Head-on-Pillow Defect Detection – X-ray Inspection Limitations

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Abstract

Both the number and the variants of Ball Grid Array packages (BGAs) are tending to increase on network Printed Board Assemblies (PBAs)with sizes ranging from a few mm die size Wafer Level Packages (WLPs) with low ball count up to large multi-die System-in-Package (SiP) BGAs with 60-70 mm side lengths and thousands of I/Os.

One big challenge, especially for large BGAs, SiPs and for thin fine-pitch BGA assemblies, is the dynamic warpage during the reflow soldering process. This warpage could lead to solder balls losing contact with the solder paste and its flux during parts of the soldering process and this may result in solder joints with irregular shapes, indicating poor or no coalescence between the added solder and the BGA balls. This defect is called Head-on-Pillow (HoP) and is a failure type that is difficult to determine.

In this study, x-ray inspection was used as a first step to find deliberately induced HoP defects, followed by pry-off of the BGAs to verify HoP defects and fault detection correlation between the two methods. The result clearly shows that many of the solder joints classified as HoP defects in the x-ray analysis have no evidence at all of HoP after pry-off. This illustrates the difficulty of determining where to draw the line between pass and fail for HoP defects when using x-ray inspection.

An x-ray image from this HoP study is given in Figure 1.

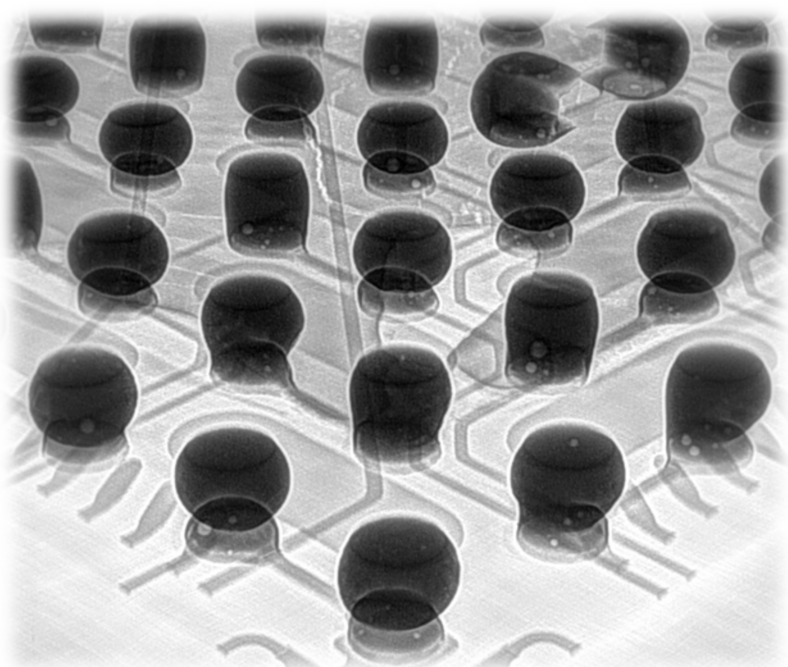

Figure 1 – X-ray image from HoP defect analysis[1].

This investigation aimed at understanding how secure x-ray analysis could be for HoP defect detections.

I. Introduction

This paper has its roots in a solder paste qualification test that aimed at finding a low, or zero, halide classified solder paste that could replace a higher halide content one. When using a "weaker" flux in a solder paste, there is a risk that the wetting towards PCB solder lands, leads and terminations will be negatively affected. Many different wetting tests were therefore performed. One of these wetting evaluations was a HoP defect test that followed a method first presented by March et al [1].

[1]Visible cracks in x-ray image originates from the die attach material.

When analyzing the solder joints in this HoP defect test, remarkable differences between x-ray inspection and prying-off the components were found that clearly show how difficult it is to determine this failure type.

II. Methodology

A HoP defect evaluation method [1] was chosen, in which two chip components are to be placed a few pad rows into the pad site of a test BGA after solder paste had been screen printed, see Figure 2.

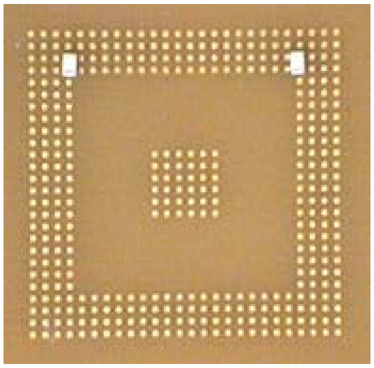

Figure 2 – Example of chip components placed on a solder paste screen printed BGA pad site[2].

After the placement of the two chip components, a BGA shall be placed partly on top of the chip components, see Figure 3.

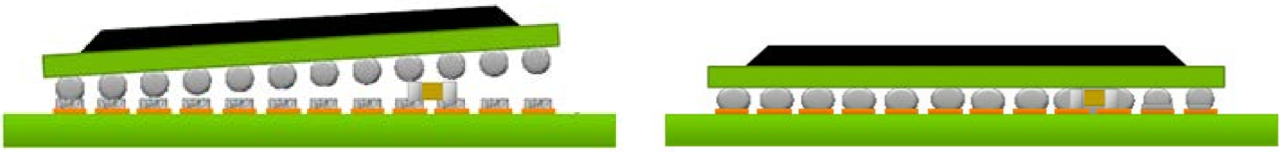

Figure 3 – Description of the used HoP test method[3].

The idea with this HoP defect evaluation method [1] is that the different rows of BGA solder balls will get in contact with the solder paste flux at different times during the reflow soldering process. Some solder balls will be in contact with the solder paste flux from the very beginning, while others will not get in contact until the solder has completely melted and "embraced" the chip components.

The following activities were performed in this evaluation:

- Measurements of components and boards.
- Preparation of stencil, SMT-program, reflow profile etc.
- Screen printing of test boards.
- SPI measurements of the screen-printed solder paste deposits.
- Placement of two chip resistors on each test BGA site.
- Placement of BGA on the sites with the two chip resistors.
- Convection reflow soldering in air atmosphere.
- X-ray inspection and analysis.
- Prying off the BGAs and analysis of results.
- Comparison of the results from the x-ray and the prying analyzes.

A. Discussions about the Chosen Methodology

Using the above described methodology to compare HoP susceptibility of different solder pastes requires extensive knowledge of packages, boards, added materials and processes. The following must be known and under control:

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[2]Picture source: Frank March et al., [1]
[3]Ibid.

- BGA solder ball heights.
- Chip heights.
- BGA solder ball coplanarity.
- Solder paste print heights.
- The distance the components are pressed into the solder paste deposits during placement.

By choosing a relatively small BGA component and a symmetrical board layout, the warpage during soldering would in this case have a negligible effect on the result.

III. Test Vehicle

In this HoP defect evaluation, a test board originally designed for a BGA ball and BTC/MLF thermal pad solder joint void test was used. For the HoP defect test, 0402 chip resistors and 256 ball BGAs with 1.0 mm pitch were chosen. For the assembly, nine different SAC305, No Clean, type 4 solder pastes (named A to I) were tested.

A. Test Board

A two-layer, 2.1 mm thick, test board with ENIG pad finish was used in this test. There were five sites for five different BTC/MLF components and three different BGAs as well as a big PA transistor on each board, but for this HoP defect test, only one BGA site per board was utilized. Panels with two test boards each were used in this test.

The NSMD PCB pads for the HoP defect BGA assembly test were round with 0.41 mm diameters and 0.53 mm solder mask openings.

The test board panel can be seen in Figure 4.

