As originally published in the 2009 SMTA International Conference Proceedings.

THE CHALLENGES OF PACKAGE ON PACKAGE (POP) DEVICES DURING ASSEMBLY AND INSPECTION

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ABSTRACT
Ball Grid Array devices, BGAs, are widely used in a vast range of products including consumer, telecommunications and office based systems. As an area array device of solder joints, it provides high packing density with a relatively easy introduction cycle. However, over the last couple of years engineers have started to experiment, and in some cases implement, stacked packages, of the type often called Package on Package, or POP. In simple terms, POP devices are the stacking of components, one on top of the other, either during the original component manufacture or during printed board assembly. Such packages, allow substantially enhanced functionality but within the same footprint of a single BGA. POP packaging may include direct soldering, wire bonding or conductive adhesives for device to device interconnection.

The main industry problems associated with POP technology are open joints, warping of the two levels of component substrate and, of course, issues with the underlying printed circuit board (PCB). Reworking these stacked components, or just the top mounted part, can be challenging and when you inspect them using 2-D x-ray inspection the data can become difficult to interpret because of the multiple levels of ball interconnection and wire-bonding that may occur within the package.

This paper will outline the process associated with soldering stacked packages using dip flux and dip solder paste that are specifically designed to overcome the incidence of package warp. Based on the process issues involved, inspection results will be presented to better illustrate the challenges in implementing POP, or stacked packages, into production.

Key words: Package on Package, POP, components, x-ray inspection, defect, optical inspection, assembly.

INTRODUCTION
Ball Grid Array (BGA) and Chip Scale Packages (CSP) have become ever more widely used in a vast range of electronic products. Their area array of interconnections provides high packing density, yet is relatively easy to implement into production using existing assembly equipment. Developing from this, in recent years there have been experiments and, in some cases, implementation of stacking of these packages into what are often called Package on Package, or POP, devices. For example, cell phone manufacturers have been using a POP device with two stacked levels that contains a total of four silicon die.

As a simple definition, a POP device represents the stacking of area array components, one on top of the other, either during the original components' manufacture, or during printed circuit board assembly. For example, rather than placing a logic device with one, or more, memory devices adjacent to each other on the board, stacking these items takes up less surface real estate but does so with some increase in height. However, advanced package and silicon design now allow the building blocks of the POP to be thinner using wafer thinning and flip chip interconnection. In addition, should the POP combination be created during PCB assembly then it offers additional flexibility as to the functional capability of the same product. For example, it allows the board assembler to be able to add different sizes of memory module to the same logic device at the point of manufacture. JEDEC standard outlines exist [1] for both lower (attachment to the board) and upper package levels of a POP with both 12 x 12mm and 14 x 14mm becoming popular sizes in the industry, all be it with smaller footprint devices becoming available through demand by system designers.

Individual POP devices may include direct soldering, wire bonding or conductive adhesives for device layer to device layer interconnection. Generally, the logic device is on the bottom of any stack, as there are more connections out of that package than from the memory devices. As stated previously, the OEM, or contract assembler, can take the two, or more, device layers and form the POP interconnections, as well as the board interconnections, during assembly or the POP elements can be already combined by the original manufacturer as an individual package for direct placement, as if it were a BGA.

Industry suppliers have highlighted the advantages of POP to be:

- Faster product time to market
- More flexibility in device selection
- Higher density but with equal PCB layout complexity

When considering implementing POP devices into new product designs the following aspects should be understood:

- The package body's final height
- The solder ball size(s) throughout the device
- The pad termination size(s) throughout the device
- The whole POP constructions potential for warping during assembly

All of these points need to be considered as they will impact the device layer to device layer stand-off height and the possibility of opens during reflow.

