the same 3-dimensional volume - such as is typically found in a double-sided printed circuit board comprising of components on both sides and multiple layers of circuitry, vias, blind vias, etc., in between - it means that the simple 2D x-ray image is often too cluttered with over-lapping features to allow for the easiest analysis (see figure 1).

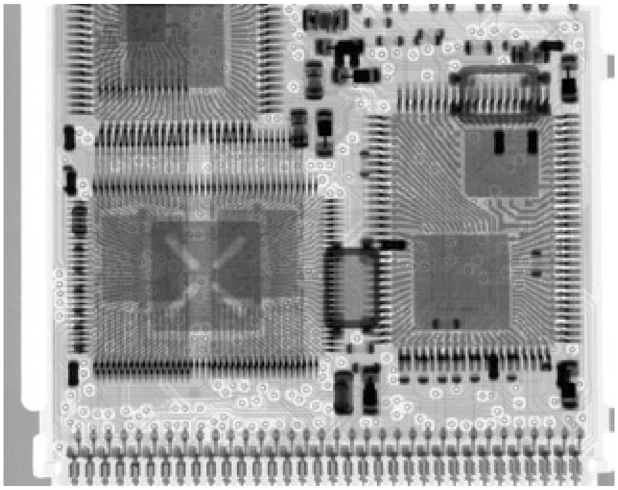

Figure 1. 2D x-ray image of a double-sided PCBA where the components from either side overlap each other in the view.

Some of this clutter can be removed by using oblique angle x-ray views of the sample. This can be achieved by tilting the sample with respect to the x-ray tube to detector axis within the x-ray inspection system [2]. However, this method typically reduces the available magnification that can be achieved. This is why system manufacturers offer an alternative approach where the same result can be achieved by tilting the detector relative to the sample (see figure 2).

This allows the sample to remain in close proximity to the x-ray tube and so retain the available magnification, something that becomes ever more important as the feature sizes within electronics continue to shrink. Whilst an oblique angle view may well separate overlapping features and allow the best view of joint size and shape variation for analysis, this is increasingly being challenged because of the increasing use of finer pitch components and Package on Package (POP) devices and similar. With POPs, the separation between different joint layers is much smaller than for components placed on the two sides of a typical board, making it much more difficult to separate the multiple layers using oblique views so as to enable the best analysis.

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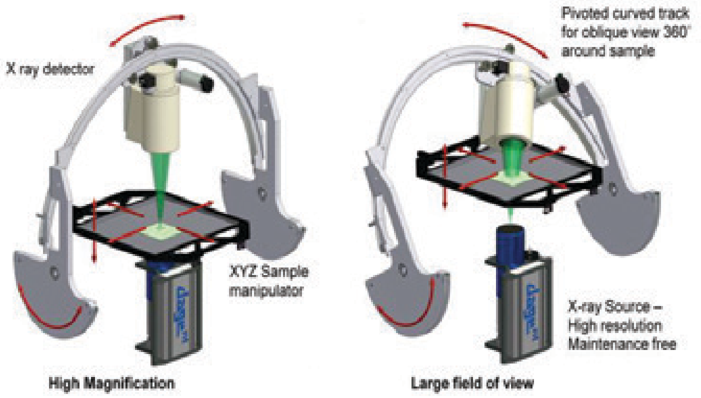

Figure 2. Schematic of x-ray system manipulator movements enabling oblique angle views without compromising the available magnification.

With these increased demands on the inspection task for electronic applications what can the x-ray technique now provide in addition to 2D analysis? In short, as has happened in the medical field, the use of CT scanning techniques. Micro Computer Tomography (µCT) analysis for electronic applications has been used for many years but typically has been limited for specialist applications and failure analysis. In part, this has been due to the vast computational requirements necessary to produce and handle the many 2D x-ray images that need to be acquired, each containing often Mpixels of data, and processing them to produce a µCT model. The µCT model is a representation of the sample within a 3-dimensional density array that can be virtually sliced and diced in the computer to provide the required analysis. Recently, the continuing increase in the speed of computational processing plus the ready availability and 'number-crunching' power of off-the-shelf Graphics Processor Units (GPUs) means that realistic µCT reconstruction and analysis is now achievable in seconds or minutes rather than in tens of minutes or hours, as was the case only a short time before. As a result, there are now three possible CT techniques that can be applied to electronics problems. These can be designated as 'full µCT', 'in-line partial CT' and 'off-line partial µCT'. Each of these tomographic techniques can provide additional information to help in the analysis of electronic components and circuit boards. Which is the best to use for a particular application is not necessarily so simple to choose, as each, like so much else, has its own benefits but also its limitations as well as its price!

Full µCT

What we will call 'full µCT' is the technique whereby a series of 2D x-ray images is taken all around the sample and an accurate maintenance of the position and geometry of the images is maintained relative to the sample. This is achieved either by keeping the sample still and rotating the axis of the x-ray tube to detector around the sample (as they do in the hospital - where the patient remains stationary and the x-ray tube and detector rotate around the circle that the patient is fed into). Alternatively, and the method used for electronics applications, is where the axis of the tube to detector remains fixed and the sample is rotated relative to this plane (see figure3). Whichever motion paradigm is chosen, a dataset of 2D x-ray images is acquired from all angles around the sample. The time to acquire the original 2D x-ray images for full µCT is not trivial. It will depend on the number of images desired to be taken around the sample and the image averaging that may need to be applied to each image so as to improve the signal to noise ratio.

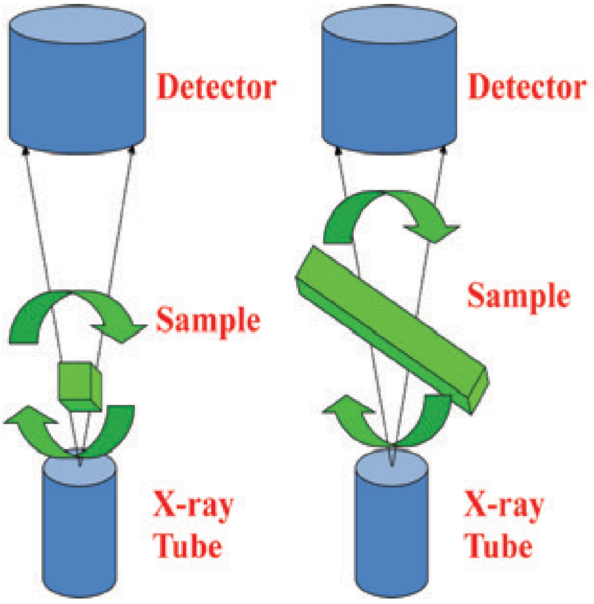

Figure 3. Schematic representation of a µCT system configuration where the axis of x-ray tube to detector remains fixed and the sample rotates perpendicular to this axis. The limitation on making a large sample get close to the x-ray tube and therefore limit magnification is also shown.

Once acquired, this 2D x-ray image dataset is then processed, or reconstructed as it is called, into the 3-dimensional density array of the features within the sample, typically using commonly available algorithms to provide a µCT model. The more, and better, images that are taken and the greater averaging for each then the better the dataset you have to make the final µCT model but the longer it will take to acquire. The most widely used CT algorithm to produce the final µCT model is called the Feldkamp Cone Beam algorithm [3] that uses a filtered rear projection approach to create the 3D model. The time to capture the 2D images may well be the most time consuming step for the overall CT analysis when compared to the time needed to make the model reconstruction because of today's current processing speeds and use of GPUs. Following µCT reconstruction, the user then has a 3D array of volume pixels, or voxels, showing the density variations within the sample, which bespoke or commercially available CT visualisation software is able to then virtually slice and / or cut in any plane within the model as well as provide 3D rendered views. As there is 2D x-ray data from all around the sample, the results are consistent in any plane or orientation of the µCT model – allowing the best analytical results in x, y and z directions within the CT model.

A difference occurs between medical CT and electronic µCT because of the need in electronics to take high magnification 2D x-ray images so as to see the ever shrinking features. Such magnification is not typically required for human diagnostics. However, if high magnification 2D images are required then this has limitations on the sample size that can be realistically imaged under full µCT. This is because the geometric magnification that can be applied to an x-ray image is determined by the proximity of the sample to the x-ray tube relative to the distance to the x-ray detector [2]. So the higher the magnification that is required then the closer the sample must come to the tube (assuming the tube to detector distance has a fixed value). This is why the 'sample rotation' method is used in full µCT for electronics, as maintaining the proximity of the sample relative to the tube when the tube and detector rotate in the other method would be tricky to achieve. When rotating the sample, however, if the sample is large then it necessitates moving the sample away from the tube as otherwise it will strike it during the 360° rotation (see figure 3). Unfortunately, moving the sample away from the tube reduces the magnification that can be achieved, thereby making each 2D image of a lower magnification and therefore providing less detail for the smallest features, such as the joints. In turn, this means less detail is available for the µCT reconstruction. Such limitations mean that overall a trade off must be made in full µCT analysis for electronics applications of the practical sample size that can be used against the magnification and detail available in the final µCT model. For most commonly available electronic µCT x-ray systems this sample size limit is ~ 2" x 2" (50 x 50 mm), or smaller, and is typical of the size of a sample that is normally cut out from the circuit board from which to make a full mechanical cross-section. Larger volumes for analysis are possible but will require larger area detectors within the system so as to capture the larger volumes in the higher resolution needed to see the smallest features. However, the larger detectors needed are often silicon-based CMOS arrays which become substantially more expensive as their area increases.

Therefore, using full µCT to inspect PCB electronics can be considered as an optimum technique ahead of making a full mechanical cross-section, where the sample has already been cut out of the board and allows a 3D model to be made in minutes that will permit virtual cross-sectioning anywhere within the model. Whilst the µCT data will not have the same resolution as that seen in a SEM, the virtual cross-sections in µCT are available in a fraction of the time that it will take to allow for the epoxy to harden and then polish the sample, as is necessary for the mechanical cross-section technique. In addition, the µCT technique does not introduce additional mechanical defects within the sample volume, which is always a concern with mechanical cross sectioning. At best, full µCT will show the flaws in the sample quickly and reduce, or completely eliminate, the number of mechanical cross-sections that have to be taken. At worst, it will identify to the user where the polishing of the cross-section must be made such that an over-polish will not destroy the exact location that needs to be viewed. Overall, full µCT provides the optimum analytical information for electronics applications using the CT technique but unless the whole sample is very small, it will require destruction of the original sample in order that there is sufficient resolution in the final µCT model to make the necessary analysis.

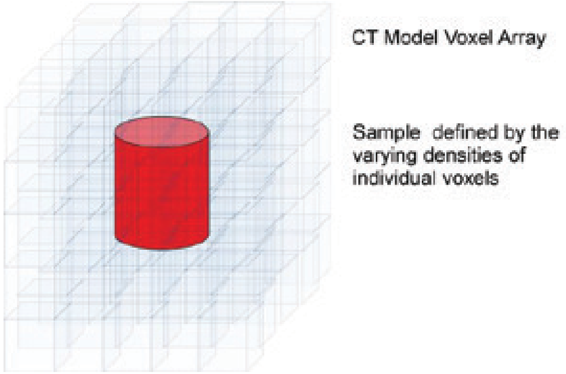

Figure 4. CT model voxel array showing how the sample is defined within the final µCT model.

The resolution that can be achieved during full µCT analysis is dependent on the size of the sample volume that is being reconstructed. µCT models are described in terms of the number of volume pixels or 'voxels' that they contain. For example, the reconstructed object is defined and shown as a density distribution within a cubic array of voxels that can be 512 x 512 x 512 (or 5123 - see figure 4) in dimension, 1024 x 1024 x 1024 (10243), or more. The larger the voxel array size then the more voxels will cover the sample and therefore improve the resolution. The ultimate resolution in full µCT is determined by the original size of the sample, the field of view for the CT scan, and the capability of the x-ray tube and image detector. The smaller the analysis volume, the better the resolution you have because you are dividing the same number of voxels over a smaller volume.

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Having more voxels will improve the resolution for the same size sample volume but, for example, a 10243 voxel array contains 8 X more information than a 5123 array and therefore will take ~ 8 X longer to reconstruct. So, if it takes ~ 2 minutes to reconstruct a 5123 model then it will take ~ 16 minutes to reconstruct a 10243 model. This reconstruction time would have to be added to the time for acquisition of the original 2D images to fully appreciate the workflow times necessary for µCT analysis. Reconstruction times (and µCT model manipulation / analysis) are directly linked to PC and GPU performance and PC memory size. Therefore, a low specification PC would take substantially longer to make the reconstructions (and manipulate the final model) compared to a high specification PC / GPU.

By understanding that the µCT volume is made up of voxels, it means that as the sample gets larger then the smallest details within that volume will be covered by far fewer voxels - making analysis difficult if not impossible. As an example, consider a board of 100 x 100 mm in size containing a BGA of 25 x 25 mm with a 20 x 20 solder ball array whose pitch is 1 mm and each ball is 0.5 mm in diameter. If we were able to reconstruct a 5123 voxel model of the whole board (ignoring the limitations mentioned above) then each voxel in the µCT model array would be of 195 microns by side (100 mm/512). In this case, each BGA solder ball, the features that need to be analysed, would only be covered in a linear direction by ~ 2.5 voxels (which is ~16 voxels for the whole BGA ball assuming it is round) - hardly sufficient for analytical detail! By cutting the BGA out of the board and using this as the sample (because you cannot get sufficient magnification when it is still part of the board without colliding with the tube during sample rotation) then each voxel would be 49 microns by side and the BGA ball would be covered in a linear direction by ~ 10 voxels (and ~ 1000 voxels for the whole BGA volume) – providing more data for better analysis. Using higher magnification on this smaller sample (assuming it is possible), increasing the voxel number (5123 to 20483), and / or cutting down the sample size further will improve the resolution that can be achieved. So a trade-off between the sample size, the time of acquisition / reconstruction, the achievable magnification and µCT resolution always exists.

In-line Partial CT & Off-Line Partial µCT

Whilst full µCT offers many benefits for failure analysis, the fact that it will almost certainly require the board to be cut up and destroyed makes it a technique that would usually only be used at the last resort, especially for printed circuit board assemblers. However, the need to have a µCT ability still remains, particularly as the complexity of today's double-side boards and stacked packages means that the 2D x-ray information is complicated and the features to be analysed are obscured by other (second side?) objects (see figure 1). So being able to separate different board layers, for example, and de-clutter the 2D view for analysis is highly desirable, especially if the sample does not have to be cut up. This can be achieved using the Partial µCT (PCT) technique. There are some limitations in the results compared to the full µCT but not having to cut the board makes it most attractive for PCB electronic applications before taking more drastic action.

The method for undertaking PCT is the same for both in-line and off-line techniques. A number of 2D images are taken around the sample with the detector at an angle relative to the axis of the tube and the sample (see figure 5). The method of achieving the necessary manipulator and detector movements to produce the various images at the angled views varies from supplier to supplier. However, once the 2D x-ray images have been taken around the region of interest then a version of CT reconstruction is performed. This generates a CT model in the same way as the full µCT described earlier and which can then be sliced (most usually into the plane of the board) so as to separate the various layers. The difference between in-line and off-line versions of PCT is that with in-line PCT only a relatively few images are taken at, usually a fixed, angle around the sample (typically between 8 and 12, or less, depending on the supplier). This is because the emphasis of in-line equipment is on speed of sample throughput and the taking of more images would increase acquisition time. To generate a CT model, in principle, only requires a minimum of a few images from around the sample. The CT model that this produces, which will also be dependent on the quality of the 2D images that are used, gives adequate information to produce from the resulting CT model separate reconstructed 2D image slices into the plane of the board. These individual slices can then be automatically analysed. For example, slices at different layers within the BGA on one side of the board can be inspected to see how, and if, the solder ball diameter varies at different layers within the BGA so as to help indicate poor joint quality. In-line PCT can be considered as using the tomographic technique to produce laminographic x-ray data within the board by using computational methods rather than the mechanical methods that were possible in earlier in-line systems. However, a limitation of all in-line PCT systems is that they want to run as fast as possible to keep up with the beat rate of the line, but to get better data requires more and / or better images so as to improve the quality of the CT model. But taking more images means it takes more time and that compromises the speed of sample throughput. So a balance needs to be struck between coverage, inspection speed / quality, type of defects detected, and the guarantee of no escapes in the results but minimising the level of false calls. As feature sizes continue to shrink then these various trade-offs only get more difficult to balance.

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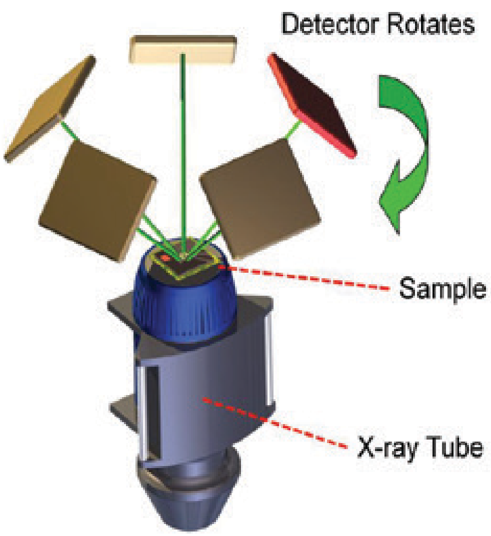

Figure 5. Schematic showing an off-line PCT system configuration where the detector moves at an angle around the area of inspection to obtain the images from which the PCT reconstruction can be made.

In contrast, when using off-line PCT, the user is typically under less time pressure than the in-line scenario and therefore can have the time to acquire many more images around the sample (72, 180, 360, or more) so as to improve the quality of the final CT model and possibly, depending on the supplier, can also set the detector angle at different values for different PCT analysis. Setting the detector at greater oblique angles allows more information to be captured over a greater solid angle in each image. Therefore more information is available for the reconstruction. However, very large oblique angles for electronic applications may well result in other components / features within the sample overlapping the region of interest. This will vary the density values of the features under test substantially as the detector is rotated around. If the density of the same feature varies in value over the total captured data then it makes the reconstruction less precise and so introduces further error into the CT model. Ideally, the same feature should have the same density in all acquired images. In electronics, this does not happen because of the different densities of the material and their thickness plus the likelihood of obscuration by second side features. So there are already density variations in full µCT and PCT as the image data is captured but when you then add additional variation caused by features that will only be seen in some images because of the oblique angle selected and the rotation angle of the detector then this will affect the final CT model more. As an example, taking an oblique angle view of > 50° on a BGA will often cause an adjacent row of solder balls to overlap each other at certain rotational angles. By using lower angle views for PCT then this additional density burden is not imposed on the 2D image dataset.

A further advantage of off-line PCT is that it possible to concentrate on a smaller area / volume of inspection compared to in-line and full µCT approaches. This is because the magnification is not limited compared to full µCT, as the sample can always be placed as close as possible to the x-ray tube and does not rotate into the tube. With in-line PCT, although the magnification could and can be increased, the result is that many more inspection points need to be made to cover the same inspection area as when using lower magnifications and therefore will substantially increase the inspection time, something that may be unacceptable for the beat rate to the manufacturing line.

2D Planar View image Quality	Full CT	Off-Line PCT	In-Line PCT
Z (into board)	Excellent	Very Good	Good
X, Y (left to right and front to back through sample)	Excellent	Good to Acceptable	Very Poor or Not Available
Other Planes	Excellent	Good to Acceptable	Very Poor or Not Available or Shown
Limited sample size	Yes	No	No
Cut sample	Yes (unless very small)	No	No
3D Rendering of data?	Yes	Yes	No

Table 1. Comparison of relative capabilities of CT echniques used for electronics inspection.

Prior to the availability of the tomographic approach to generating and separating various board layers for in-line Automated Inspection Systems (AXI), a mechanical approach to achieve the same end was available. This did not use any computational methods to achieve the separation but mechanical movements to highlight the slice at a critical depth in the sample and the other slices would be removed from the view. This was called laminography and can be seen as a 2.5D approach. It was only able to provide layer information into the board. There was no detail in any other plane. The production of these layers depended on a knowledge of any warpage on the board and ultimately the image quality of the result was compromised because of smearing / disappearance of the other layers was never perfect. As a result the image quality was poor and as this was used to make measurements at different layers to identify faults then the poorer the image quality then the greater the false call rate would become in order to offset the guarantee of an escape not happening in the tested samples.

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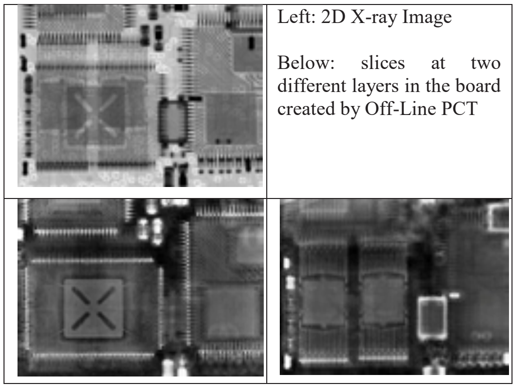
As a result, these systems generated many boards, especially as the board complexity grew, that had to be re-evaluated manually after automated inspection, often using a high end 2D x-ray system, requiring additional, expensive personnel. More recently these systems have been replaced with the in-line PCT approach where a highly computational approach is made much simpler but the resultant image quality is still poor because of the need to have high throughput so as to match the beat rate of the manufacturing line, thereby only permitting relatively few 2D images to be taken for each inspection area. So although in-line systems use PCT, it is really a method to generate layer information so as to potentially make pass / fail measurements.

With off-line PCT systems, there is less time pressure on the analysis compared to in-line. Therefore, there is the time to take more 2D images and each image can be better as averaging can be applied so as to improve the signal to noise ratio in each. The key for all CT techniques is to have precision and consistency for all the 2D images that are captured. If the dataset is not consistent then it will result in poor CT reconstruction. Achieving high precision sample motion for in-line systems is usually achieved by including high precision motors and controls on sturdy system frames, all of which require additional costs in manufacture. In the off-line systems offering PCT, the requirement to have accurate motion alignment can be achieved either by high resolution motion control or sophisticated computational adjustments. The former approach requires additional hardware; the latter can use less expensive motion control but still achieve the same ends. The implications of cost of equipment against providing the PCT functionality within the production and failure analysis environment must always be considered.



Left: 2D X-ray Image

Below: slices at two different layers in the board created by Off-Line PCT

Figure 6. 2D x-ray image (figure 1) and 2 off-line PCT slices showing the separation of the components on different sides of the board.

Off-line PCT generates very good views into the plane of the board without any cutting necessary and is available anywhere within the inspection area of the x-ray system. Off-line PCT does also provide valuable and useful information in the other planes but not as good as full µCT would provide because the dataset for the CT reconstruction only has limited information in the original 2D images compared to the data all around the sample gathered in full µCT. A comparison of the relative merits of all three CT techniques is shown in table 1. An example of the results of an off-line PCT examination is shown is figure 6, where slices at two separate layers into the board (figure 1) are shown so that the different components on the different sides are now easily distinguished.

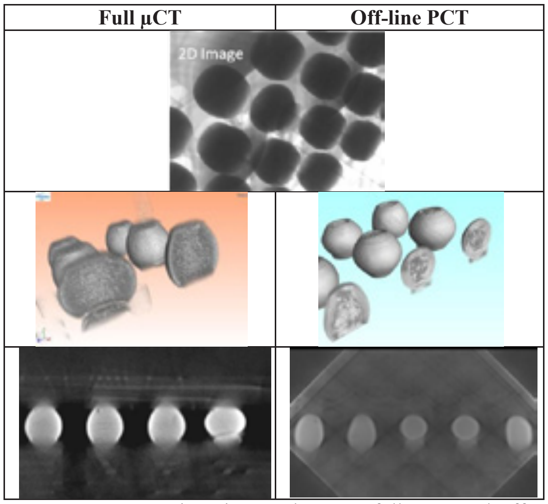


Figure 7. Comparison images between full µCT and off-line PCT for a Head on Pillow (HOP) joint. Samples are not identical but serve to illustrate relative capabilities.

Example

The difference between full µCT and off-line PCT can be considered using the example of a Head on Pillow (HOP) joint under a BGA. Assuming it is possible to fully rotate the BGA in the full µCT system, then as images are taken all around the BGA then some of those 2D views will include images from the side of the device showing the gap in the separation of the head and the pillow of the joint. Therefore, this information is available to the CT reconstruction and this separation will be shown in the full µCT model. In contrast, in PCT as the 2D images are only being captured at an angle from above the sample then the dataset has a much more limited content of information and, unless the separation of head and pillow is very large, the head of the joint will always obscure the pillow to some greater or lesser extent in each 2D image. Therefore the reconstruction data does not have the full information to see the separation. As a result, in full µCT

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you see the separation between the head and the pillow but in PCT there is a different bond shape, perhaps like an 'hourglass' type shape. So a difference is still seen in the bond shape under PCT but not the same as in the full µCT (see figure 7).

The best that is expected from in-line PCT, because of the emphasis placed on speed of throughput, is to see a variation in the diameter of the joint at different levels into the board. Calculating any diameter differences may show the presence of the HOP joint. However, with the less information and hence less detail from this CT approach then it makes a good test more difficult to do and increases the opportunity for false calls in the results in order to prevent escapes from occurring.

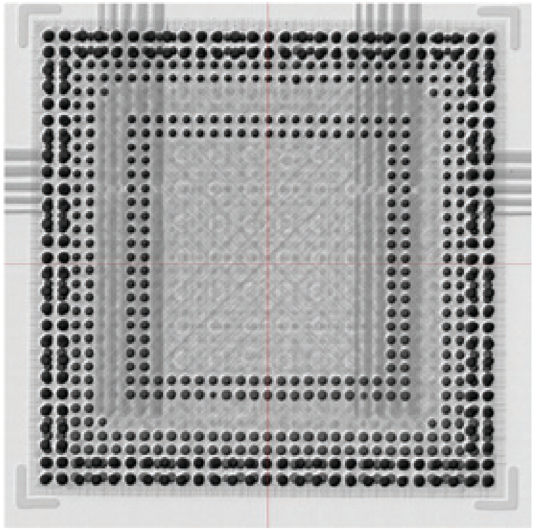

Figure 8. 2D x-ray image (top-down view) of a 2-layer POP device showing top and bottom layers overlapping.

Real Life Examples for PCT

A Package on Package (POP) is a device utilizing vertical integration with the obvious benefits of saving space and improving the electrical inter-connection characteristics. Unfortunately, vertical integration naturally makes the job of the conventional 2D x-ray inspection technique more difficult as features are automatically overlapping each other in the 2D view. For example, figure 8 shows a 2D x-ray image of a POP device. It is obvious that the apparent interference between the 2 layers of interconnects makes the inspection task quite difficult for the operator.

Oblique angle 2D x-ray views (see figure 7, 13) can improve the opportunity for a defect to be found in such a sample, however what is the PCT technique able to do? PCT is also sometimes called Board Level CT - BLCT. Figures 9 and 10 show the 2 layers of the POP in figure 8 separated using PCT – from a fast and low magnification scan technique. Layer 1 (figure 9) appears flawless. However, from the PCT image representing level 2 (figure 10) we can clearly see that two joints are incomplete (red arrows) and something abnormal is going on inside the red box area.

Figure 9. Fast, low magnification PCT scan of POP device in figure 8. The virtual cross section through the plane of layer 1 looks consistent and good.

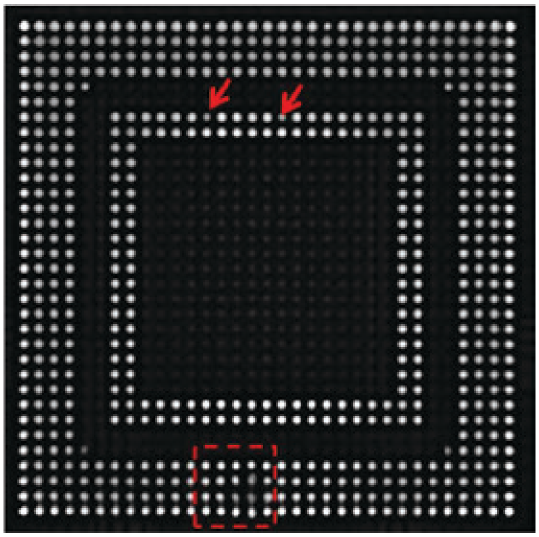

Figure10. Fast, low magnification PCT scan of the POP device in figure 8. Virtual cross section through Layer 2 shows incomplete / open joints (red arrows) and abnormal joints (red square).

The missing / open joints are obvious (red arrows in figure 10). However, the next step is to do a fast PCT scan at higher magnification concentrating on the area within the red box of

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Figure 10. The results are presented in Figure 11, which shows virtual cross sections through the suspected joints in (a) a vertical plane, (b) a horizontal plane and (c) a 3D rendered view of the CT model. It is obvious the joints in the red box did not reflow properly, resulting in open, or intermittent connections.

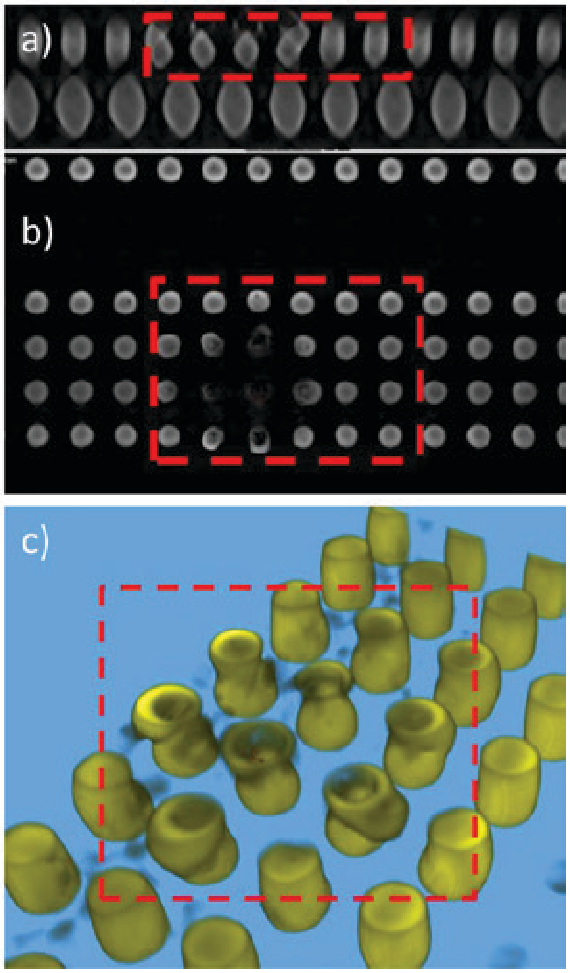

Figure 11. PCT scan of the area within the red box in Figure 10. a) Virtual cross section through a vertical plane, b) virtual cross section in horizontal plane through the open / intermittent joints, (c) 3D rendered view of CT model.

Intermittent connections can be even more devastating as the device could pass the electrical tests and end up failing in the field. The possible cause for these defects is contamination of the package / PCB or deposition of an incorrect amount of paste.

Figure 12 is another example of a defect that is very difficult, or impossible, to diagnose just using 2D x-ray / oblique angle techniques. The bottom layer of the POP device (rendered in gold) looks fine. The joints of the top layer (rendered in red) are angled away from the lower layer with the angle increasing towards the outside of the package. The reason behind this fault could be mismatch and / or package warping.

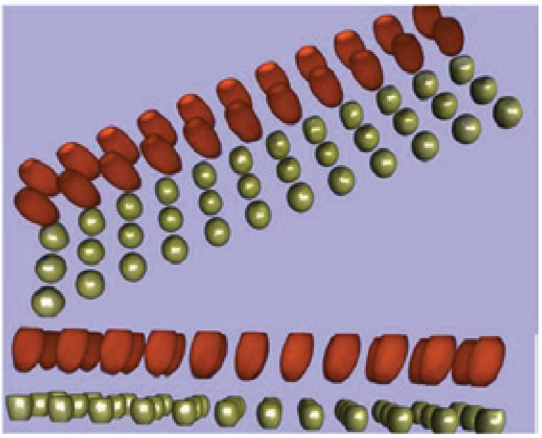

Figure 12. Top layer of POP device (rendered in red) shows misalignment and / or warping compared to the bottom layer (rendered in gold).

Head on Pillow Joints

Head on Pillow / Head in Pillow (HOP / HIP) defects are quite common [4, 5] and often difficult to detect using AXI. 2D x-ray / oblique angle view systems are usually the choice for diagnosing HOP. A 2D angled x-ray image is presented in Figure 13 showing a suspected HOP joint.

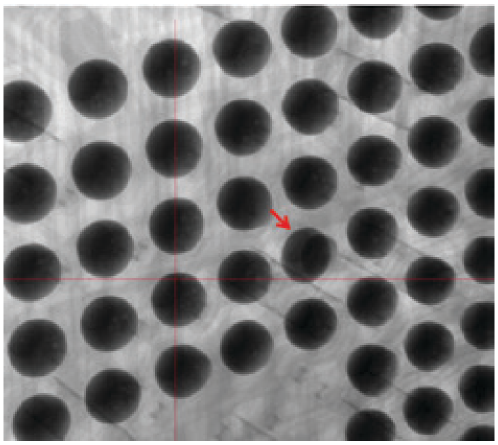

Figure 13. 2D angled x-ray image of suspected HOP joint (red arrow).

The results of PCT analysis of a different area of the device in figure 13, but which has similar defects, is shown in figure 14. 14a is a virtual cross section in the horizontal plane of the pad area, 14b is a cross section in the vertical plane and 14c is the 3D rendering overview. One can position the cutting plane very precisely using off line PCT, which is not the case with AXI. The result is that the HOP defect is much easier to identify using PCT compared to AXI or 2D x-ray inspection, and the diagnosis is clear and final.

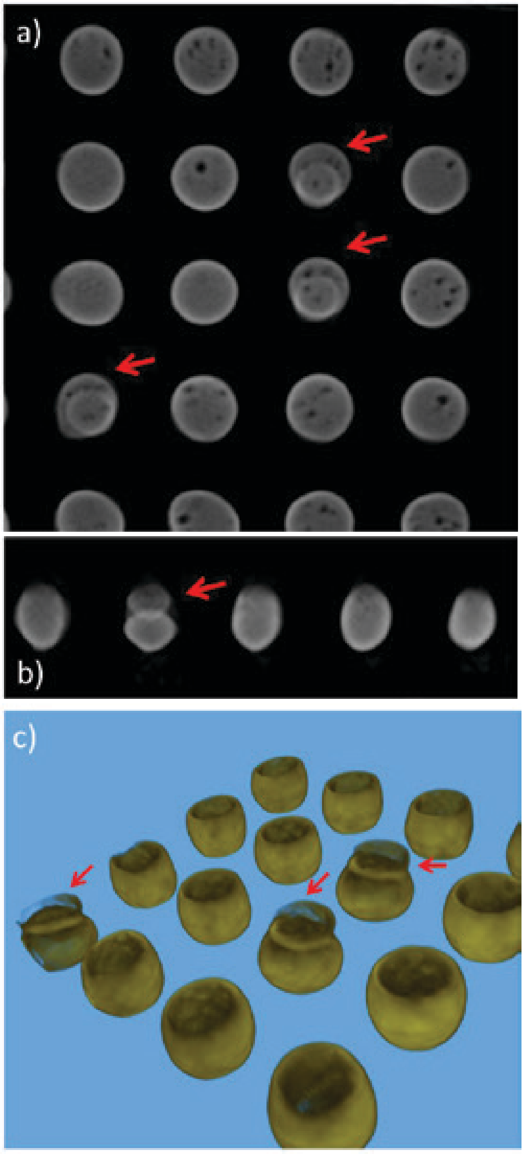

Figure 14. PCT clearly diagnosing HOP / HIP defects (red arrows). a) virtual cross section in the horizontal plane of the pad area, b) cross section using a vertical plane and c) 3D rendering overview

It is interesting to point out that even the section in the horizontal plane (figure 14a), easily identifies the HOP defect due to its obvious signature, while the vertical section (the usual way a mechanical section is performed) and the 3D rendered image make the verdict undisputable.

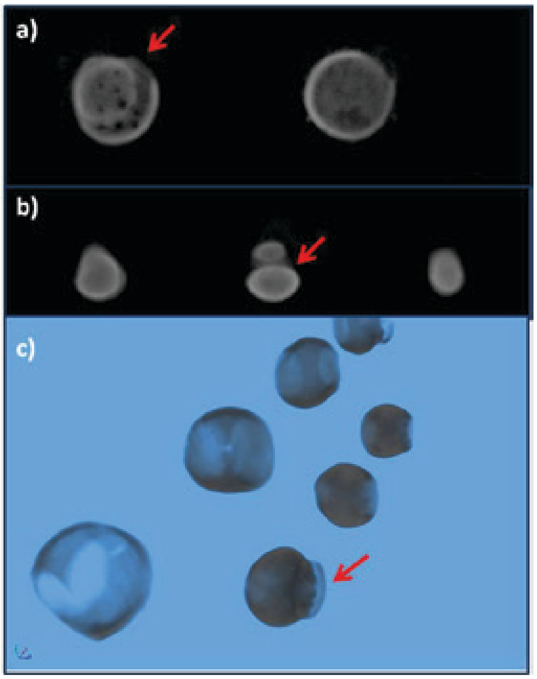

Figure 15. PCT showing HOP / HIP defects second example. a) virtual cross section in the horizontal plane of the pad area, b) cross section using a vertical plane and c) 3D rendering overview

Figure 15 shows another example of HOP defect for a different device. Again the diagnosis is very fast and convincing.

Connectors

Verifying how well a complex connector is engaged / soldered within the assembled product has always been a challenge. Historically, the only way to confirm this was to mechanically cut the board / assembly, which results in destroying the expensive assembled product. The full µCT option is also destructive in this case, as usually the connector is mounted on a large board within a large assembly, and the only way to do a CT scan and get reasonable data with useful resolution is to cut the connector out of the board. Undertaking 2D x-ray is also not practical as the 2D image is very complex, and can be cluttered with all the other parts surrounding the connector in question, as shown in Figure 16. Figure 16 shows how it is very difficult, or impossible, to verify how well a connector engages using the standard 2D x-ray technique even with oblique angle viewing. For this particular example, we are showing an entire smart phone assembly.

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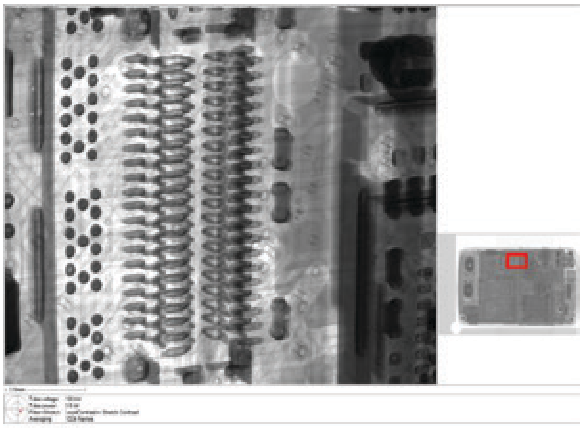

Figure 16. Angled 2D x-ray view of a connector within a smart phone assembly. The connector is in the area marked by the red box. Correct engagement cannot be verified even using multiple viewing angles and higher magnification.

In Figure 17, we show virtual cross sections of the same connector in figure 16, produced by PCT, while keeping the whole assembly (smart phone) intact. Figure 17a is a section in the horizontal plane and Figure 17b is a section in the vertical plane.

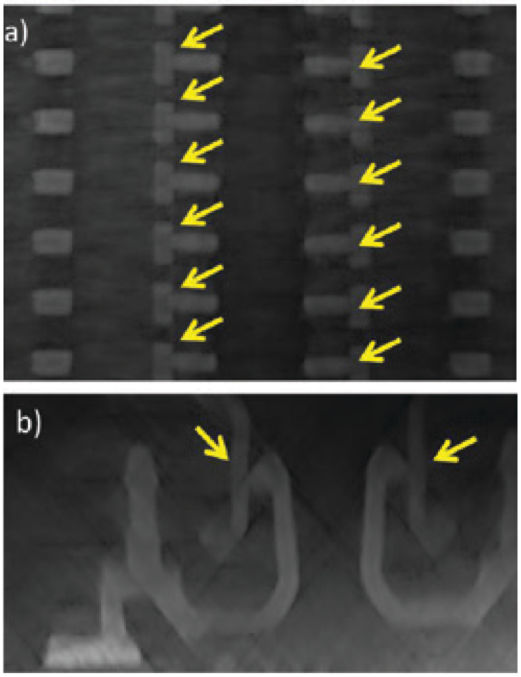

Figure 17. PCT virtual cross sections of a connector within a smart phone assembly. a) section in the horizontal plane, b) section in the vertical plane. Satisfactory engagement is verified in the areas shown by the yellow arrows.

The PCT scan resulted in eliminating the clutter evident in the 2D images. Using virtual cross sectioning in the right locations clearly shows that satisfactory engagement of the connector took place at the areas indicated by the yellow arrows. Confidence of this result is even higher as the phone worked before placement in the x-ray machine!

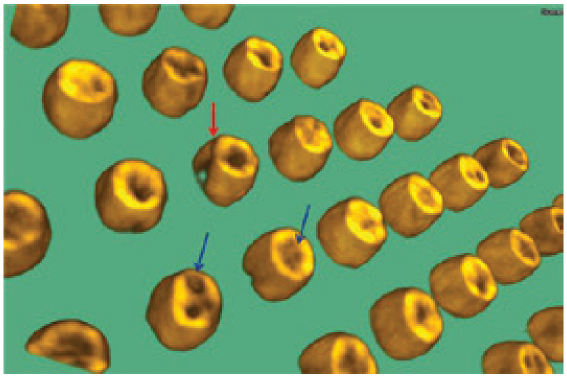

Figure 18. PCT of 100 micron diameter bump interconnects showing cracks resulting in the bump being split in half (red arrow). The blue lines point towards interfacial voiding.

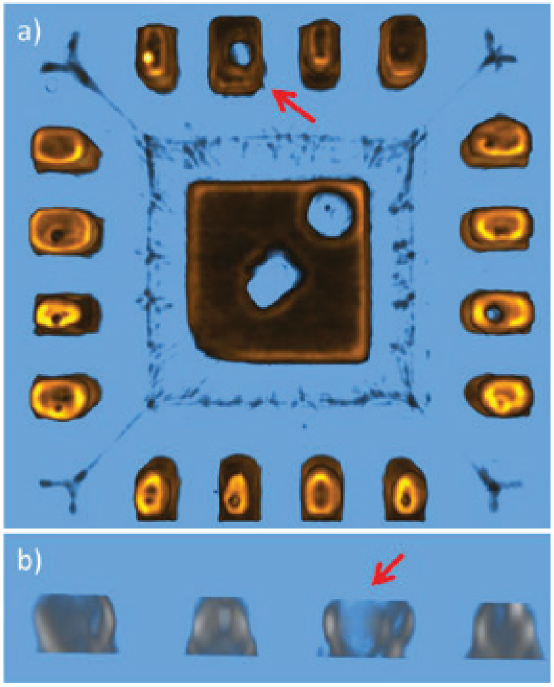

Figure 19. PCT 3D model of a QFN device. Extremely large void is shown going through the whole solder joint - suspected in overview (a) and confirmed in section view (b).

Solder Bumps

While PCT was developed mainly as a PCB inspection technique, it has been found to be very useful as a 3D non-destructive method for examining micro bumps on a wafer or package level. Wafer bumps are getting smaller and smaller with 20 - 30 micron diameter bumps not uncommon today. Figure 18 shows a PCT of a micro-bump sample. The red arrow points to a crack defect in a bump which has resulted in the bump in question being split in half. The blue arrows show some interfacial voiding, which could also pose a future problem by reducing the possible joint reliability.

Area Voids

A PCT model of a QFN device is shown in Figure 19, where 19a represents a section overview of the whole QFN device. The joint marked with the red arrow demonstrates an extremely large void apparently going through the whole solder joint. This is confirmed by Figure 19b which is a section through the joint in question, as well as its neighbours. This extremely large void makes the solder joint very unreliable and likely open or intermittent in function. Precise locating of voiding positions is a known strength of the CT technique and nicely demonstrated here with this PCT case.

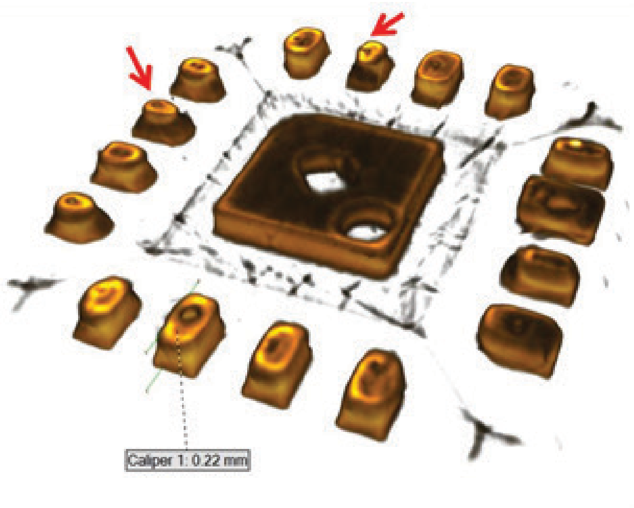

Figure 20. PCT 3D rendered model of a QFN device showing insufficient joints (red arrows). The solder thickness is also able to be measured in the rendered view.

In Figure 20, we have the same QFN device seen in figure 19 but shown at an angled PCT section overview. The solder joints indicated with the red arrows are clearly insufficient when compared with their neighbours. In addition, figure 20 demonstrates a very important additional feature that is available - measurement capabilities such as that of solder thickness as well as volumetric information pertinent to the solder joint – i.e. solder and voiding volumes. Thus the PCT technique lets us not only examine in detail the solder shape and variation but also can produce very important numerical data.

Conclusion

In this paper we have discussed the various CT techniques that are available for electronics inspection including the off-line partial µCT (PCT) technique, also known as board level CT. This comparatively novel technique presents us with the capability of creating, in a short time, very reasonable quality 3D CT models of areas within large PCBs or other electronics assemblies. This is achieved in a completely non-destructive fashion, something that is not usually true when full µCT is undertaken. The PCT technique has been illustrated using a wide variety of examples of SMT devices that have included real life defects. By producing non-destructive defect diagnosis in a fast and convincing manner through virtual cross sections of samples, this makes PCT a powerful alternative / precursor to mechanical cross sectioning. In addition linear measurement and volumetric data are readily available, thus providing important quantitative data to be added to the qualitative analysis.

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