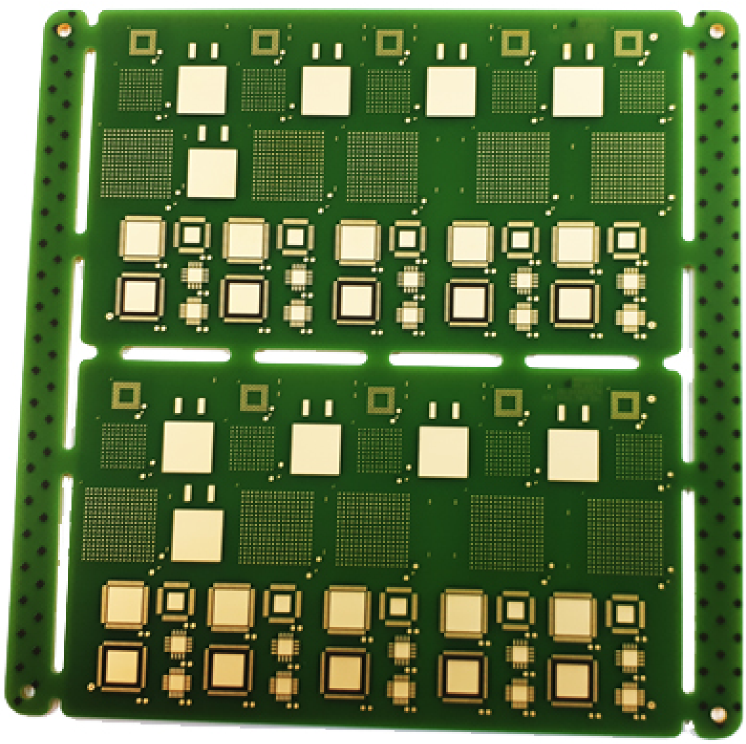


Figure 4 – Panel with two test PCB intended for solder paste void test and for HoP defect test.

A. Test Components
Standard BGA256 packages and 0402 chip resistors were used in this test.

Images of the test components are shown in Figure 5.

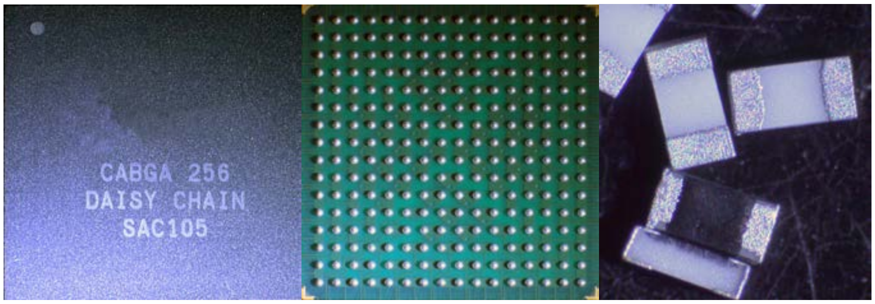


Figure 5 – HoP test components BGA (two left images) and 0402 chip resistors (right).

The BGA package had 1.0 mm pitch, daisy-chain pattern, SAC105 alloy solder balls and 17 mm side lengths. The BGAs' ball heights varied from 0.36 to 0.39 mm before soldering.

Measurements of the resistors showed heights between 0.29 and 0.32 mm.

IV. Assembly

The assembly process started with solder paste printing onto the BGA site pads followed by placements of 0402 chip resistors and BGA256 components. Finally, the assembled test boards were reflow soldered in an air atmosphere.

A. Screen printing
In the screen printing process, a 0.127 mm (5 mil) thick, laser cut, stainless steel stencil with 0.41 mm square apertures with 0.05 mm corner radii was used.

The paste deposit heights and volumes for each solder deposition and for each solder paste were measured using a production SPI equipment.

An example of a typical solder paste deposit height distribution for one of the tested solder pastes is shown in Figure 6.

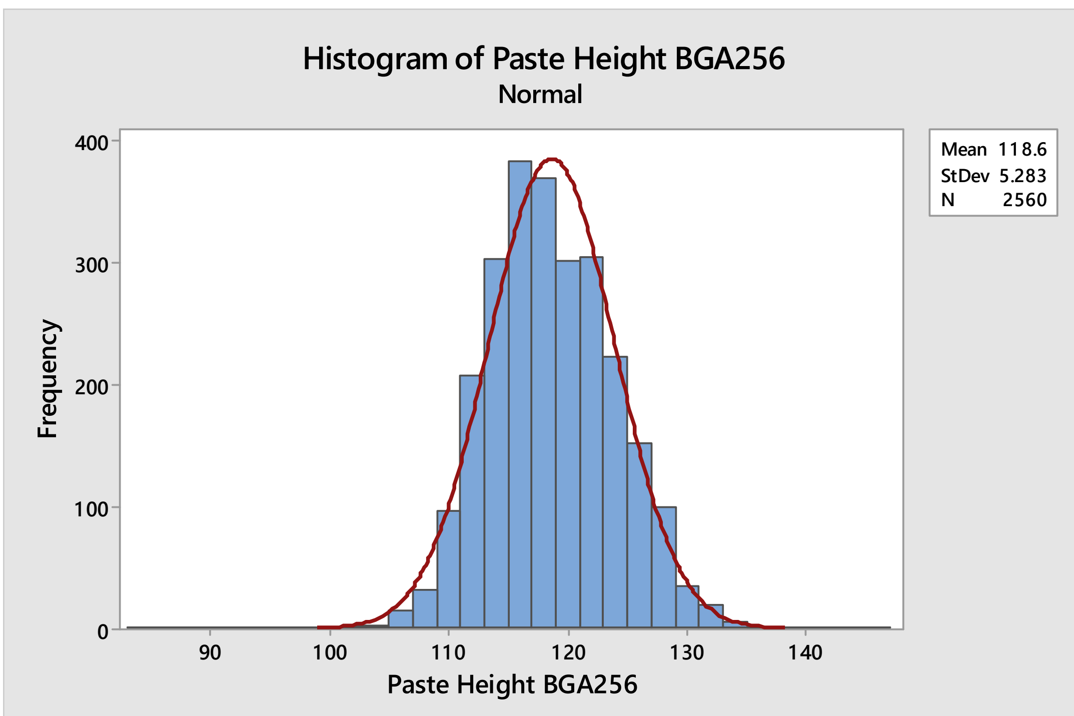


Figure 6 – Example of solder paste height variation for one of the tested solder pastes.

All tested solder pastes showed stable height and volume distributions for the solder paste deposits on the pads for the BGA sites.

B. Component Placement

After screen printing and SPI measurements, two 0402 chip resistors were placed four pad-rows into each of the BGA packages' pad sites, see Figure 7[4]. Please note that the 0402 chip resistors were rotated 90˚ compared to the study described in Figure 2 and Figure 3 [1]. The reason for this was to get equal pressure from the BGA balls on both terminations of the chip resistors at the same time, thus minimizing the risk of "tombstoning" the 0402s underneath the BGA.

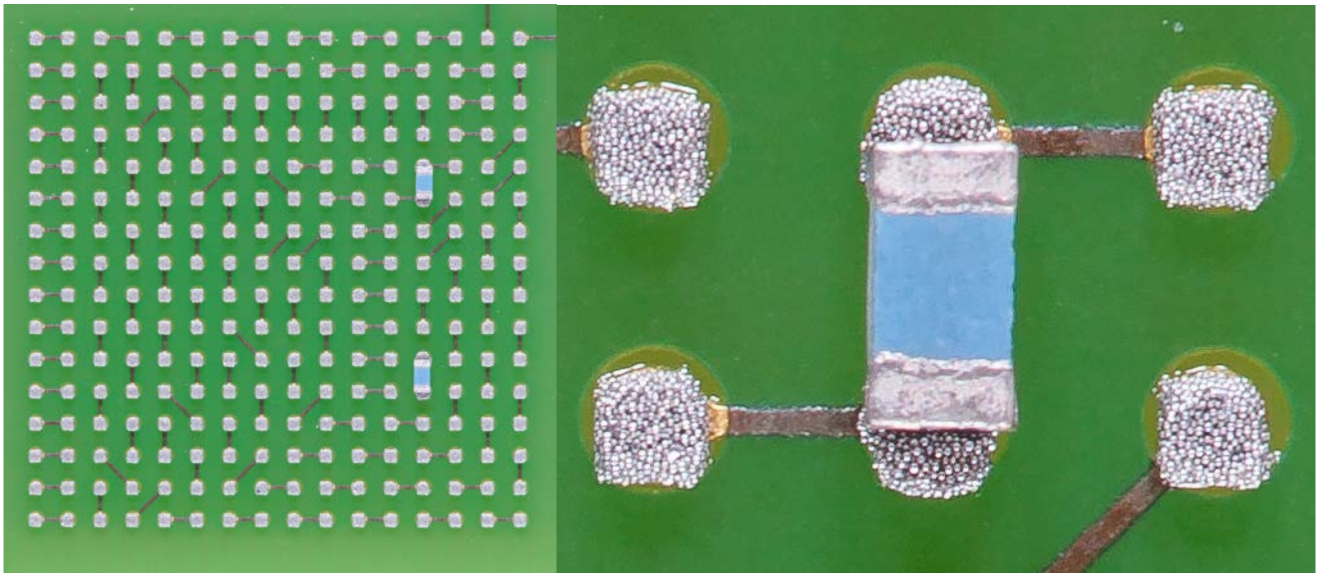


Figure 7 –BGA pad site with screen printed solder paste and two 0402 chip resistors placed[5].