'Home-Made' POP Devices

During the pre-planning stage of a special conference/show feature, we illustrated stacked package assembly. To save costs, this was accomplished using a 'home-made' POP package (see picture 1). In addition, we considered the implications for the rework process required for such devices. This allowed us to see, first hand, the main industry problems associated with this technology. These were:

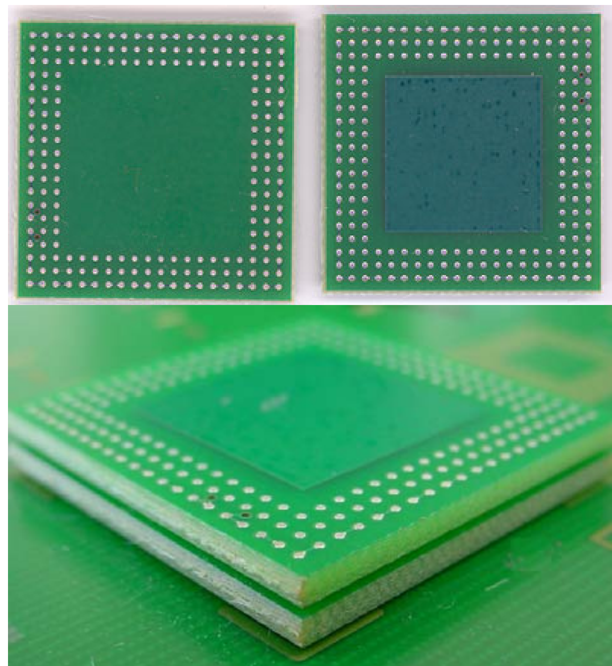
- Open joints
- Warping of the substrates
- The whole issue of having to rework some or all of the elements within the POP

Through modified design rules we hoped to investigate warping and open joints created during the assembly process, using daisy-chain circuits on the printed board and within the stacked packages. Although the layers of the home made POP package has thick laminate, which are not representative of the commercial parts used in manufacture, they do exaggerate some of the typical process issue problems seen during testing.

Producing the assembly for the experiments took the following sequence:

1. Print the circuit board with solder paste.
2. Place all components, including the bottom POP package level into the surface of the solder paste.
3. Place second, or third, level POP packages onto the bottom level package layer after being dipped into a layer of flux or solder paste.
4. Reflow solder the board assembly.

This approach does assume that any POP packages would be on a side-two build and not on both sides of the board design.



Picture 1: Optical images of the individual elements and a 'manufactured' example of a 'home-made' POP device. These home-made packages were made using the DEK balling process with solder spheres and tack flux provided by Indium Corp.

Solder Paste Printing

The solder paste printing process for the bottom (board) mounted layer is defined by the termination dimensions, pad size and the device pitch, like any other parts on a surface mount board assembly. Currently, fine pitch stencil printing is normally between 0.005" – 0.004", or a combination of both, in a step stencil design using a laser cut or electro-formed foil. Most companies these days have migrated to type 4 particle paste, as the price has decreased, but many fine pitch applications can be still be conducted with type 3 – it all depends on the definition of fine pitch!

For bottom layer POP packages there is no specific difference for printing than on any other fine pitch application. What is necessary is good control and repeatability of the printing process with 100% paste transfer; simply the same that is required for existing BGA assembly. These requirements would today normally be confirmed by paste inspection via the printer or the use of a separate AOI system with three dimensional solder volume measurement.

Placement and Second Level Package Dipping

All the major suppliers of placement systems will be able to place the first package on the board, as it is no different than a standard BGA build. Placement of a complete POP package/module should also be the same. However, if the POP is to be configured and built by the board assembler, the critical control/handling of the upper level packages will need to be reviewed. Within the placement machine, accurate control of the Z dimension will be critical along

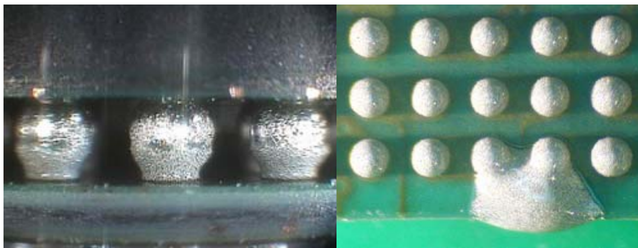
with any issues regarding board vibration/shock during transportation. However, all high end placement systems should be able to handle the requirements.

Where there may be some issues regarding placement systems is with the integration of a dipping module, for either flux or paste, to coat the upper level packages. Whilst some suppliers have experience of flip chip assembly with automatic application stations, not all may offer this choice. Redesign, or development, of a paste dip station with minimum feeder footprint has been a challenge to some suppliers.

Final inspection of the device balls after dipping and prior to placement has also been a challenge due to the colour of existing flux materials. In the case of flip chip, or now POP packages, there was little contrast change visible after flux application to the solder balls. This forced suppliers to change the colour of the materials to aid optical inspection. The material colouring agents used so far have been white, blue and red. However not all placement camera systems work well with the same colour. The colouring agents used in the flux is also prone to some separation.

Solder Paste Dipping

Solder paste dipping has become a more popular process to overcome the variations that occur between the ball mounting positions on the different levels of the POP device (see picture 2). Using paste has been found to be a far more forgiving process than using flux and easier to inspect on the surface of the terminations before placement. The term ‘Dip Paste’ has been coined to describe a paste with the special qualities that satisfy the needs for this application. The dip paste is applied directly onto the balls of the device on the placement platform. Typically, there are two methods of doing this and the method chosen depends on the placement supplier. The methods used are either a rotary applicator, which were developed for applying liquid flux, or flat tables with a printing blade to provide a defined surface and thickness of dip paste for each placement.



Picture 2: Left image shows satisfactory application of paste on the balls. Right image shows what happens if the paste is not evenly distributed on the paste plate, or if the component moves during separation from the paste, leading to the presence of excess paste.

The depth of the paste in the applicator must be controlled, as must the depth of insertion of the device into the paste. Trials have shown that if the solder balls are pressed into the paste by more than 50% of their height then the solder paste tends to wrap around the ball terminations, which increases the amount of paste pick up. This can then lead to excessive paste deposits, which, in turn, leads to the increasing possibility of solder shorts.

Placement Considerations for POP Devices

Care needs to be taken during reflow to make sure that there is minimal evidence of vibration in the conveyor system. Stacked packages, by virtue of their multi-layer structure, have more opportunities to suffer from misplacement. Such checks should be part of any regular process maintenance routine. It should also be noted that random vibration may occur at higher convection rates and chain stretch in the reflow oven may also occur.

As a minimum, placement inspection systems should be able to detect missing paste or flux on balls. It is common for all placement systems to detect missing balls but, in reality, this rarely occurs these days. The placement system should also be able to detect paste shorts between balls. Excess paste between solder balls may occur through; excess paste being applied from the application plate; incorrect insertion depth of the solder balls into the paste or changes in paste viscosity. There may also be changes in the properties of the dip paste due to the local environment, excessive working in the applicator and its time of exposure to air.

Close examination of the paste surface after dipping is important to see the changes in paste deformation. Ideally, like a liquid flux, any deformation in the surface of the paste recovers and the spreading/levelling blade is maintaining the height of the material rather than filling in the displacement voids. The depth of paste is controlled by a metering blade which sweeps across the paste surface, based on machine programming. The actual depth of the material can be checked with a simple comb depth-gauge where the individual comb teeth are at different heights.

When using dip paste on a placement system, the total tack force on the package must also be considered. As the number of balls contacting the paste surface increases, so the force holding the package to the surface of the paste will increase. Therefore, the vacuum force, or the size of the pick up tool area, may need to change to avoid poor, or incomplete, pick up. Any lateral movement of a POP layer from the surface of the paste will increase the potential for wet paste shorts between terminations prior to placement. Paste between a few solder balls may clear when reflowed with the solder wetting back to adjacent terminations but it is more likely to form shorts.

Tacky Flux Dipping

The initial use of flux-only dipping (see picture 3) was probably due to the industry’s experience gained with flip chip placement. With silicon-only construction there was little package warpage during reflow – only the board could warp – and with such a small surface area it would not

result in opens. However, with POP packages you have a minimum of two surfaces (board to base layer, base layer to upper layer, etc.) and each could potentially warp relative to each other. Increasing the depth of immersion in a flux bath will not lead to shorts but is likely to increase the amount of residues around the joints. This may be an issue if the packages are to be subsequently underfilled.

Picture 3: Left image shows an example of a satisfactory dipping process prior to placement using a material coloured blue to aid automatic optical inspection. Right image shows how the solder balls look with, and without, flux coating. This difference may have been caused by variations in the placement height, the flux height or co-planarity issues within the package.

Whichever method of POP assembly is chosen, using flux or paste, it is necessary to establish how much flux or paste is required for a successful assembly process through making process trials. In this way, the various issues mentioned above can be tested and optimised for individual applications. However, some aspects may be difficult to assess. For example, it is extremely difficult to determine the amount of liquid flux on the solder balls, yet the amount of paste on the solder balls can be assessed by the weight gain on the package after dipping.

Reflow Soldering

Generally, the small thin POP devices are less demanding from a reflow perspective when considering delta T, the difference in temperature between the device and on the surface of the board. Convection reflow and vapour phase reflow can both work successfully in a lead-free process. However, as with all best practice on SMT assembly, good temperature profiling should be performed as part of the process development to confirm the optimum reflow profile. It should also be remembered that as most of the POP devices are in plastic packages then correct moisture prevention procedures must be retained so as to prevent the potential for popcorning.

Optical Inspection of POP Devices

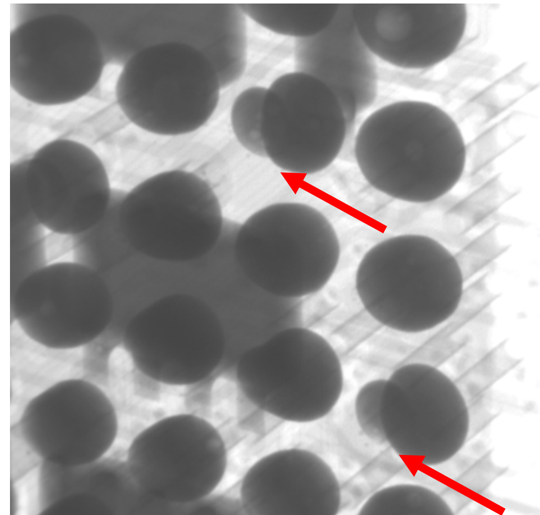
The same fundamentals apply for both optical and x-ray inspection of POP devices as with standard BGA terminations. Start inspection at one corner and move around a minimum of two sides of the package. In most cases this is simple, if time consuming, to do. It cannot practically be conducted on every device on every board in production, and so therefore should be undertaken on a sample basis. It is recommended [2] that the first few boards of a manufacturing batch are inspected initially and subsequently one board every 20 or 50 built (or whatever, to suit the particular application). With POP devices, there will be the need to assess the additional layers optically but this will require there to be adequate clearance available for the view. This is less likely to be available on cell phone applications owing to the closeness of components on such small real estate.

A major issue with POP assembly is the potential for warping and therefore measurement of the stand-off height on the corners and the centre edge of components could be considered to watch for such issues. This type of laser measurement feature is available on some AOI systems.

X-ray Inspection of POP Devices

2D x-ray inspection of POP devices allows non-destructive examination of the quality of the solder joints within the POP device. Inspection should start at one corner and, ideally as for BGAs, move around the whole of the device [3]. Any great variations in solder ball diameter, when measured between solder balls on the same layer, could indicate that there are problems post reflow. For example, the solder balls may be larger in diameter at the centre of the device compared to those at the edges. In this case, it might indicate that popcorning of the package has occurred [4]. Bridges and missing balls will also be clearly visible.

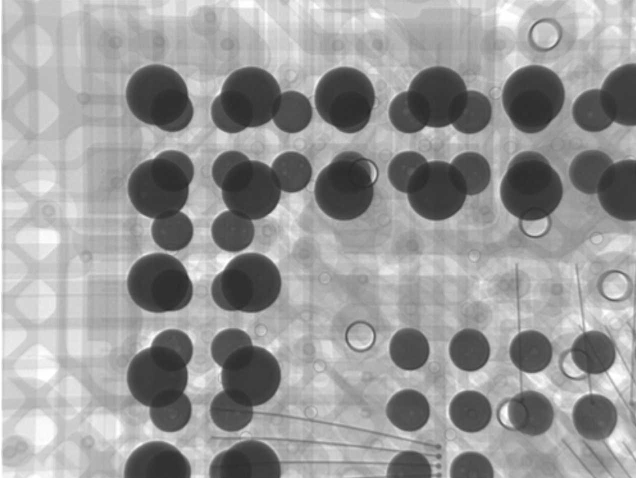
Additional x-ray inspection should be undertaken at oblique angle views, as any variation in solder joint reflow or joint shape will be more obvious when seen in this way. For example, Head in Pillow (HIP), or open, solder joints (see picture 4) are more visible at oblique angle views, as are the joint interfaces between the board, the device and upper POP layers.



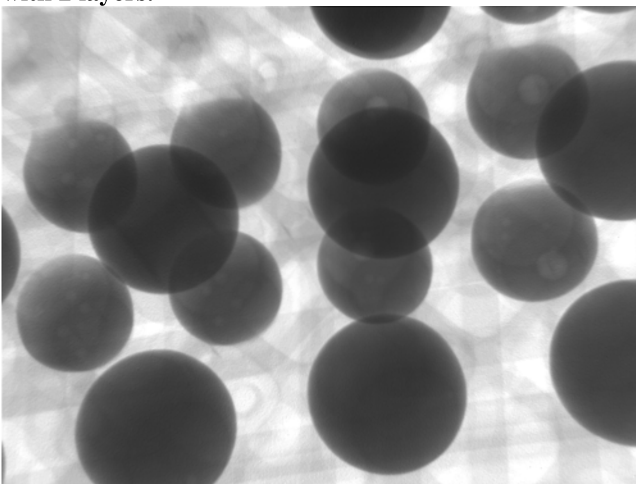
Picture 4: Oblique view x-ray image showing Head in Pillow (HIP) failure

X-ray inspection of POP devices differs from that of standard BGAs because all of the device layers are seen at the same time in the same image. Therefore, looking just from the top down, for example, could mean that lower POP layers are obscured by upper layers, should the layout

of the joints occur in this fashion. Using oblique angle views to separate the various layers will prove beneficial for analysis but there may be a limited angle that can be achieved before there is co-incidence with another row of solder balls in the device. This limit to the available oblique angle view may still occur even if the various layers are staggered with respect to each other (see pictures 5 & 6).



Picture 5: Top down x-ray image view of POP device with 2 layers.



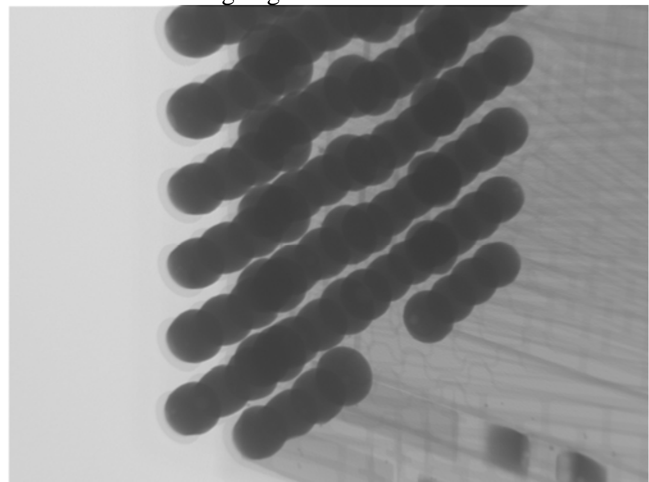
Picture 6: Oblique angle view x-ray image of a section of the POP shown in picture 2.

When analysing POP device x-ray images it must be remembered that there will be an effect from the geometric magnification of the x-ray system. This means that objects placed closer to the x-ray tube within the inspection system will appear at greater magnification in the resultant images, compared to objects that are further away from the tube. Therefore, if the solder balls used in the POP device are of the same size throughout, then the layer(s) that are placed further away from the x-ray tube will be seen as smaller than the closer layer. This may well assist in analysis in identifying at which level a fault is occurring. However, it is not uncommon in commercial POP devices to have different solder ball diameters at the board interface compared to the upper layers. In this case, should the smaller solder balls be closer to the tube than the larger ones then the whole device may appear to have solder balls all of similar size. So, with consideration of the package being inspected, measurement of the relative ball size in each plane can help to show that consistent solder reflow has taken place. Variation in measurements of solder balls in the same layer of the POP can indicate the presence of warping between the layers. Repeating this type of inspection on different layers is also possible but time consuming.

Laminographic x-ray systems, as opposed to 2D systems, could, in theory, differentiate between the various layers of the POP device by removing from the field of view all except the layer of interest. However, the vertical resolution of these laminographic systems may be insufficient to separate the various layers in a POP device. Furthermore, the method of production of these laminographic image layers may result in poor image quality that can compromise the analytical information that is available. Using such an approach needs to be evaluated and validated prior to use in production.

As will be investigated further by the results of this paper, it may be possible to make measurements of ball sizes at different levels from the 2D x-ray images and from this identify, or at least have a perception for, the stand-off height of the package, which if different at the corners and centre of the package could indicate possible warping of the different layers within the device.

As another example, a stack of memory devices may feature all the balls with the same pitch on each layer. This causes the x-ray image to have joints between the separate layers appearing in groups like pillars, or sausages (see picture 7). With a logic device and a memory package on different pitches, the ball termination points are separated but not at all viewing angles.



Picture 7: Oblique angle x-ray image of a four-layer POP device with bump interconnections.

Rework and Repair

Rework and repair of POP devices can be challenging but it depends what is being reworked. If the removal and

replacement of a POP is required, where the whole device has two, or more, area array levels and with no underfill between the layers, the challenge is to consider which layer are you applying heat to you and therefore which one are you reflowing? Is it the correct layer? For example, during rework using top and bottom heating, the initial reflow of the balls would occur at different layers, but also at different balls on different layers. The reflow spread would be caused by the different thermal demands and different heat paths to each interconnection.

Package suppliers may have tin/silver/copper balls on one package reflowing between 217 – 221°C and another with tin/copper/nickel reflowing at 227°C. Controlling the heat input to the package to reflow the top layer but not the bottom is challenging, even if topside heat only is used. Suppliers have introduced clamping systems to help lift the top package or the complete module.

If the individual layers are bonded/underfilled when supplied, the removal and replacement is much like conventional area array reflow. However it is still possible to reflow the device and leave open interconnections, or shorts, between layers if there are voids in the underfill material. Therefore, investigation by x-ray inspection post rework is vital to confirm good connections.

POP Assembly and Soldering Process Defects

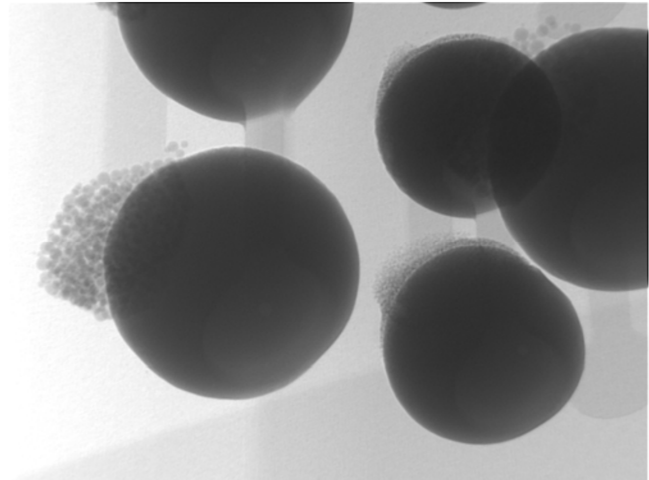
There are many possible specific defects that can occur in POP assembly and these may include:

- Open solder connections
- Solder balling
- Package warpage
- Excess paste
- Paste shorts
- Excess flux
- BGA voiding
- Package cracking
- Solder mask damage
- Mask misalignment

A set of wall charts will soon be released highlighting inspection and quality control issues for each stage in the POP process [5]. They will be released to coincide with the introduction of an interactive CD-ROM on Package on Package Assembly and Inspection [5].

Solder Ball X-ray Measurements in POP Devices

X-ray inspection will clearly see any shorts and missing balls, subject to a consideration of any overlap in the field of view between different POP layers. However, using x-rays systems that offer oblique angle views, especially those that do not compromise the magnification when viewing at oblique angles, will allow the different layers to be separated in the field of view to allow better analysis of individual layers (see picture 8). Picture 8, taken on a Dage x-ray inspection system, not only shows the effect in the image of geometric magnification on solder balls of the same size at two different levels in the POP device - they appear as different sizes - but also how the interfaces between the different layers appear – seen as feint ellipses 'embedded' into the solder ball. However, this image also shows that, for this example, too great an oblique angle view cannot be used as the solder balls will start to coincide with the next layer along. As this image was taken before reflow of the device, it also shows the difference in the solder particle size used for standard solder paste and dip paste.



Picture 8: Shows an oblique angle view x-ray image of a 'home-made' POP with two layers before reflow. The solder balls are of the same size but the effect of geometric magnification at the two POP levels causes the balls to appear as different sizes. This image also shows the larger sized solder paste particles in the unreflowed solder paste at the board layer compared to the much smaller solder paste particles in the dip paste that was used to attach the upper POP layer.

The reason that the solder balls in picture 8 are seen as if at different sizes can be understood by considering a schematic of the home-made POP device, see figure 1. The solder balls were 0.75 mm in diameter and the intervening PCB layer were 1.2 mm thick.

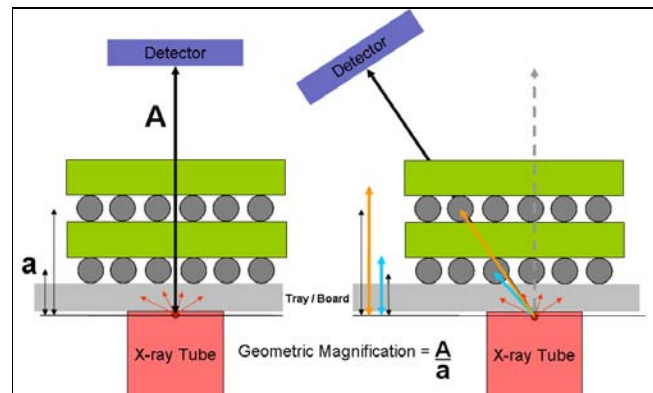


Figure 1: Schematic of home-made POP device and the effect of geometric magnification in x-ray inspection.

The geometric magnification seen in an x-ray inspection system is the ratio of the distance (x-ray tube focal spot to detector, or '**A'** in the diagram) divided by the distance (x-ray tube focal spot to sample, or '**a'** in the diagram) [6]. So if the distance '**A**' is kept at constant value, whether the view is from the top down or at an angled view, then any increase in the distance '**a**', will reduce the magnification in the image. With such a large relative distance between the POP layers in the home-made device, it makes the difference in magnification at the two levels obvious. At an oblique view, the relative magnification difference between the two layers remains the same but the magnitude of their values is reduced compared to the top down view because of the longer path length that the x-rays must traverse. I.e. there is an increase in '**a**' which lowers the overall magnification at both package levels.

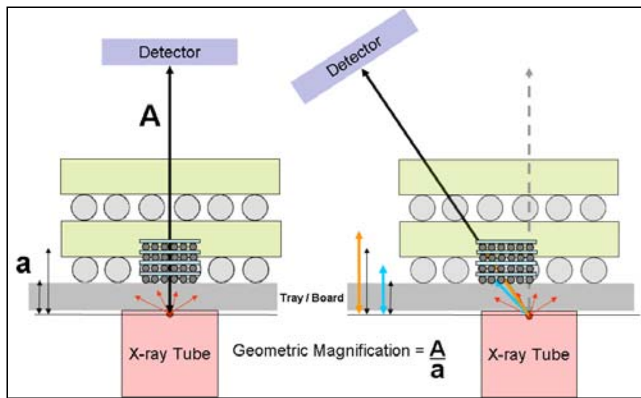
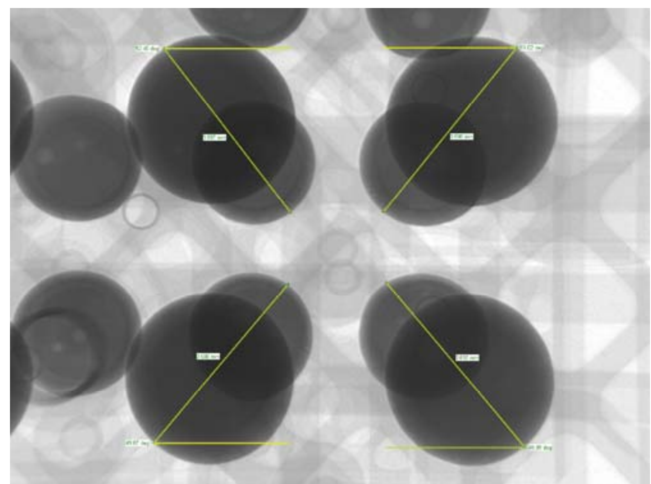


Figure 2: Schematic of geometric magnification for a four-layer POP device with thinned silicon layers and 200 micron diameter solder bump interconnections.

Figure 2 shows the effect of geometric magnification with a more typical POP device. In this case, a device, such as that shown in picture 7, with four silicon layers each of 50 micron thickness and solder bump interconnections of 200 micron diameter. As the various layers are much closer together compared to figure 1, then the variation in magnification between the bottom and top layers is much less. This means that the four layers of solder bumps all look to be of similar size in picture 7. This consistency effect is further helped if the tray and / or board upon which the device sits is thicker then that shown in figure2. This is because the relative difference between the top and bottom layers of the device becomes less significant with such a thin package as the board / tray size increases.

With X-ray inspection being the most commonly available non-destructive technique that is able to see through all layers of the POP device and probe its various interconnections, is it possible to make measurements using x-ray images that will help identify additional faults caused during production? In particular, can simple measurements be taken that will identify warping within the device?

Before making any measurements with x-ray images, it should be remembered that, ideally, such measurements should be made when the sample is perpendicular to the x-ray tube to detector axis (i.e. in a top down view) instead of at an angle view. This is because the x-ray tube is a point source of radiation and therefore is affected by gun-barrel distortion when seen by the detector. In other words, the further away from the center of the detector you go then the more gun barrel distortion will occur and this will be more noticeable for taller objects. This can be accounted for by making the measurements consistently in terms of the magnification and field of view used. However, if you make the measurements at an oblique angle view then small changes in angle can have a greater effect on the precision of the measurements, especially as the measurements move away from the centre of the image. Overall, it is better to make measurements from the top down view and to treat all of these measurements as relative and not absolute in value as a method of investigating any warpage within the device.



Picture 9: Measurements made on the x-ray image of one corner of a two–layer POP device

Position	Measurements				Average	Std. Dev.
Corner 1	0.597	0.694	0.584	0.585	0.615	0.053
Corner 2	0.600	0.618	0.593	0.601	0.603	0.011
Corner 3	0.587	0.598	0.588	0.610	0.596	0.011
Corner 4	0.596	0.597		0.591	0.595	0.003
Average	0.615	0.603	0.596	0.595	0.602	0.009

Table 1: Measurements of the distances shown in picture 8 for the four corners of a particular device.

In this experiment, and in view of the comments above, we ensured that the same magnification and top-down field of view were used throughout. The measurements taken were as shown in picture 9. Using the on-screen measurement functions of the Dage x-ray system, distance measurements were taken of a line running along the longest axis of the feature formed by the overlap of an upper and lower layer solder ball. This was repeated for 4 locations in each corner of the device. High magnification images were used so there would be a good number of pixels in the distance to be measured. The 4 measurements made at each corner of

the device were then averaged and compared to the values at the other corners. For the particular device used in picture 9, one corner only provided three measurements because the interconnection layout did not have a board connection at that position.

An example of the data taken is shown in table 1. In this example, no measurements were taken at the centre of the device. By looking at the average measurements and comparing the four corners to each other it is hoped that this will identify, in a clear and simple manner the presence of any warpage within the device. It may also allow the identification of a 'distortion' level value that could be used as a future pass or fail criteria for automated inspection of these devices. For example, the results in table 1 indicate that the standard deviation of the average data for the measurements made at the four corners of the device is ~ 1.5%. Therefore, if this value exceeded 5%, for example then this might indicate unacceptable warpage within the POP device. More results will be presented during the conference as well as some corroborative optical measurements.

CONCLUSIONS

Making measurements during the x-ray inspection of POP devices may not only provide a method to quickly confirm the quality of the solder joints within the various package layers but also highlight if there is any warpage that might affect devices where variation in stand-off height can affect performance. A trade off may need to be made in making many measurements over the whole sample against the speed of measurement throughput. Taking additional measurements at the centre of the device, as well as at the corner, may also be beneficial.

REFERENCES

[1] JEDEC 95, Design Guide 4.22, Issue B, 2007

[2] "Practical methods of optical and x-ray inspection of solder joints", previously presented at a seminar at SMTAI 2008, Florida, available from www.ASKbobwillis.com

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

[4] Bernard D. and Willis B., "Correlating the Presence of Popcorned BGA Devices Post Reflow with Solder-Ball Diameter Measurements from X-ray Inspection", Proceedings of SMTA International, Chicago, September 2005

[5] "POP Assembly, Inspection and Defect Guide Wall Charts" and "POP Assembly, Inspection and Rework Interactive CD-ROM" by Bob Willis, ASKbobwillis.com, are available from the SMTA and IPC. See www.smta.org and www.ipc.org

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