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USE OF COMBINATION 2D AND CT SCAN X-RAY IMAGING FOR SOLDER JOINT INSPECTION

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ABSTRACT

Connector technology used in the high density printed circuit boards demands high speeds and low signal to noise ratios. In order to improve the connector density, more and more connectors are going surface mount, with very high I/O count. I/O counts in excess of 5000 connections on a single connector site, are not uncommon. In order to provide connections to all the I/O's, the connectors often tend to be dense and have a very high profile. A reliable inspection of these connections is essential to reduce the defect levels and assess the long term reliability of solder joints. A unique combination of conventional 2D X-ray inspection and CT scan (3D reconstruction) is used to inspect such joints. This unique combination has made possible, a reliable inspection of solder joints for defect like shifted connectors leads, low solder volume, solder climb, solder thieving etc. A quick identification of these defects was used to drive process corrective actions and reduce the test down times. This paper discusses the combination techniques and shows various illustrations of defects which are normally difficult to detect.

One great advantage of such a system is the ability to use it as a combination tool, or two stand-alone tools that can be used for various other types of inspections when needed. For instance, a 2D inspection tool was also used to inspect solder joints on standard SMT connectors, pin-thru-hole connections etc, and for analyzing internal component defects. The CT scan could be used for understanding other types of defects, such as, shorts internal to the components, internal structures of circuit boards etc.

Key Words: High density connectors, 2D X-ray inspection, CT scan, solder joint, IPC requirements for solder joints, automation.

INTRODUCTION

Real time X-ray imaging has been used in the past and continues to be used at present, for inspection of solder joints. Due to greater and greater surface component density of complex printed circuit boards, lead length and surface pad sizes have become smaller to a point that microscopic inspection of these solder joints is no longer reliable, this is because a significant portion of the solder joint is sometimes hidden by the connector body itself. Simple two dimensional X-ray inspection provides a reliable means to inspecting such solder joints.

Sophisticated automated inspection algorithms are available for various types of solder joints. This includes area array components such as ball grid arrays. An automated inspection program can also be written for simple multi-leaded components which can not only reduce the inspection time significantly, but can also eliminate human errors. All these algorithms make use of grey level difference arising from materials, thickness variations and joint integrity. A necessary requirement for these algorithms to be successful is the relative 'transparency' of the component under inspection. In other words, the component itself must be relatively transparent to x-rays. Because most of these components are made of ceramics or organic substrates; or some type of polymers like LCP, the transparency requirement is easily met. When a connector system becomes complex, and there are layers of metal connections shadowing the solder joints, such simplistic 2D inspection becomes impossible. A new method needs to be developed for such an inspection.

BACKGROUND

It is now well known that plated through hole connections limit the connector density. Circuit boards used in current high end server applications use upwards of 30 internal conducting layers. In order to reduce crosstalk, the conductive layers must be interspersed with intermediate layers of dielectric material. This makes the circuit boards very thick. Aspect ratio limitation imposes a restriction on how small a hole can be, in order to make a reliable connection. It is therefore, preferable to select surface mounted connections instead. Besides, alternating signal and power connections reduces signal to noise ratio.

During the development of a new system in 2006, it was necessary to use a very high density connection system. This particular connector has in excess of 5,000 connections, has a cross section of 2 in x 2 in, and is about 10 inches long. Signal and power connections are achieved by alternating J-leads. Figures 1a and 1b show the connector and leads. When the connector is mounted to the board, almost 70% of the solder joint length is shadowed by the dense internal metallurgy of the connector. To make matters worse, tests algorithms were still being developed to test such a system reliably.

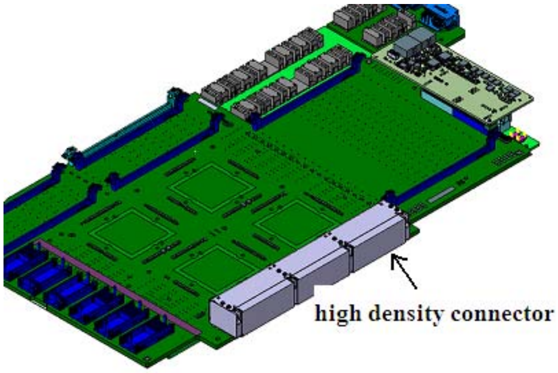

Figure 1a: High density connector with 5040 connections

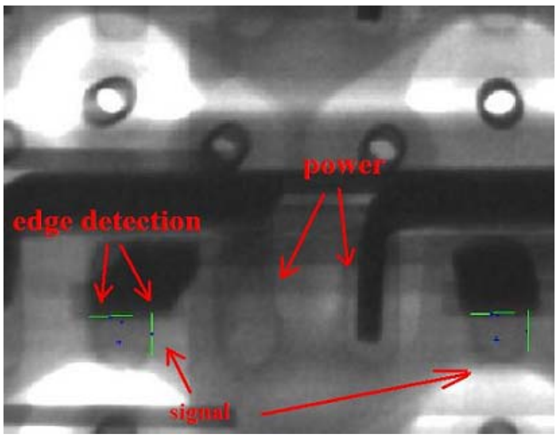

Figure 1b: Lead geometry and connection points

It was necessary to develop a reliable method of inspection of these leads after attach. Conventional x-ray systems available in house proved to be inadequate for the task. It was time for a paradigm change.

PROGRAM DEVELOPMENT

Very few systems were available for evaluation, due to the large board size and the need for large scan areas. Initial trials were started on the Phoenix Micromex system that was selected for this inspection. Small source size combined with high kV selection made this the ideal choice to penetrate dense circuit board, and still maintain the resolution needed. To our satisfaction, initial trials revealed that though only a small portion of the lead was visible, it was possible to predict the overall quality of solder joint based on the information contained in the exposed portion of the image.

Several test samples were prepared by intentionally inducing defects. These included low solder volume, missing solder volume, bent leads, poorly aligned leads, and solder smears. Development work took almost a whole year. At the end, the manufacturer was able to develop a very intelligent software program to detect all of these defects. Fiducial detection was used to precisely locate the connector in the same spot each time. This was important because the algorithm was expected to define a 'region of interest' around the lead being inspected. It was necessary for the lead to 'fall' in this region each time a board is indexed from one frame to the next, and for each new run.

Figure 2a shows a typical 2D image of the leads under inspection at the start of the inspection algorithm. The x-ray manufacturer developed an edge detection software that sweeps a detection tool across the region looking for steep changes in the grey levels within the image. A sweep is made both, in X and Y directions. Grey levels are continuously recorded along vertical and horizontal directions. An edge is said to have been found at a point where a sudden change in grey level is detected. Thus, vertical and horizontal edges of the visible portion of the lead are defined. These two edges now define a 'solder stripe' area which is then used to detect various features of the solder joint going across from left to right and top to bottom. Differences from a preset 'acceptable solder stripe' are then flagged as potential solder defects.

Figure 2b shows a result of such an inspection. When a mismatch is detected, the algorithm draws a rectangle around the 'failing' lead, with nomenclature showing the type of defect it suspects. A typical low solder condition will show as a uniform grey intensity across the lead region, compared to a good solder joint which typically shows a transition from light at the edge of the pad, to dark at the edge of the lead and then to light again. A shifted lead will show a 'double edge' where the first one being a true edge at the edge of the lead on one end, and the other at the edge of the board pad, causing the algorithm to fail the site.

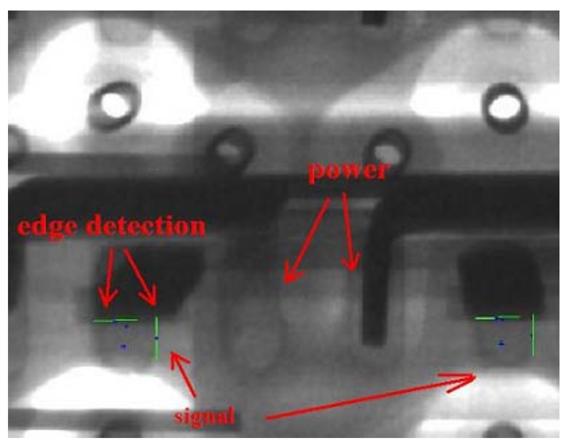

Figure 2a: Program execution initial stage showing vertical and horizontal edge detection

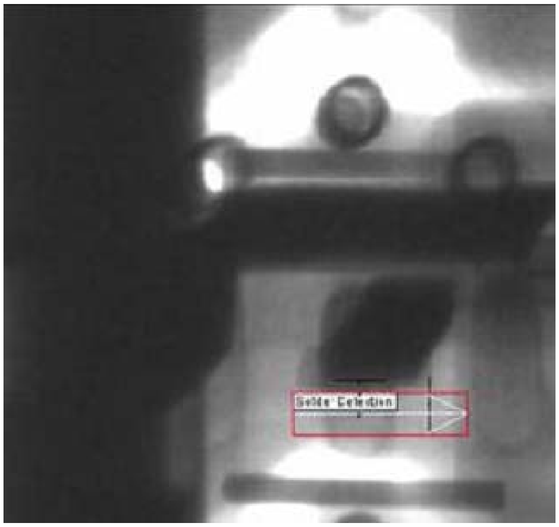

Figure 2b: Program conclusion showing stripe failure at vertical edge

Figure 3 shows progress of a typical inspection, showing right and top edge definitions on acceptable leads under inspection. In a typical inspection frame, up to 10 leads may be selected for inspection. Since x-ray beam is divergent, parallax effect comes into play. The appearance of leads at the top of the frame, is significantly different from the appearance of leads at the bottom of the frame. Only the leads in the bottom two rows are selected for inspection from the entire frame. This is because these two rows have minimum shadowing from connector metallurgy. One hundred percent of the signal leads are sequentially indexed through these two rows.

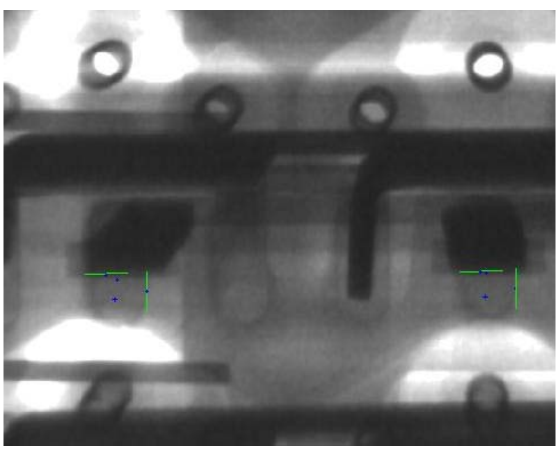

Figure 3: A typical inspection sequence showing acceptable solder joint quality

It takes about 20 minutes to inspect the entire connector. In order to ensure that all possible defects can be detected by the use of this algorithm, it was also necessary to make the program 'over critical'. Thus a certain number of 'false calls' are desirable during each run. This ensures that the program is actually working as expected. At the end, all the defect images are compiled into an output file and presented to the operator for review. IPC certified operators are trained to review these defects and accept or override the calls made by the program.

Figures 4 through 10 show typical 'low solder' x-ray defects detected by this algorithm.

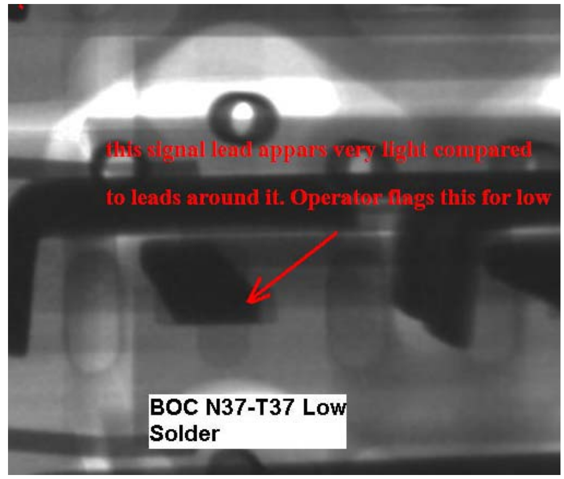

Figure 4: Showa potential defect flagged by 2D inspection as low solder. Note that the area of the lead does not show any edges

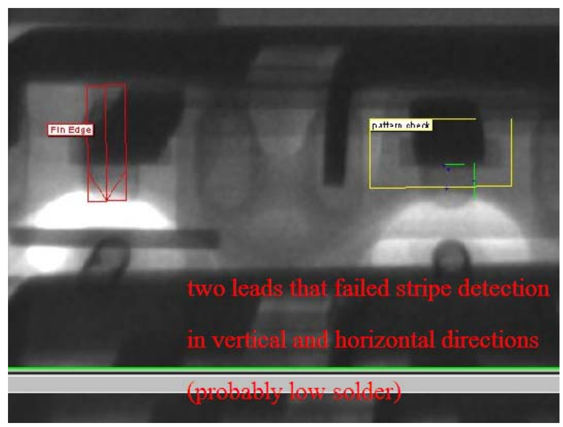

Figure 5: A combination fail. One lead failed for vertical stripe detection, the other failed for solder compare

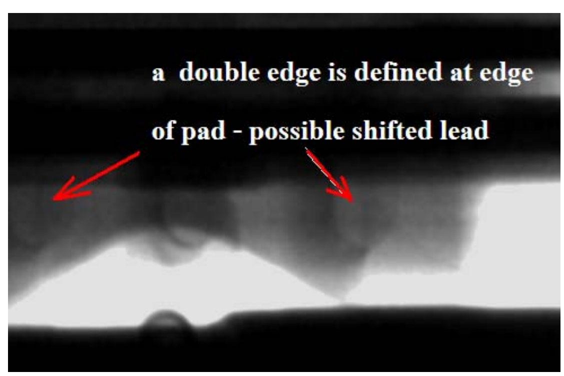

Figure 6: Leads that appear to be shifted at least 50% off the pads were flagged by the algorithm

Shorts are typically more difficult to detect on such a high density connector. The exception to this is when they occur close to the toe portion of the lead. However, a majority of shorts are high resistance type, that are caused either by some type of contaminant, or by solder filaments or fibers. These types of defects are difficult to detect using x-ray imaging.

One of the more useful types of solder defect that we were able to consistently detect as the formation of solder balls between leads, and the presence of tiny solder balls distributed randomly in the connector footprint. Subsequent investigation led to the conclusion that the solder balls or splash is observed predominantly on boards that had gone through multiple screening operations. If the screened paste needed to be wiped off for some reason, the wiping action drove a lot of paste inside via holes. During subsequent reflow, this trapped paste could have coalesced, causing solder balls and solder splashes. Solder balls that spans at least half the distance between adjacent leads, would be a cause for rejection.

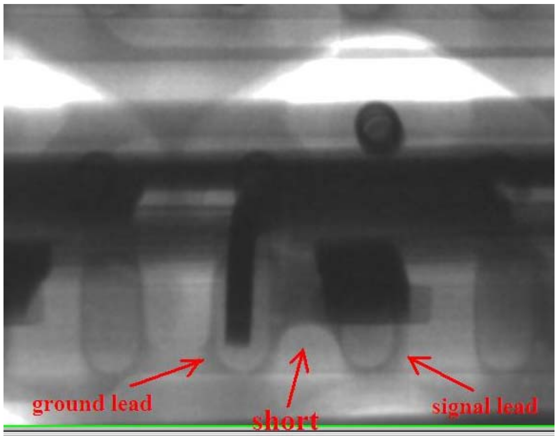

Figure 8: An example of solder short that was caused due excess paste deposition

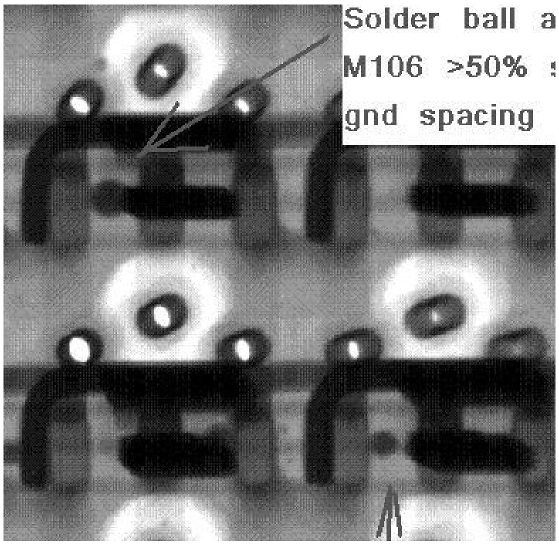

Figure 9: Example of solder balls that span about 50% lead to lead spacing

Solder balls are particularly of interest and we are happy to report that these are being successfully detected by means of these algorithms. The reason for concern with solder balls is that these do not fail any of the EOL (end of line) tests and these have never caused actual shorts. However, from a reliability perspective, these are undesirable because they pose a latent failure risk.

Solder splash defects are also detectable by means of this algorithm as long as these splashes 'fall' within the 'region of interest' around the lead. These are not necessarily cause for rejection, unless they are too numerous. However, their detection definitely serves as a process monitor and lead to corrective actions.

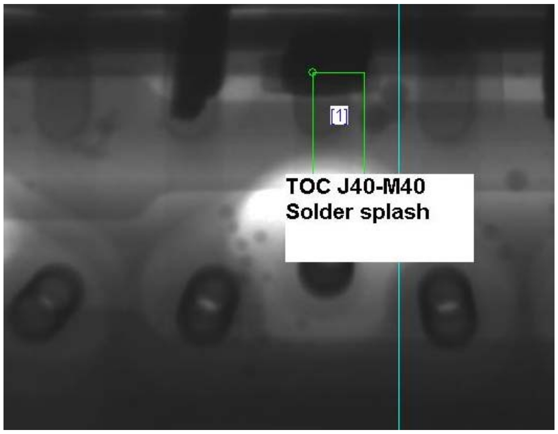

Figure 10: Typical example of solder splash showing numerous tiny solder balls, dispersed in the footprint

REPAIR ACTIONS

A logical next step after inspection is to send the board back to the repair sector if a defect is detected. Unfortunately, the repair action is very expensive, because it requires removal of the entire connector and replacement with a new one. Repairs are performed on a local vapor phase tool and can take as much as four hours per connector. Additionally, there is always a concern of copper dissolution during rework. Connector repairs are therefore limited to two per board. If a rework fails twice, the board must be scrapped. Moreover, every repair action means loss of production time and increased cycle time, both undesirable entities in an efficient manufacturing environment. Each repair action has its own intrinsic fail rate, resulting in a secondary repair action.

A quick analysis of X-ray yields and projected connector repair yield showed us that there would be about 10% loss of the product to unsuccessful repair action, in the early stages of the program.

These considerations put a lot of focus back on the X-ray inspection operation. It was of prime importance that the call made by X-ray inspection be accurate such that repairs are performed only on 'true defects', and not on 'false calls'. Yet, at the same time, it was also essential to have a certain number of false calls to make sure there would be no escapes. This is the balance of alpha error risk versus the beta error risk, a common 'catch 22' situation.

A NOVEL SOLUTION

At around the same time, the same supplier had also started marketing an industrial CT scan inspection system. Our next logical step was to see if we could inspect the solder joints in a different view to make a more accurate assessment of the solder joint quality. The system used is a second generation CT scan system as shown in figure 11 below. A 225 kV X-ray source was used to generate X-rays. An Si diode array digital detector is used to capture images.

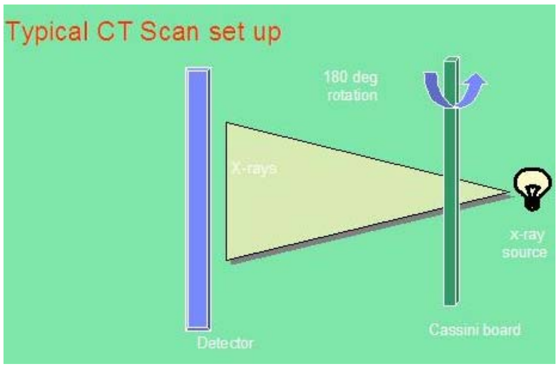

Figure 11: Schematic of a typical CT scan system. Work piece is rotated between the source and the detector

The technique involves rotating the workpiece (connector, in this case) through an angle of about 200+ degrees, using between 800 and 1000 intermediate steps. It each indexing step, an averaged image is captured and recorded by the detector. A proprietary software program is used to integrate these individual images and integrate them into a 3-dimensional X-ray volume. A standard slicing software program is then used to inspect through sections of the workpiece in any direction. Initial trial with the software showed encouraging results.

Soon it became apparent that we would need at least about two hours per inspection on CT scan. Since high resolution images were necessary for a satisfactory inspection of joints, physical dimensions of the inspection area were necessarily small. At a time, we could only inspect about a half inch square area of the sample. Inspection quality was however, excellent. It was obvious that we could not possibly inspect the entire connector containing 1680 leads of interest. Yet, need for CT scan inspection was clear.

COMBINATION INSPECTION

A logical step in the progression was to combine the 2D and 3D (CT Scan) inspection techniques. A system routing was set up to carry out gross inspection using the 2D inspection method. Once the operators reviewed the defect images, they would determine which fails were potential true defects. CT scan would then be used only in these specific locations to validate 2D inspection calls. If there were multiple defects flagged by 2D inspection, CT scan would only look at a few of these to point to the root cause.

Figure 12 shows a typical CT scan image of a 'low solder volume call from 2D inspection, for example, as shown in Figure 4. Low solder volume can sometimes be deemed acceptable, depending upon whether the solder joints meet the acceptability requirements of IPC.

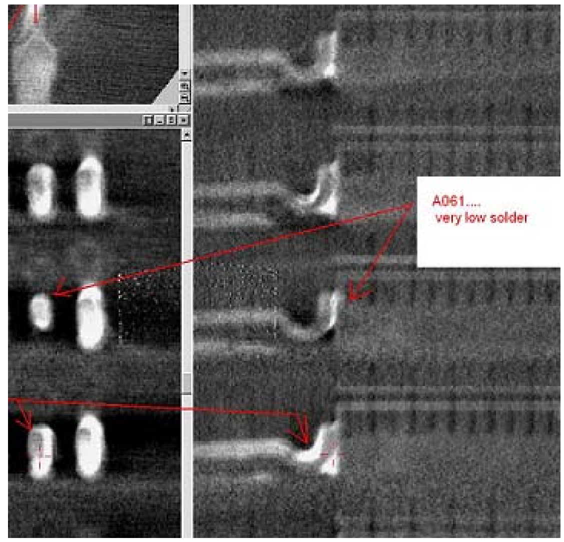

Figure 12: A typical lo solder volume defect detected by CT scan showing planar and side views of the same lead

The image recognition capabilities of the CT scan reconstruction software presents three orthogonal views of the same viewing area. Different areas can be selected to view the entire field of view. Figure 12 above shows a CT scan image of a lead that was called out for 'low solder' by 2D inspection. The side view of the questionable connection in fact, shows low solder volume in the joint, The top down view to the right, shows a foot print that is smaller that the pads surrounding the defective pad. The beauty of this detection is that this type of solder joint is normally impossible to find, as it will pass all electrical tests. Yet, it is quite evident that a joint of this type is certainly unacceptable according to IPC standards. There is hardly any heel fillet.

A good solder joint will typically look like the images shown in Figure 13. The top down and the side view of the leads show good solder fillets and sufficient foot print indicating that the solder had covered the entire pad. Several such images are stored in the library and can be used as training aids.

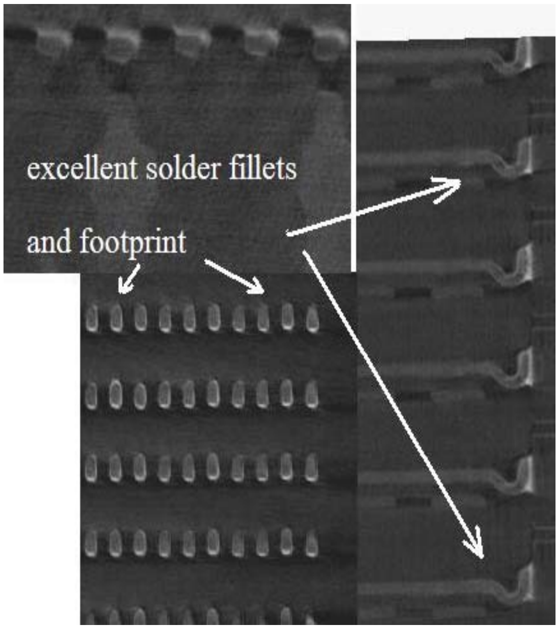

Figure 13: A Typical good solder connection. The fillets are nicely formed, joint thickness is uniform and foot print shows good coverage

A frontal view of the leads is typically most useful for assessing lead to pad mis-registration. As shown in figure 14 below. This image would typically correspond to a 2D image shown in figure 7. The lead position as apparent in the frontal view, is off the underlying pad foot pint by more than 50%. Once again, a defect of this nature will definitely pass all tests, yet this would not be a satisfactory solder joint, and is likely to fail stress test.

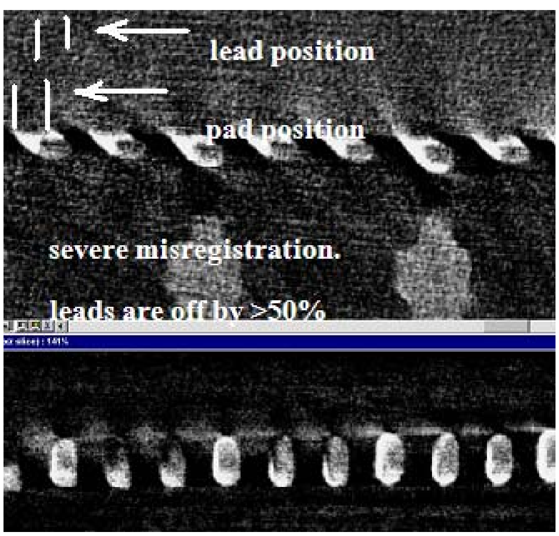

Figure 14: Typical frontal view of a mis-registered lead. The relative position of the lead is off by more than 50%

A different type of defect was occasionally observed in manufacturing samples. A low solder joint call may show solder climb as shown in Figure 15 below. In this form of defect, there is sufficient solder to begin with, but during attach process, the solder leaves the joint area and 'climbs' into the belly of the connector. This defect is typically caused by less than ideal reflow thermal profile. Hence detection such as this one, serves as an excellent process monitor.

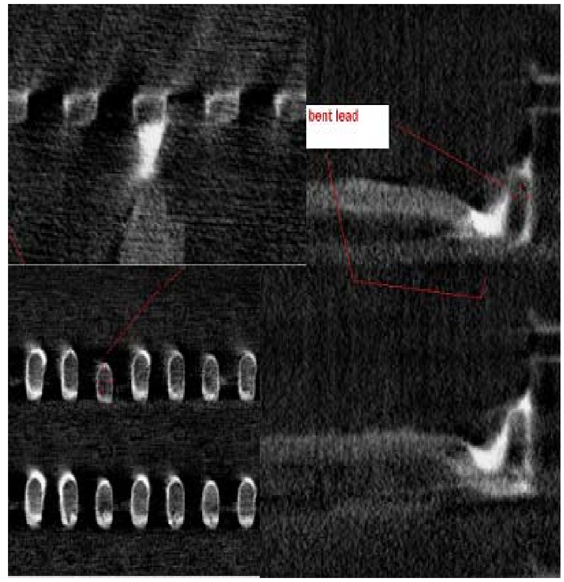

Figure 15: Solder Climb defect that has resulted in smaller footprint (bottom right), indicating that there is now less solder in the joint

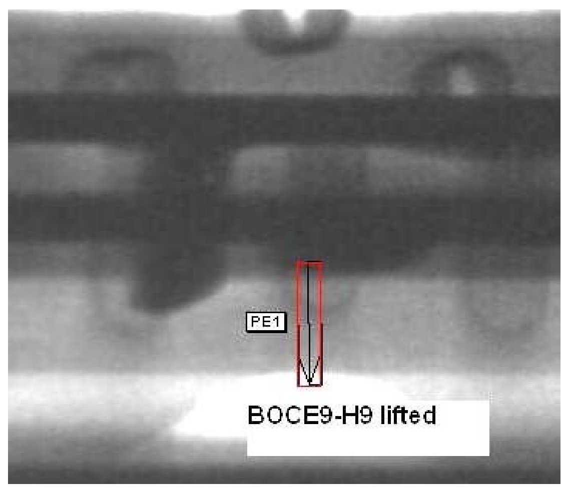

Figure 16: A bent lead detected by 2D inspection algorithm. Lead position is slightly shifted up

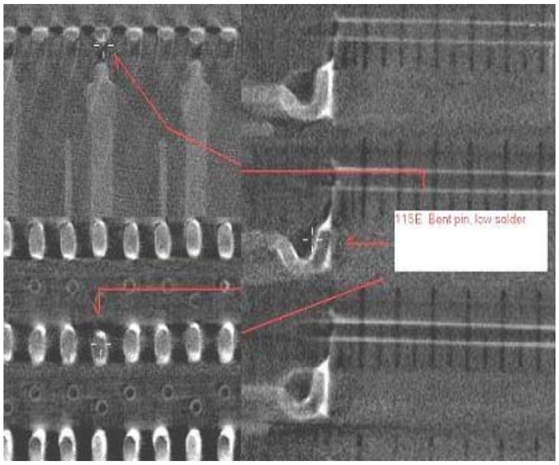

Figure 17: A bent lead defect flagged by 2D is easily validated by 3D. The center lead is bent differently

Bent lead defects are impossible to detect via normal inspection, especially if they happen to fall somewhere in the middle of the connector body. Figure 16 shows a bent lead defect as flagged by 2D inspection. The foot print of the lead in the center is slightly above that of its adjacent leads. Based on their experience, the operators flagged this defect as 'bent lead'. Figure 17 shows a corresponding image in 3D (CT scan). The lead in the center can be seen slightly raised compared to the leads adjacent to it.

It is important to note here that though 2D inspection flagged this image and 3D confirmed it, the solder joint quality was deemed acceptable per IPC standards. There is sufficient solder fillet on the heel, a good solder thickness in the joint and no indication of solder climb. This is an example of a defect that may be flagged by 2D inspection, but will be overridden by 3D inspection. In cases like this it is important to note that we have avoided an otherwise, unnecessary rework.

CUT-OFFS

Since rework of these large connectors could only be done by removing the entire connector, it is typically necessary to confirm just one true defect on the CT scan to decide if the board needs to go to rework. Further analysis with CT scan is usually not needed if all defects flagged by 2D inspection are of a particular type. This conserves time at CT scan, which typically is in high demand. We may sometimes decide to do several scans if more than one defect type is flagged by 2D inspection, or if more scans are needed to make an accurate assessment of the root cause. This methodology reduced the CT scan work load and reduced the cycle time.

As can be imagined, 2D inspection algorithm can be tweaked to make it more or less sensitive as desired. An over sensitive algorithm increases the verification time needed to review all the defects. Obviously, an algorithm cannot be made too lenient in order not to miss true defect. After several trials, we decided that about 50 defect calls per board with 1680 joints, was a reasonable level of sensitivity. Review time is typically less than ten minutes. Only a handful of boards with defect calls would typically proceed to CT. More than 90% of the boards go through 2D inspection clean. We settled on about 60% confirmation rate on CT scan. In other words, CT scan confirmed about 60% of the defects flagged by 2D inspection. The other 40% of the boards are typically deemed acceptable. This was later validated by test. We had to make sure the test did not experience high fallout. This was then determined to be a satisfactory operating point for us. This detection percentage assured us that the 2D inspection was in fact slightly over critical, which is what we intended by design.

INSPECTION CALIBRATION

A Process monitoring board was built with various forms of defects intentionally introduced. Defect locations (referenced designators) were recorded in a file. This board was run each week on both, 2D and 3D. Defects pointed to by these two inspection techniques were compared with the actual defects to make sure they were consistently the same. One product board was also run each week on CT scan, selecting specific locations on the connector which were know to have a larger population of defects. Records of this calibration are separately maintained.

CT SCAN VERSATILITY

Overall, CT scan inspection has proven to be a very versatile tool. Other than using it for 2D inspection verification, we have used it for inspecting internal circuit layers of the boards, detecting cracks in solder joints, shock and vibration test verification etc. Figures 12 through 16 show some examples of such defects.

Accidents are not uncommon in any factory environment. Damage to connector can occur during shipping, handling and plugging. It is important to determine non-destructively, if the solder integrity is still maintained. CT scan is a very useful technique for finding cracked solder joints which are typically very difficult to detect. In many instances, if there is sufficient mechanical connection between the connector and the PCB, these cracked solder joints will also pass electrical tests.

Figure 18 shows an example of a cracked solder joint from a connector that was accidently bumped.

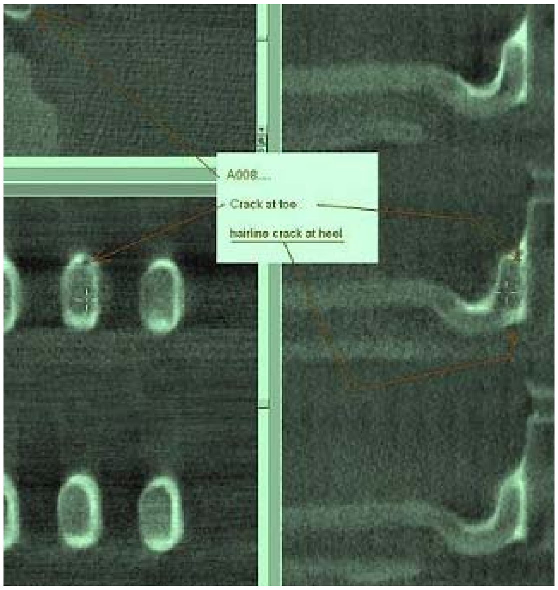

Figure 18: Connector lead in the center shows an evidence of a stress crack near the toe

It is important to note that a crack of this nature would be impossible to detect with 2D inspection, as the appearance of solder from top down view would be normal.

CONCLUSION

Over two years, we have determined that the success rate of this 2D-3D combination was better than 95%. Stated differently, more than 95% of the boards deemed good by 2D and CT scan combination pass all EOL testing. Reducing defect levels at test is very critical, since the board have a lot of value add by the time they get to test. In most instance, a lot of additional hardware is added before the boards get to test. Tester time is of prime importance. It is usually very time consuming to isolate and verify defects caught at by the tester. Also, a lot of hardware disassembly is sometimes necessary before the board can be sent to rework.

Early detection of defects has a couple of big advantages. Since x-ray inspection immediately follows SMT attach steps, x-ray feedback is almost real time, which is much more effective in correcting process glitches. It is also more cost effective to capture defects early in the assembly cycles to eliminate lost value add. A library of defects could be made available to the operators on line, which serves as a comparison template. It is also useful as a training guide.

This inspection combination has proven to be a valuable addition for enhanced product quality.