The 0402 chip resistor placements were manually inspected before the BGA256 were placed on top.

An image of a BGA256 placed onto a site with two 0402 chip resistors underneath is shown in Figure 8.

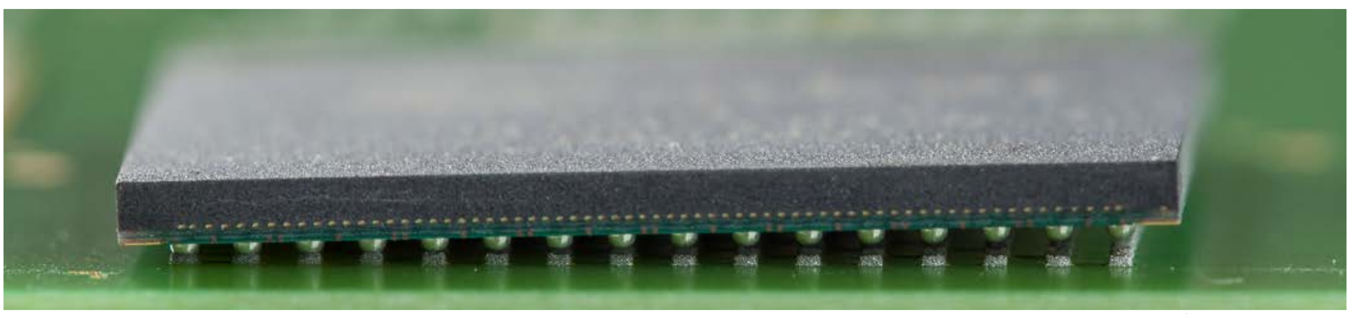


Figure 8 –BGA256 package placed on printed site with two 0402 chip resistors underneath[6].

Separate measurements of placements of the 0402 chip resistors and BGA256 packages showed that the chip components were pressed into the printed solder paste so much that their total height after placement was about 0.36 mm to 0.38 mm. This means that from the fifth or sixth row from the left in Figure 9, the solder balls do not touch the solder paste until the solder paste and BGA solder balls start to melt.

[4] 0402 chip resistors were placed on two BGA256 pad sites for all tested solder pastes except for paste A where only one BGA site had chip components.

[5] Photo: Binas Nisic

[6]Ibid.

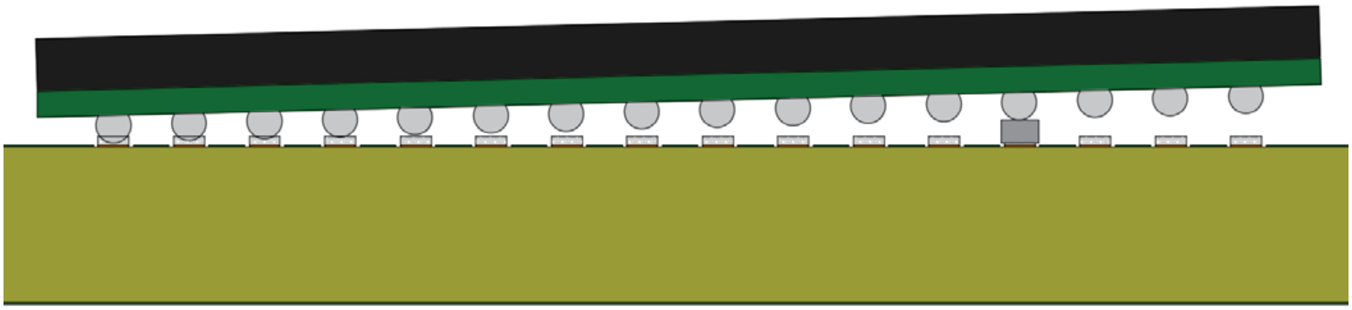


Figure 9 – Cross-section sketch on BGA256 package placed on printed site with 0402 chip resistors underneath.

B. Reflow Soldering

Reflow soldering was performed in a 12-zone convection oven in air atmosphere using a reflow profile that suited all tested solder pastes. The BGA solder joint temperature profile is given below:

- Time above liquidus for the SAC105 solder balls: 75 s
- Time between 150-220 ˚C: 94 s
- Max ramp: 2.0 ˚C/s
- Peak temperature: 245 ˚C
- Peak reached after 4 min 0 s

The reflow soldering profile is shown in Figure 10.

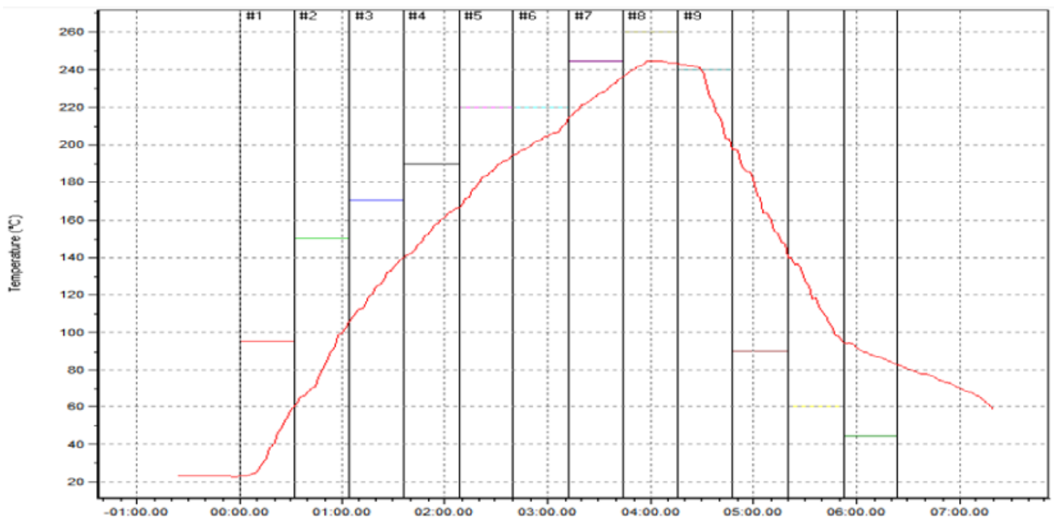


Figure 10 – Reflow soldering profile for BGA256 solder joints.

B. Assembly Results

Inspection of the test boards showed good results with correctly placed components, good wetting and well-formed solder joints. One example of an assembled test board panel, with the HoP defect test packages encircled in dark blue, can be seen in Figure 11.

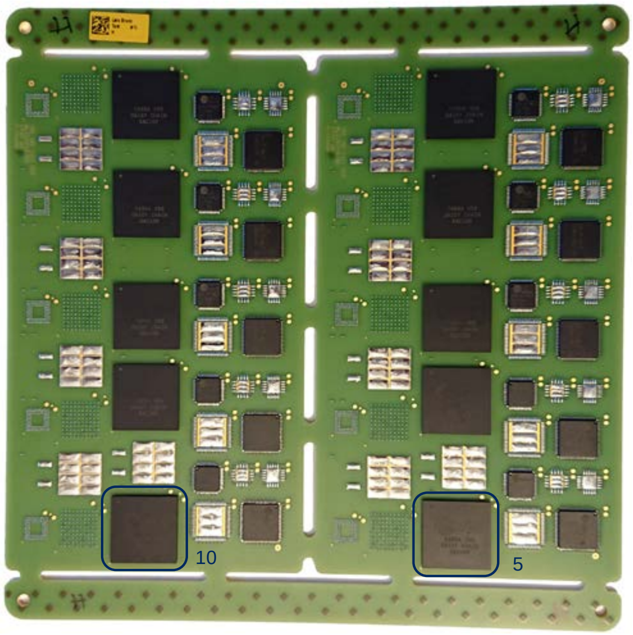


Figure 11 – Test board panel with encircled HoP defect BGA test components.

The HoP defect packages positions are called No.5 and No.10, see Figure 11.

One post reflow side view image of a soldered HoP test BGA256 is shown in Figure 12. Please note the difference in standoff between the solder joints to the left, that are furthest away from the pre-placed 0402 chip components, and the solder joints to the right, which are closer to the chip components.

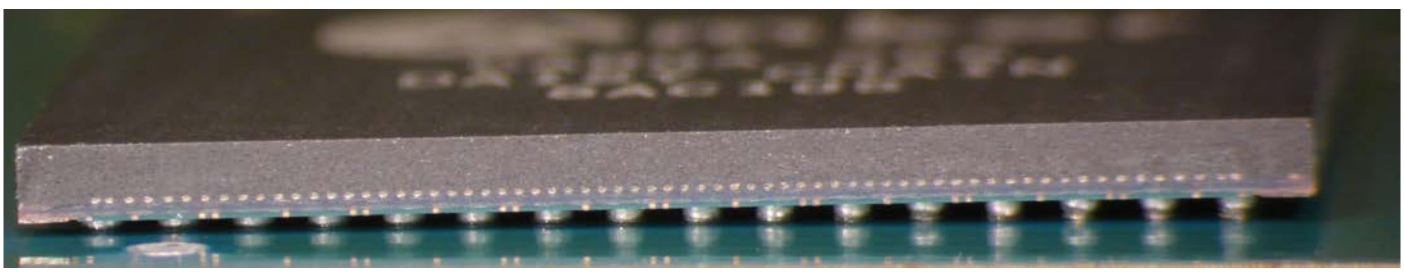


Figure 12 – BGA256 package placed on printed site with two 0402 chip resistors underneath after soldering.

All test boards were successfully assembled.

V. HoP X-Ray Inspection

The most common, non-destructive, method to inspect hidden BGA solder joints is to use x-ray inspection[7]. In this study, a modern 2D/2.5D x-ray equipment with oblique views up to 70˚ and 360˚ sample rotation was used, see Figure 13.

[7]All x-ray inspections, measurements, x-ray images and the analyses of the x-ray images in this paper have been performed by the author Benny Gustafson.

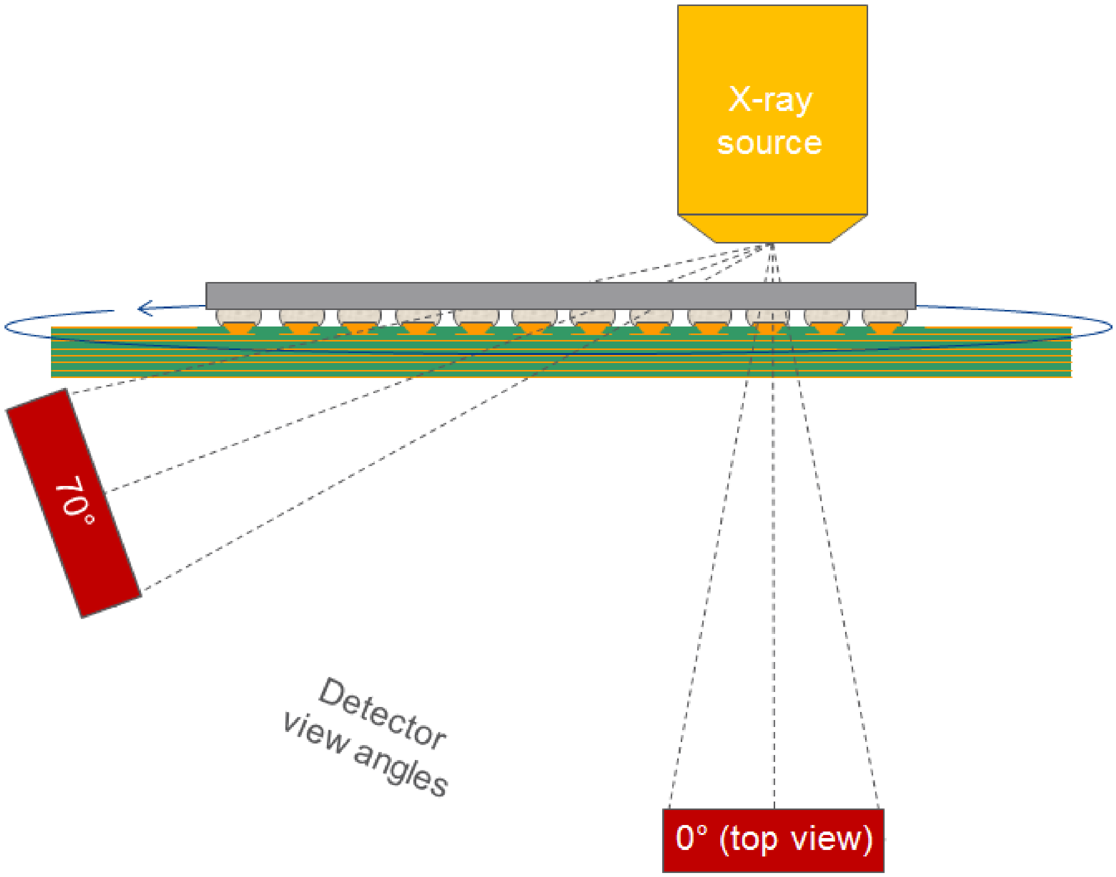


Figure 13 – X-ray inspection – detector view angles from 0˚ to 70˚ and 360˚ sample rotation.

In these BGA solder joint inspections, the x-ray detector was tilted 70˚ and the inspection sample table rotated 45˚. An example image from one of the x-ray inspections using this view is shown in Figure 14.

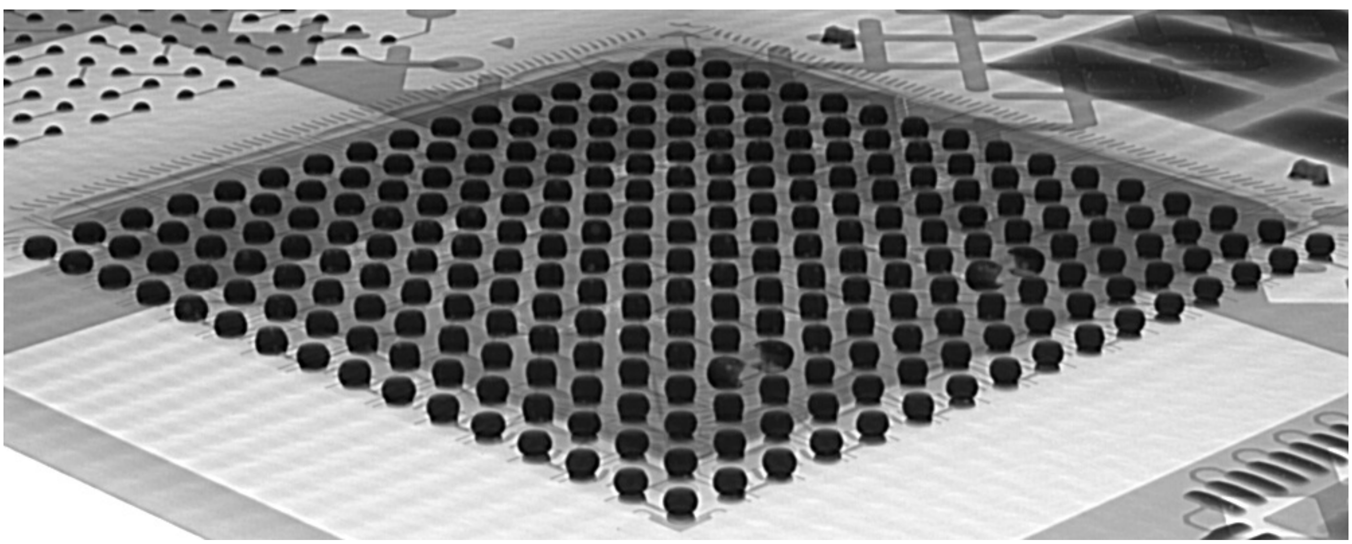


Figure 14 – X-ray inspection – detector view angle 70˚, sample rotation 45˚.

In Figure 14, the 0402 chip resistors placed underneath the BGA256 are visible as well as the different shapes of the solder joints. The risk of getting solder joints with poor coalescence (and possible HoP defects) between the BGA balls and the applied solder increases towards to lower right of the image. The standoff decreases towards the upper left and the risk for HoP defects decreases in this direction.

The same BGA as shown in Figure 14 is shown in a top view (0˚ tilt) image in Figure 15.

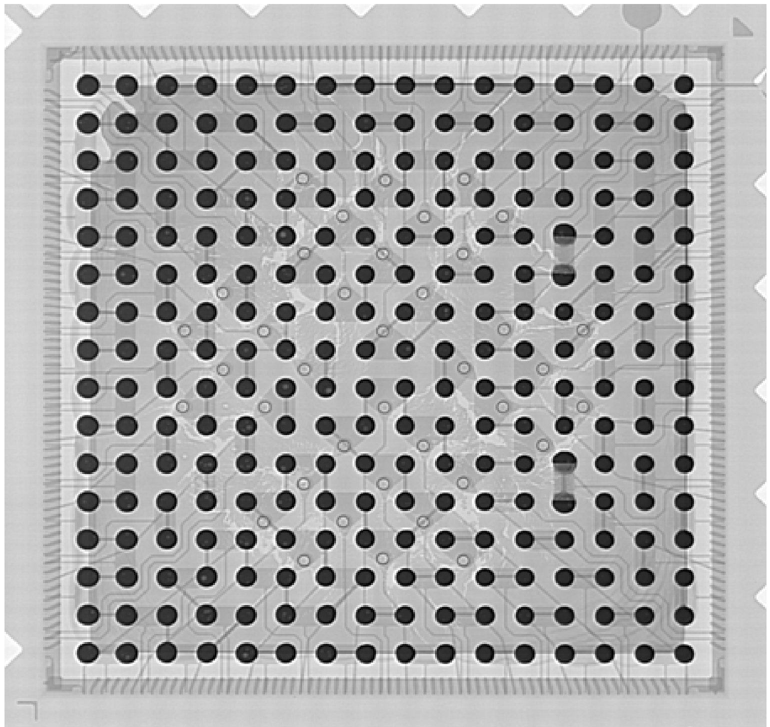


Figure 15 – X-ray inspection – top view (0˚ tilt).

The two 0402 chip resistors are also visible in Figure 15 and it is clearly shown how the solder joint diameters increase when looking at the solder joints further to the left of the x-ray image above, most far away from the chip components. Larger solder joint diameters are a sign of lower standoffs.

A. X-ray Criteria for HoP Defects

When inspecting the x-ray images of the solder joints that had been formed after having placed and soldered BGA256 packages on component sites containing two 0402 chip resistors each, it was necessary to decide exactly which solder joint shapes that should be judged as potential HoP defects. Some of the solder joints produced in this test may have been classified as "fractured solder connection" or "waist" defects according to IPC-A-610G Acceptability of Electronic Assemblies [2], but it is, in many cases, difficult to draw the line between these two error types and HoP defects. Therefore, all these three error types were classified as HoP defects in this evaluation according to the following criteria.

- HoP defects:
  - Solder joints with two distinct structures - poor/no coalescence between the added solder paste and BGA ball.
  - Solder joints with a "waist" at the lower section of the joint - not full wetting between the added solder paste and the BGA ball.

Examples of images with solder joints judged as HoP defects in this x-ray inspection are given in Figure 16.

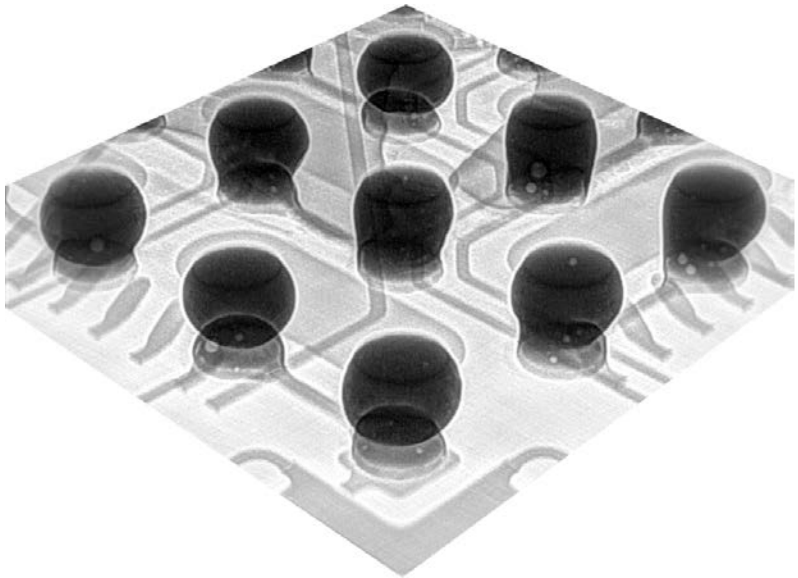


Figure 16 – BGA solder joints - all regarded as HoP in this x-ray inspection.

Solder joints regarded as good, with no HoP defects, were fully wetted with a single solder joint structure formed between the board pad and component side BGA pad. These correct BGA solder joints, regarding the HoP failure mode, could be both fully collapsed or elongated.

Examples of good solder joints (no HoP) are shown in Figure 17.

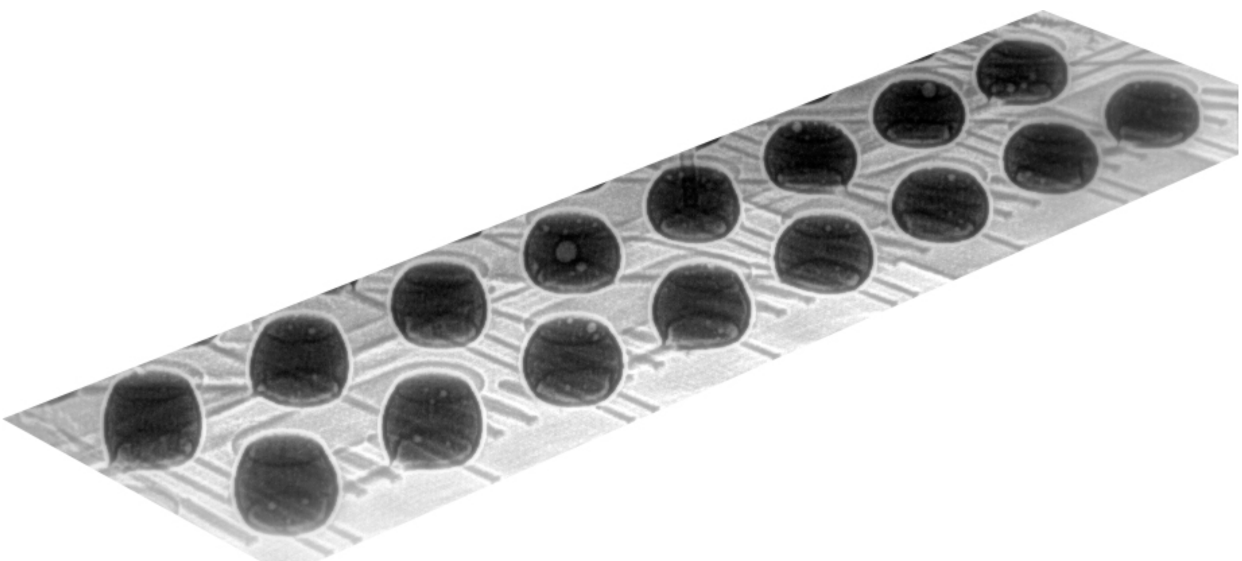


Figure 17 – X-ray image of good solder joints - regarding HoP.

Examples of the best and of the worst performing solder pastes in this HoP investigation are shown in Figure 18 and Figure 19.

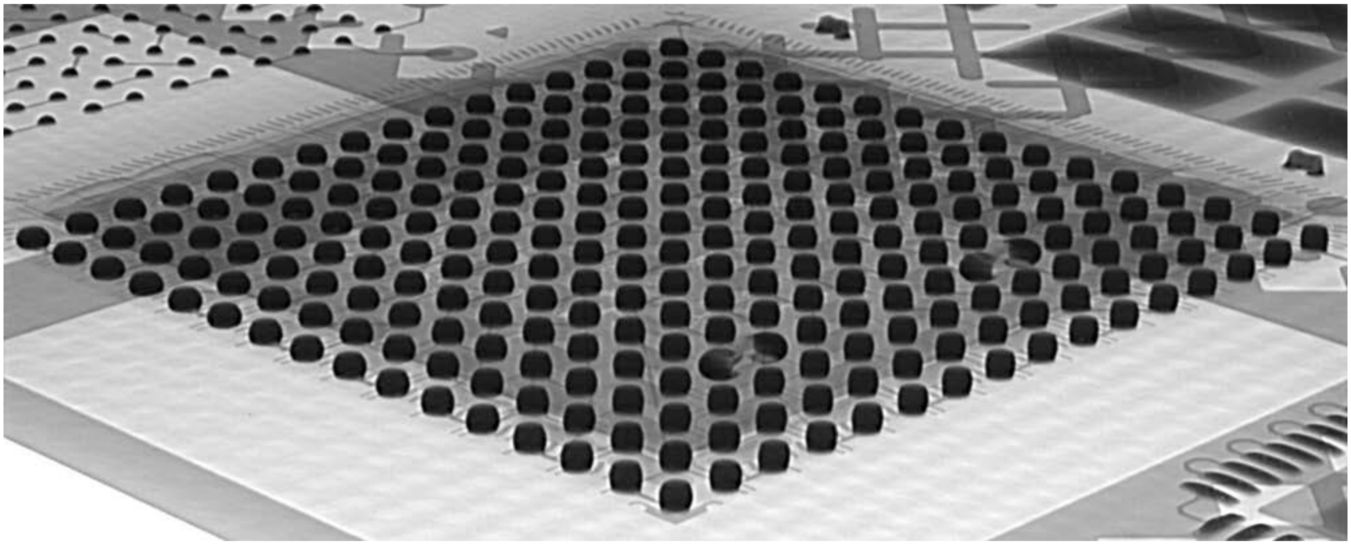


Figure 18 – X-ray image of the best performing solder paste's solder joints.

As can be seen in Figure 18, all BGA solder joints have one single structure even though they have different shapes; with elongated solder joints where the standoff is at its highest and more compressed solder joints on the component-side furthest away from the 0402 chip resistors. This was the solder paste with the very best result in the HoP evaluation with no HoP defects found.

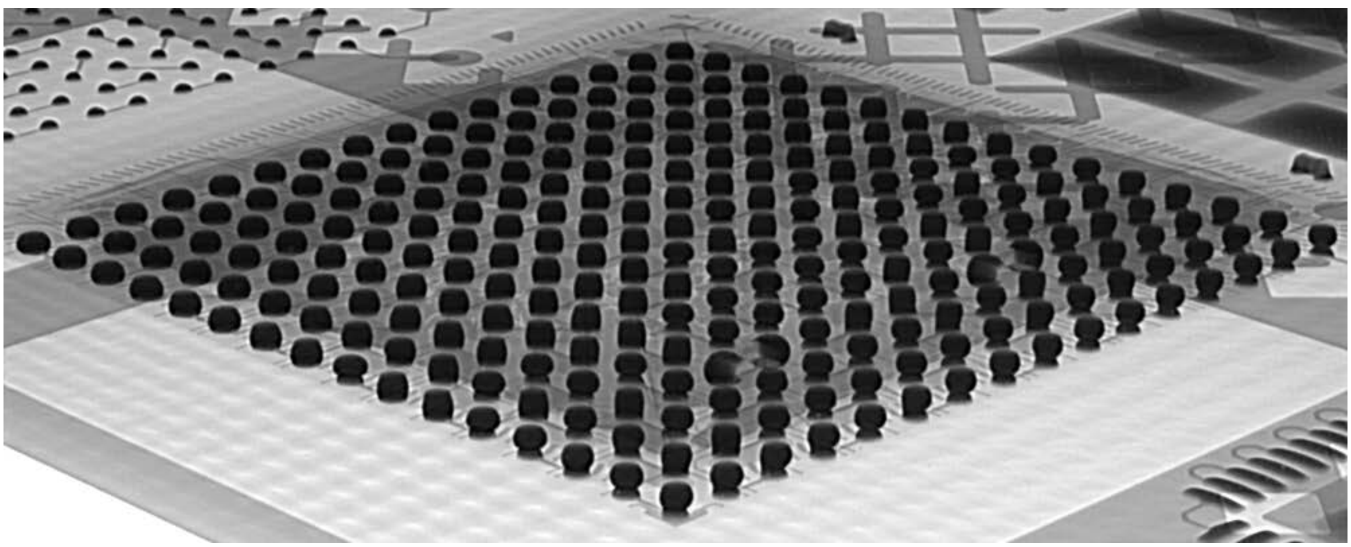
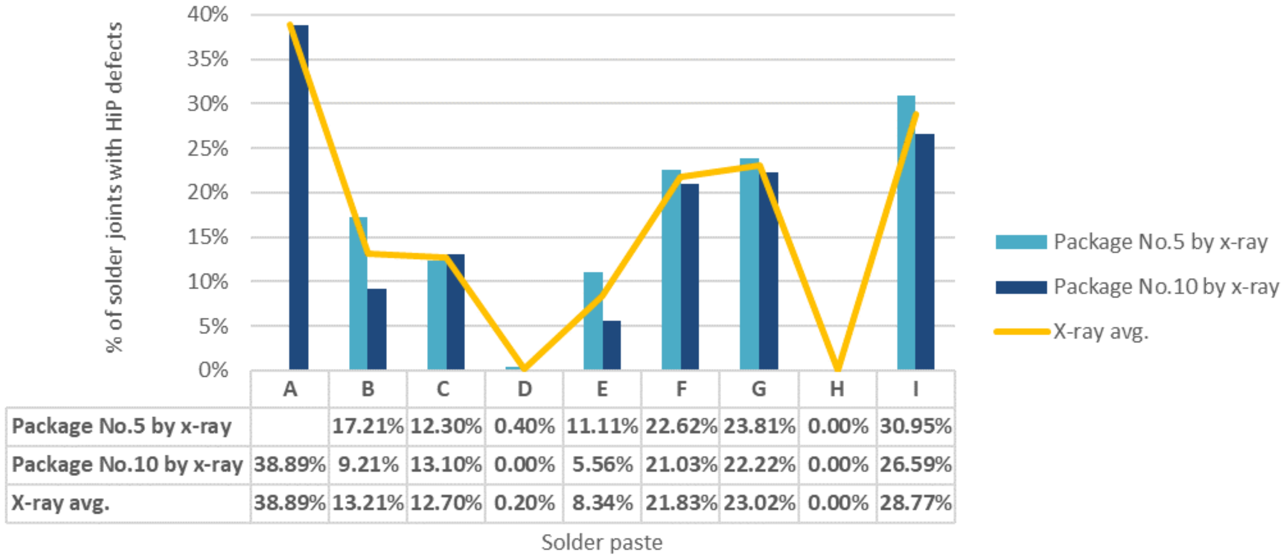


Figure 19 – X-ray image of solder joints created with a solder paste with poor HoP mitigation properties.

In Figure 19, many HoP defects can be found at the BGA solder joint rows with the highest standoff. There is a decreasing number of HoP defects towards the center solder joints of the BGA and no HoP defects at all at the BGA solder joint rows with the smallest standoff from the board. In many of the rows containing HoP defect solder joints, some of the HoP defects are found adjacent to correctly formed solder joints.

In the calculations of HoP failures in this evaluation, 252 (256-4) solder joints per BGA were considered as defect opportunities. The best solder paste had 0% failures (the x-ray image shown in Figure 18) and the worst 38.9% (the x-ray image shown in Figure 19). A summary was made, showing the nine different solder pastes' ability to mitigate HoP defects. This summary is given in Figure 20.



	A	B	C	D	E	F	G	H	I
Package No.5 by x-ray		17.21%	12.30%	0.40%	11.11%	22.62%	23.81%	0.00%	30.95%
Package No.10 by x-ray	38.89%	9.21%	13.10%	0.00%	5.56%	21.03%	22.22%	0.00%	26.59%
X-ray avg.	38.89%	13.21%	12.70%	0.20%	8.34%	21.83%	23.02%	0.00%	28.77%

Figure 20 – Solder paste HoP defect rates for nine different solder pastes – BGA256.

Figure 20 displays that the HoP mitigation ability differs greatly among the nine evaluated solder pastes. Solder paste D and solder paste H are for e.g. HoP defect-free (or close to) while solder paste A and I are the worst performers with around 30%, or even more, of the solder joints expected to have HoP defects.

The x-ray HoP defect judgements were difficult to perform and needed to be verified. The components were therefore pried-off and both the pried-off components and the board component sites were then inspected.

VI. Pry-off Components

In order to verify the HoP defects in this study, the x-ray inspected BGAs were pried-off and then both the boards and the packages were inspected[8]. All pry-offs were made in the same manner, starting from the BGA edge furthest away from the 0402 chip resistor placements.

After having pried-off the components, it was very easy to assess real HoP defects using microscope inspection. When a HoP defect has occurred, the BGA solder ball remains at the packages side and have a dimple from the solder on the removed board pad. There is no cracked area on the remaining solder ball and the ball-edges around the dimple are smooth. An example of HoP defects verified by prying-off a component is shown in Figure 21.

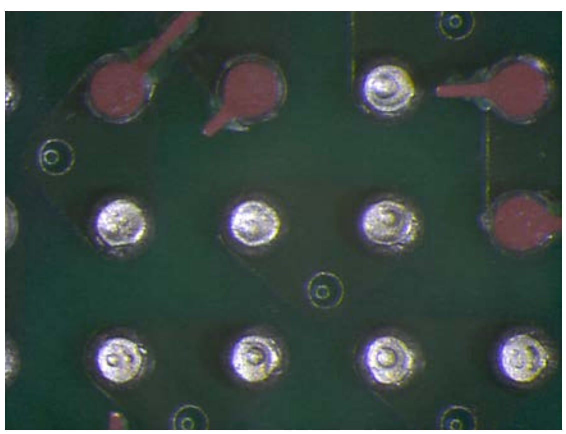


Figure 21 – Eight HoP defects verified after prying-off a test BGA.

[8] All component pry-offs, optical inspections, measurements and images (except figure 24 and 25) of pried-off components and boards in this paper have been performed by Jesper Wittborn.

When prying-off correctly formed BGA solder joints, the balls are most often completely removed together with the pads, either from theboard or from the package. These solder joints could also break, leaving cracked solder surfaces on both the board- and package-sides.

An example of two pried-off components, soldered with solder paste I, is shown in Figure 22.

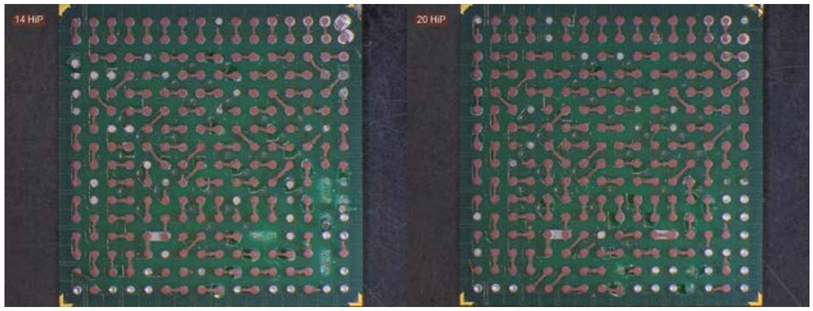


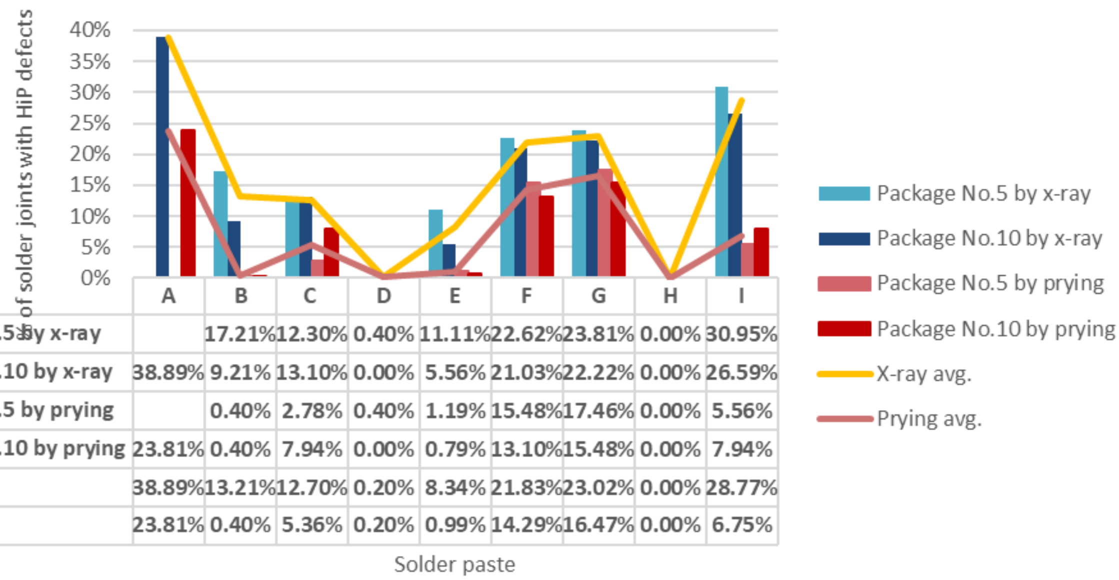
Figure 22 – HoP defects verified after prying-off two test BGAs -solder paste I.

By prying-off the BGA test components, an easy and secure verification of real HoP defects could be performed. This is, however, a destructive method that cannot be used on real products.

VII. Comparison of X-Ray Inspection and Pry-Off

When counting the real HoP defects after having pried-off all test packages, a comparison between the previously judged HoP defects found by x-ray could be performed.

A summary of this comparison is given in the graph in Figure 23.



	A	B	C	D	E	F	G	H	I
Package No.5 by x-ray		17.21%	12.30%	0.40%	11.11%	22.62%	23.81%	0.00%	30.95%
Package No.10 by x-ray	38.89%	9.21%	13.10%	0.00%	5.56%	21.03%	22.22%	0.00%	26.59%
Package No.5 by prying		0.40%	2.78%	0.40%	1.19%	15.48%	17.46%	0.00%	5.56%
Package No.10 by prying	23.81%	0.40%	7.94%	0.00%	0.79%	13.10%	15.48%	0.00%	7.94%
X-ray avg.	38.89%	13.21%	12.70%	0.20%	8.34%	21.83%	23.02%	0.00%	28.77%
Prying avg.	23.81%	0.40%	5.36%	0.20%	0.99%	14.29%	16.47%	0.00%	6.75%

Figure 23 – HoP defect rates – comparison of results between x-ray and prying off test BGAs.

As can be seen in Figure 23, the differences between HoP defects found in x-ray inspection and after prying-off the components could be large. As the HoP criteria used in this x-ray analysis also included fractured solder connections and "waist" defects it was expected that slightly more HoP defect registrations should be made when performing the difficult x-ray image judgements compared to the verified HoP defects after prying. A ratio of at least 70-80% correctly verified HoP defects was estimated to be found. However, in many cases, the differences were much bigger than this which are shown in Table 1.

Table 1–HoP defect rates ratio – prying versus x-ray.

Paste	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
X-ray avg.	38.89%	13.21%	12.70%	0.20%	8.34%	21.83%	23.02%	0.00%	28.77%
Prying avg.	23.81%	0.40%	5.36%	0.20%	0.99%	14.29%	16.47%	0.00%	6.75%

Ratio prying/X-ray	61%	3%	42%	100%	12%	65%	72%	100%[9]	23%

It is obvious that many solder joints that look as real HoP defects in x-ray are not HoP defects in reality.

Comparisons of x-ray images and microscope images after having pried-off components were performed. One BGA package corner from this comparison is shown in Figure 24[10].

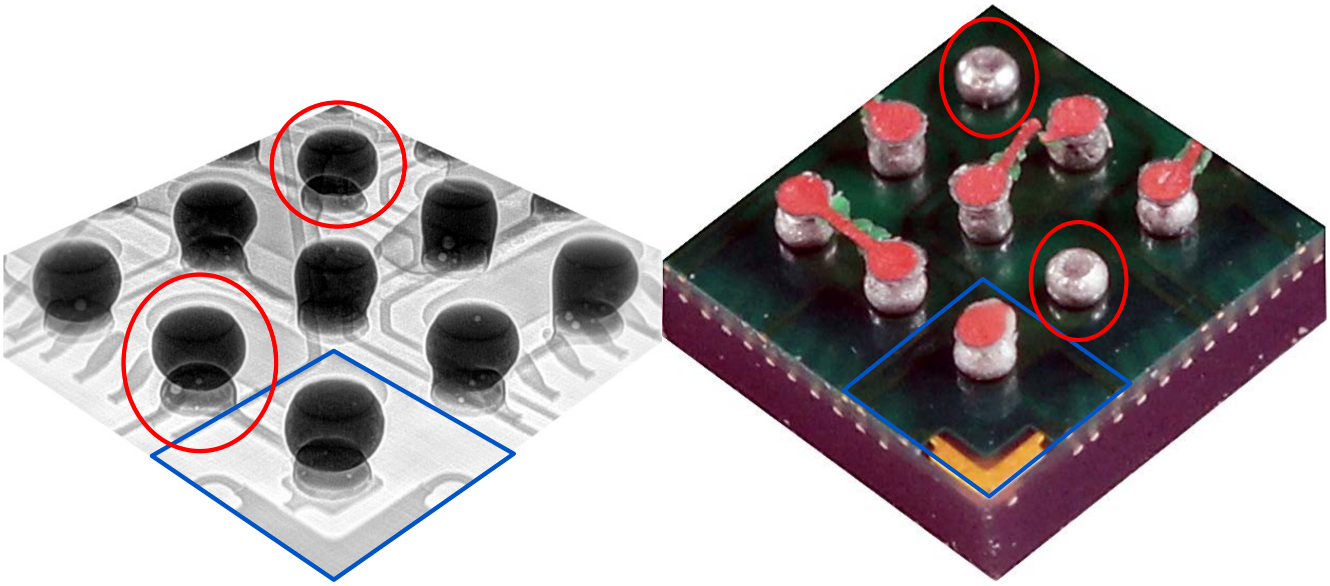


Figure 24 – Comparison of x-ray image (left) andpried component (right) –red encircles show verified HoP defects.

In Figure 24, all nine BGA solder joints were judged as HoP defects at the x-ray image analysis. However, after prying, only two of them were verified as real HoP defects. The other seven solder joints were strong enough to even pull off the pads and the traces between the pads.

The component corner solder joint within the blue square in both images in Figure 24 is enlarged in Figure 25.

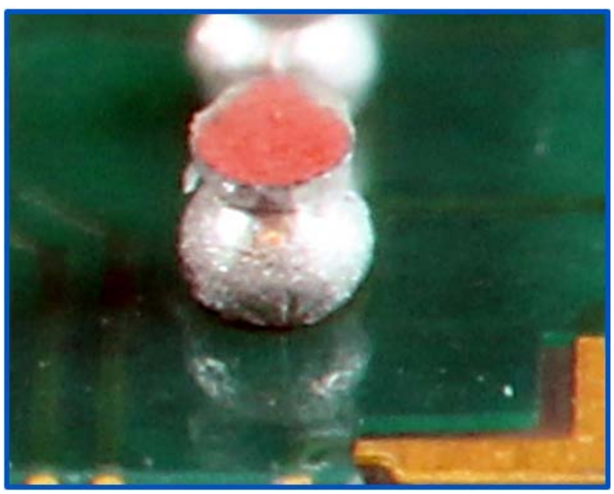


Figure 25 – Enlargement of a component corner solder joint with clear "waist" thatsurvived a pry off test.

In the x-ray image shown in Figure 24, some of the solder joints look like the applied solder and ball, at least, partly has wetted together, but it is impossible to see any differences between the two real HoP failures and for e.g. the corner solder joint within the blue square (Figure 24 and Figure 25) when studying the x-ray images of these BGA joints.

VIII. Discussion

[9] 100% means that there is full conformity between the x-ray and the pry off analyzes (even though division with 0 is not defined!).

[10] If the x-ray image would be seen from below, the same view as for the pried component image will arise. Please observe that the red encircled solder joints and the solder joint with a blue square around are the same in both images.

The previous sections show that it is almost impossible to guarantee detection of all HoP defects by only using x-ray inspection as detection technology. What is possible to see in x-ray is “HoP-shaped” BGA solder joints and these are indeed solder joints with a high risk of having much lower strength and reliability than fully wetted, homogenous ones.

In IPC-A-610 revision G, Acceptability of Electronic Assemblies [2], section 8.3.12.3, HoP defects are only shown by a photo, and it is barely possible to visibly see HoP defects other than in peripheral BGA rows and this standard gives no guidance in interpreting x-ray images. The HoP defect criterion in this standard is “ball is not wetted to solder”, which is easy to agree with. However, a “waist” in a BGA solder connection is also treated as a defect (but not classified as a HoP) and this defect is most often possible to detect with a modern x-ray equipment.

The side view images used to show HoP defects and BGA solder joints with “waists” in [2] are given in Figure 26.

Figure 26 – Defect criteria according to [2] – HoP (left) and “waist” in solder connection (right)[11].

Even though the x-ray images cannot with certainty tell if the ball and the solder have wetted together, the x-ray images could, most often, show when there is a “waist” in the solder connections which also could disqualify these solder joints.

IX. Conclusions and Recommendations

This study has shown that the occurrence of HoP, ”waist” and fractured solder connection defects are difficult to distinguish from each other using x-ray inspection. As these errors can occur both along the BGA outer rows as well as under the central parts of the package, the optical side view inspection criteria stated in IPC-A-610 revision G [2] are not sufficient as quality criteria. Consequently, an x-ray inspection criterion based on treating any “waist” in the BGA solder joints as a defect is recommended for the next revision of IPC-A-610.

X. References

[1] Characterizing the Relationships Between a Solder Paste’s Ingredients andits Performance on the Assembly Line: Head-in-Pillow Testing, Frank Murch, Derek Moyer, Krupali Patel, John McMaster, Steve Ratner, Martin Lopez, Heraeus Material Technology, SMTAi Conference 2011

[2] IPC-A-610G, Acceptability of Electronic Assemblies, IPC October 2017

X1. Acknowledgements

The authors are grateful to the following colleagues that have contributed to the development of methods, performed tests, measurements and reviewed the paper:

Anne-Kathrine Knoph, