CORRELATING THE PRESENCE OF POPCORNED BGA DEVICES POST REFLOW WITH SOLDER-BALL DIAMETER MEASUREMENTS FROM X-RAY INSPECTION

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ABSTRACT
One of the recognised implications of the transition to using lead-free materials for printed wiring board (PWB) assembly is that the moisture sensitivity levels (MSL) of devices can increase by between one and three levels from their present values. In particular, this means that there is an increased danger of the most moisture sensitive devices, such as BGAs, being used outside of their safe operating envelope during the realities of the production process. As a result, popcorning, and therefore failure, of such devices becomes more likely with the concomitant effects on product reliability, throughput and end-user satisfaction.

The popcorning of BGA devices often can be quickly identified by x-ray inspection post reflow through the presence of solder bridges between connections. However, not all popcorned BGAs exhibit solder bridging to confirm this analysis and so could well be missed during x-ray inspection. In these latter cases, it is noted that the solder-ball diameters of these BGAs can vary meaningfully between the inner and outer solder-balls of a package that has popcorned and therefore this can be used to identify the fault by using suitable measurement functionality as part of the x-ray inspection.

This paper will report on the results of solder-ball diameter measurements of suspected popcorned lead-free BGAs placed on a variety of board-finishes. The correlation of the measurements to the identification of popcorning in BGAs will be discussed.

Key words: Popcorning, popcorned, BGA, lead-free, x-ray inspection, moisture sensitivity level

INTRODUCTION
The term 'popcorning' is used within the PWB assembly industry to define a failure mode associated with moisture ingress to surface mount components. Popcorning occurs when a relatively small amount of moisture (water) trapped within the component is converted into a large of quantity of gas (steam) during the reflow process, causing the package to expand like a kernel of cooked popcorn. This sudden expansion is fatal for the component as within the package, the die and the wire bonds together with the package itself, will be distorted. The resultant failure modes for popcorned devices will therefore include broken dies and broken wires (either at the die interface or within the wire length), causing an outright total failure of the device. However, popcorning can also cause intermittent failures when the product is tested. Such intermittent faults are the most difficult to diagnose as, by their very nature, they are not consistent in their effect. The likely failure mode for the intermittent faults within a popcorned device occurs when the wire bond(s) within the package separates from the die interface because of the package expansion. Following popcorning, the package returns to its normal size and the wire bond(s) return to being in contact with the die. However, there is no joint present. So as the package warms during use, natural thermal expansion can cause the wires to become separated from the die pad once again, hence causing the failure. Whether the failure is total or intermittent, the component will have to be replaced.

The most typical cause for popcorning is the hygroscopic sensitivity of the molding compound used to protect the die. Manufacturers have been aware for many years of package moisture sensitivity levels (MSLs) [1] and have procedures in place to treat components appropriately prior to their use in the process. However, with the requirement to move to using lead-free solders that have substantially higher reflow temperatures, it makes packages much more susceptible to the threat of popcorning. This is because the peak body temperature that a package will exhibit using the Pb/Sn eutectic will be around 215 – 230°C compared with around 230 – 250°C that is needed for the commonly used lead-free alloys. As a result, it is suggested that MSLs will increase between 1 and 3 levels for the same devices when used in a lead-free process [2].

MSL	Floor life at 30°C/60% RH before reflow
Level 1	Unlimited at < 30°/85% RH
Level 2	1 year
Level 2a	4 weeks
Level 3	168 hours
Level 4	72 hours
Level 5	48 hours
Level 5a	24 hours
Level 6	Bake before use, reflow within defined time

Table 1: IPC/JEDEC J-STD-020B (July 2002) Moisture sensitivity levels classification.

Table 1 indicates the MSLs as defined in the IPC/JEDEC standard. An increase of between 1 and 3 levels for components under a lead-free processing regime will therefore impact on the material handling needs during manufacture. For example, components that are currently defined as MSL 3 with a floor life of 168 hours, could become MSL 5 or 5a under lead-free processing conditions, with as little as 24 hours of floor life before having to undertake remedial moisture reducing procedures.

Whilst the transition to lead-free manufacture continues, the appropriate labelling / handling information of components for lead-free use has not always kept up at the same pace. Therefore, the potential for popcorning has been increased because although the correct moisture sensitivity handling may have been followed, as far as the package information stated, this may not, in fact, have been correct for the lead-free process.

Although the effect of popcorning is to destroy the device, identifying the failure is not necessarily easy. The failure locations are within the package and so are optically obscured. X-ray inspection, on the other hand, allows investigation of, and within, the device and its solder joints non-destructively. The presence of broken / destroyed wire bonds within the package is usually very clear with the high resolution and high magnification x-ray systems commonly available today – i.e. that use open x-ray tubes [3, 4]. X-ray systems using closed x-ray tubes will typically not have the magnification to be able to observe this detail. Cracks in the die, will be very difficult to see in any x-ray system as silicon is transparent to x-rays and the density difference in a crack will have to be seen against the various densities of the package and board. The intermittent failure modes at the wire bond / die interface will not be seen in the x-ray images because the interface is in physical contact even if the joint is no longer sound.

Instead, the most common method of identifying that popcorning has occurred is to look at the device solder joints. This is because as the package swells, great forces will be applied to the package joints. With QFP package types, for example, then the gull-wing leads may move or re-align / misalign during the liquidus phase because of the package distortion. An intermittent failure mode may also be possible for QFPs at the package / board joints because, like the internal wire bonds discussed earlier, these joints may have lifted out of the paste when in the liquidus state but after reflow still be in physical contact with the pad. So as the package warms up during use further package distortion can occur and so create an open joint. These situations may well be seen optically for a QFP. However, such situations cannot be observed optically for a BGA, where the solder balls are all hidden under the device, and so x-ray inspection becomes vital for the analysis. Optically, there may be cracks seen in the package molding and for QFPs, it is also possible for cracking to occur along the line of the lead frame. Seeing these cracks optically is not always easy, however (see image 0).

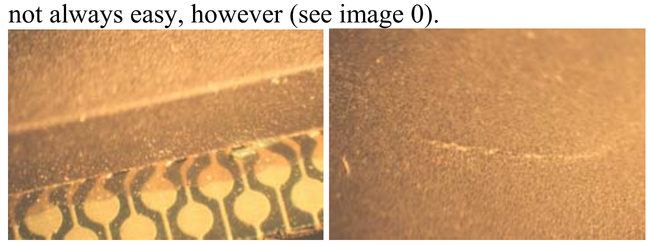

Image 0: Left image – side shot of BGA with crack between the plastic cover and the BGA substrate. Right image – crack on top surface of plastic BGA.

It should be noted that popcorning does not occur just during initial PWB assembly. Any device will be at risk of popcorning, if it has not been handled correctly, whenever it goes through a reflow cycle. Therefore, there is as much risk of popcorning happening during the re-work process as during the initial manufacture, even if the cause of the re-work was nothing to do with popcorning in the first place. This is why it is best practice to instigate x-ray inspection following all re-work, especially for BGAs, so that reflow quality is confirmed and popcorning or other potential problems are confirmed as not being present in the reworked parts before the product is sent to the customer.

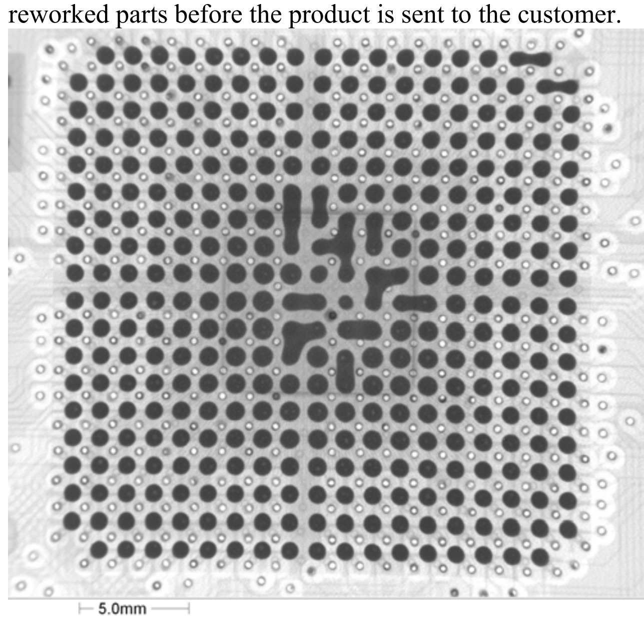

Image 1: Bridges seen in x-ray image under BGA following device popcorning.

The popcorning of BGAs is often indicated by the presence of bridging under the device. This is caused when the expansion of the package during reflow causes it to 'dish', where the underneath of the package deforms and presses down onto the solder balls underneath. As the solder is liquid at the time, it allows the solder from adjacent balls to coalesce and so produce bridges. These are very clearly seen in the x-ray image (see image1).

Whilst bridging between solder balls is a very common indicator of a popcorned BGA, it is possible that bridging does not always occur. In such cases there will still be evidence of the package deformation because the ball diameters across the BGA will not be consistent. Instead, solder balls at the centre of the package would be expected to be larger in diameter (where they have been pressed down), with the other solder ball reduced in size as the edges of the package have been lifted. Such a situation can be seen in image 2.

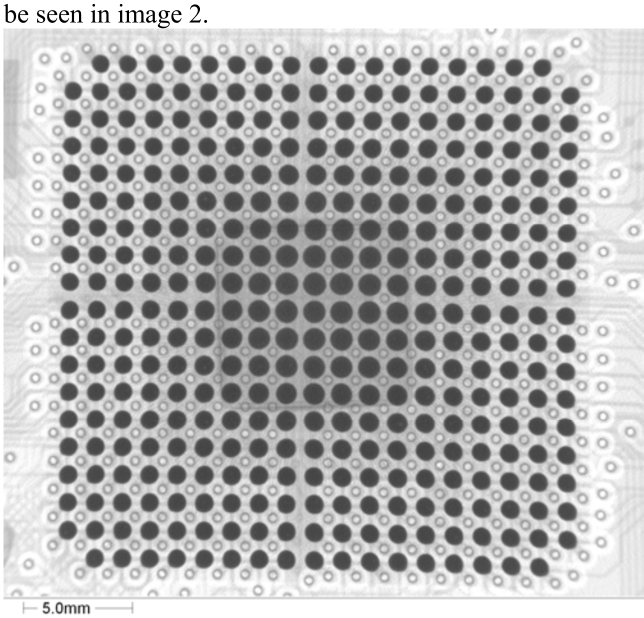

Image 2: X-ray image of a popcorned BGA, where the central solder balls are much greater in diameter than the outer solder balls but bridges have not formed.

This analysis can be confirmed through an investigation of the solder balls at oblique angle views in the x-ray system. Where there reflow is good then there is a consistency of the solder joints with a typical shape seen in image 3. In contrast, the central solder balls of image 2 when seen at an oblique angle look as shown in image 4. Although there is no bridging in image 2, the difference in solder ball diameter between the inner and outer solder balls is very clear. So this solder ball diameter variation is sufficient to flag this device for at least further investigation, or, more likely, replacement. Therefore measuring and comparing the BGA solder ball diameters offers the opportunity to identify popcorning even if the most obvious signs (bridges) are not present in the x-ray images.

The resolution and gray scale sensitivity seen in the x-ray images 1 – 4, may not be available from older x-ray systems because they do not include the recent developments made to x-ray inspection systems. These recent developments are:

- An increased use of open-style x-ray tubes for electronic applications allowing much greater magnification to be available for joint inspection compared to using closed x-ray tubes [3].
- Improved x-ray system design permitting oblique angle views of joints without compromising the available magnification - by tilting the detector and not the sample [4].

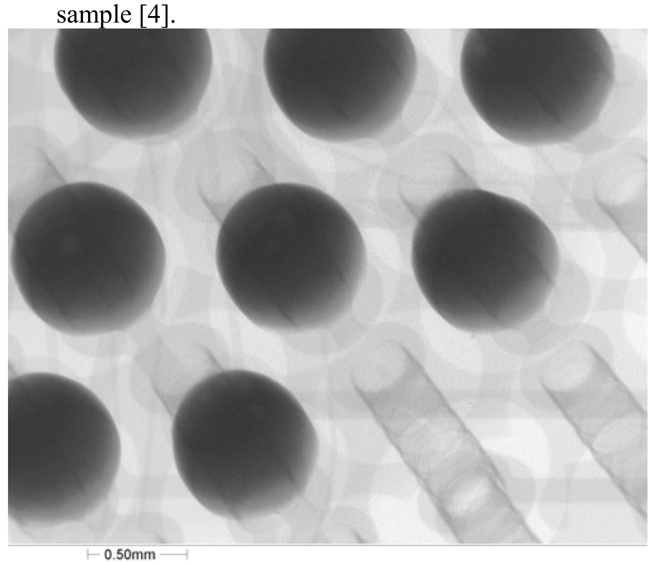

Image 3: Typical x-ray image of good reflowed solder balls under a BGA.

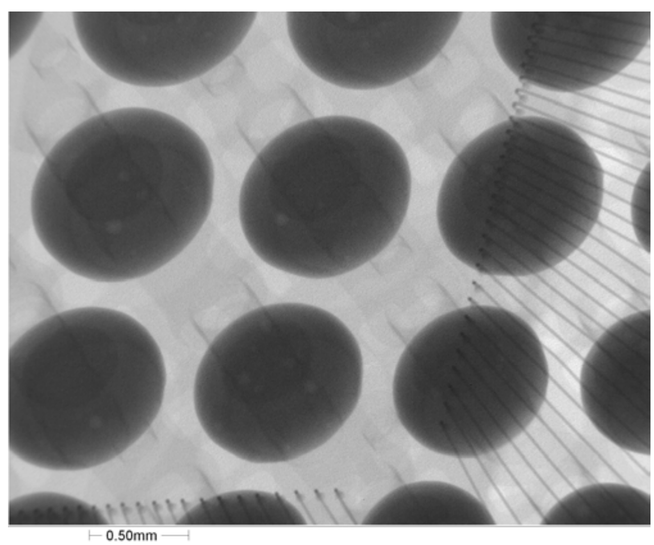

Image 4: Typical x-ray image of popcorned solder balls such as those seen under the centre of the BGA device in image 2.

- The inclusion of digital x-ray imaging detectors as standard within x-ray systems, enabling far better visual separation of similarly dense features. This can also dramatically assist fault diagnosis in areas such a non-conductive die-attach, voids in packages, micro-via inspection as well as the enhanced analysis of

BGAs by showing the joint interfaces between solder ball and the pad as well at the solder ball and the device [5, 6].

Together, these x-ray developments allow a relatively inexperienced operator to quickly assess and quantify the analysis within the production environment. With lesser x-ray inspection equipment, that lacks good magnification, resolution and contrast sensitivity, the clarity of the analysis may be more difficult to achieve. In addition, these x-ray developments enable other aspects of the quality of the lead-free process to be further investigated [6, 7].

BGA SOLDER JOINT MEASUREMENTS

During the recent Nepcon UK exhibition held in Birmingham, U.K., the 'Lead-free Experience 4' [8] was held. This workshop allowed visitors to produce their own lead-free test boards which contained a variety of components including BGAs. An x-ray navigation map of the 'Experience 4' test board can be seen in image 5.

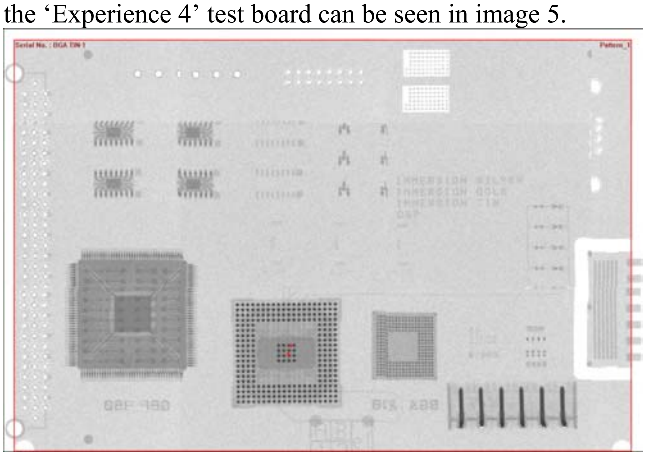

Image 5: X-ray navigation map of test board produced during 'Lead-Free Experience 4'.

Image 5 shows the layout of the connectors and other components on the board as well as being used by the x-ray system to locate the positions of any failures through a location rectangle superimposed on this map.

Boards with four different finishes were produced using the same lead-free solder. The finishes were immersion gold, immersion silver, immersion tin and OSP. Vapour phase reflow, as well as convection reflow, was used to heat the boards. Once the boards had been produced, they were analysed with a variety of inspection techniques [8], including x-ray inspection. A digital x-ray inspection system was used for this analysis. The system used had an open x-ray tube with sub-micron resolution that provided 16-bit greyscale sensitivity with an x-ray image size of 1.3 Mpixels on-screen. The x-ray images were acquired at 25 frames per second. The system was able to provide oblique angles of up to 70° at any point 360° around any position on the test board without compromising the available magnification. This is achieved through tilting the x-ray detector instead of tilting the board. Software was available on this x-ray system to provide automatic BGA measurements of ball diameter and solder ball void percentage.

To evaluate the propensity for solder ball diameter variation in popcorned BGAs post-reflow, some BGAs were deliberately exposed to moisture for a considerable period so as to exacerbate the likelihood of popcorning. This approach worked very well and, irrespective of the board finish and the reflow method used, popcorning did occur. During x-ray inspection of the finished boards, the diameter of each solder ball in the BGA was measured, together with total void percentage within each ball and the solder ball area. These measurements were taken using the standard supplied software functions of the x-ray system.

RESULTS

The success of (mal)-treating the BGAs prior to reflow resulted in all of the BGAs exhibiting some bridging under the central part of the BGA, irrespective of board finish and reflow method used. These bridges can be clearly seen in the x-ray image (see image 6) and this observation would be sufficient on its own to demand re-work and replacement of the BGA.

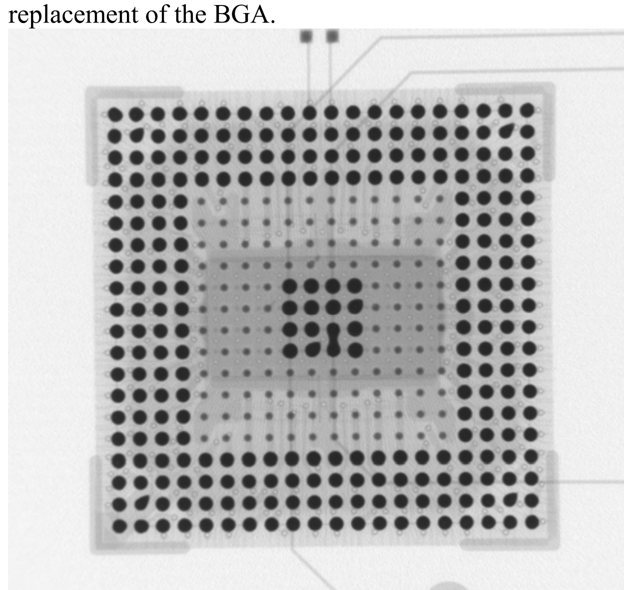

Image 6: X-ray image of BGA on gold finish board (designated Gold 7) following convection reflow. A bridge under the central part of the device is clearly seen.

Apart from the obvious bridge, variation of the solder ball diameters between the inner and outer balls is not that obvious compared to image 2. To check the ball diameters, the system software looks at the BGA under higher magnification than that shown in image 6, so that the BGA is split into a number of smaller areas. The operator can trade-off the magnification used for the analysis against the speed of throughput. In other words, using higher magnification for the analysis area within the BGA provides fewer solder balls on screen but each solder ball has a relatively high number of pixels, so enhancing measurement precision. However, many more analysis areas within the BGA must be inspected at this higher magnification. So a trade-off was made through the simple software interface to balance good precision against overall speed of inspection.

The results of the diameter measurements for each solder ball in each board analysed are shown below. The identification of each solder ball is shown in schematic in image 7. The solder ball designation could be simply defined in the software to coincide with on-board labelling, if required. Diameter measurement limits could have been set easily within the software, such that any solder ball that would measure outside of a user defined range would be indicated within the schematic diagram as a failure and therefore fail of the whole device. This feature was not used in this experiment. Instead the measured ball diameters could be easily exported into Excel spreadsheets for data manipulation and evaluation.

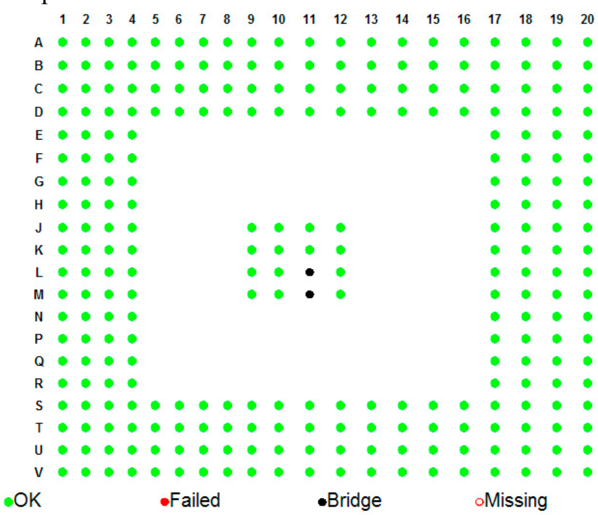

Image 7: Solder ball designation for diameter measurements under the BGA.

As all the boards provided similar results, the data below is from a selected few to illustrate the results. There are two results from immersion gold finish boards and two from immersion tin finish boards. Figure 1 shows the solder ball diameter measurements for all four boards. The data from each has been normalised to the same nominal reference diameter (840 microns) so that any diameter variation can be seen clearly and the potential for underlying natural solder ball variation between devices is removed.

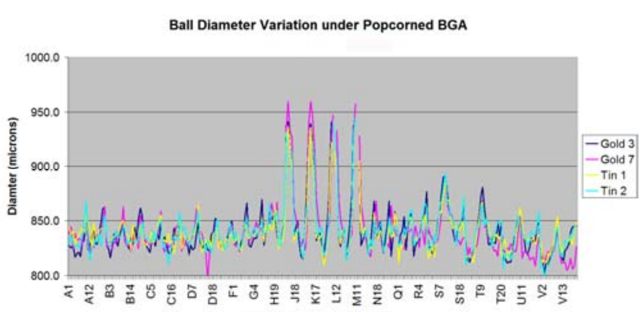

Figure 1: Normalised solder ball diameter measurements.

Figure 1 clearly shows a marked difference in the measured solder ball diameters between the central solder balls and those on the outside. This can be shown more clearly in figure 2, where the central solder ball measurements have been placed alongside, and on the same scale, as solder balls along two outside rows.

Looking at the data more closely, the average ball diameter for all of the measurements under the central area is ~ 925 µm. In contrast, the average ball diameter size in rows C and T of the device is ~ 835 µm. In other words, there is an approximate increase of around 11% in the central solder ball diameter compared to the outer balls. Such a diameter difference in percentage terms is large but, as can be seen from image 6, at low magnification this difference would not necessarily obvious to an operator. Of course, the operator would immediately see the bridge in this example. However, if the bridge was not present then the escape of a clearly faulty board could occur if BGA measurements had not been taken.

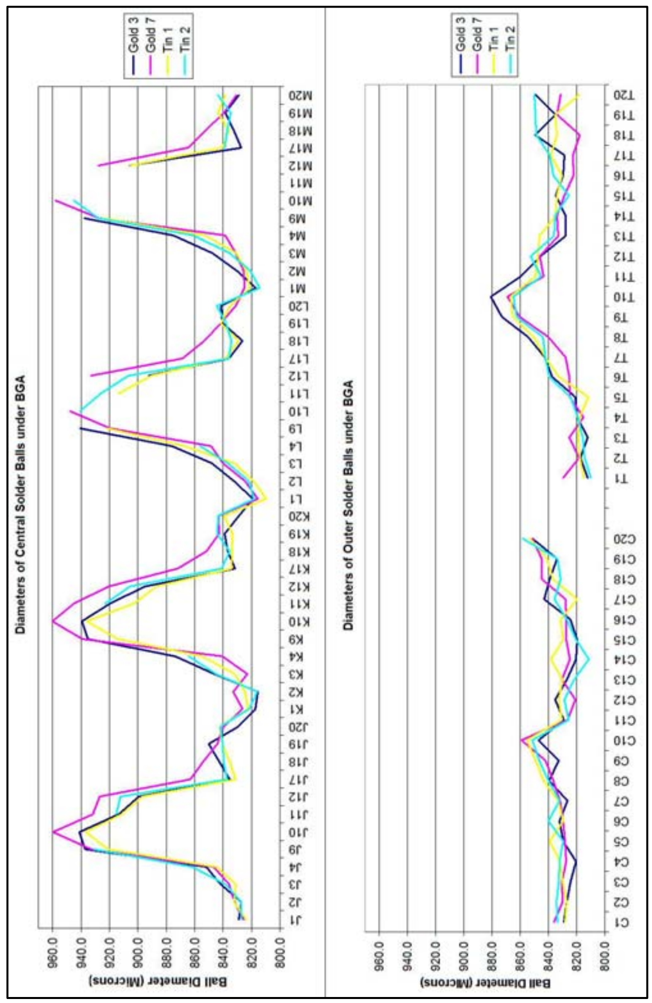

Figure 2: Central solder ball diameters compared to outer row solder ball diameters under the same scale. Gaps in the data lines are locations of bridges seen under the devices.

CONCLUSIONS

BGAs, amongst many other components, will be increasingly at risk from moisture sensitivity as the migration to using lead-free solders continues. This means there is the need to revise and implement new adequate measures within the production environment to check and prevent issues arising from this situation. Failure to do so will often result in the popcorning of devices. Popcorning may occur during initial board manufacture but is equally as likely following re-work, if the replacement components themselves have not been handled correctly.

Where the device joints are visible optically, then any failure may well be identified through optical inspection, such as through the observation of cracks in the packaging. However, where the joints are optically hidden then x-ray inspection offers a non-destructive method for seeing potential faults and confirming manufacturing quality. For example, bridging is often seen under the BGAs when popcorning has occurred. But this easy identifier need not always be present in a popcorned device. Additionally, intermittent failures caused by die and / or wire bond damage within the popcorned package may also not be able to be seen even with x-ray inspection. Instead, automatic BGA solder ball diameter measurements by the x-ray inspection system can be used to quickly identify variation under the component, show that popcorning has occurred and therefore indicate that rework needs to be undertaken. In this way variation in BGA solder ball diameter measurements do correlate with the presence of popcorned devices.

It is suggested that a variation of more than 7% in the solder ball diameter compared to the average would strongly indicate that a problem may exist. This method will be more reliable than just looking to try and see delamination or die cracks manually within an x-ray image because of the lack of available density variation in the image owing to the additional densities present of board material and packaging. This approach also means that there is no need to consider immersing the board into water for scanning acoustic microscopic analysis, for example.

Automatic BGA solder ball measurements should be taken periodically during manufacture so that a database of measurements can be built up for particular products. In this way, any subsequent change / variation in the trend of the ball diameters can be seen more easily and so quickly highlight potential process failures. In order that this data is available, x-ray inspection needs to be implemented into the test regime, not just for initial production but also following rework.

REFERENCES

[1] IPC/JEDEC Standard J-STD-020B (2002).

[2] See, for example, knowledge center information at www.cogiscan.com.

[3] Bernard D., "X-ray tube selection criteria for BGA / CSP X-ray inspection", Proceedings of SMTA International, Chicago, September 2002

[4] Bernard D., "Selection Criteria for X-ray Inspection Systems for BGA and CSP Solder Joint Analysis", Proceedings of Nepcon Shanghai, 2003

[5] Bernard, D. and Ainsworth, S., "Comparing Digital and Analogue X-ray Inspection for BGA, Flip Chip and CSP Analysis", Proceedings of APEX, Anaheim, CA, 2004.

[6] Bernard, D., Hoo, N. and Lodge, D., "Use of digital x-ray imaging as a process control tool for lead-free PWB assembly", Proceedings of SMTA International, Chicago, 2004

[7] Bernard, D and Bryant K., "Does PCB pad finish affect voiding levels in lead-free assembly", Proceedings of SMTA International, Chicago, 2004

[8] Results from Hands-on Lead-free Experience held at Nepcon UK, Birmingham, England May 2006. See www.smartgroup.org for more details.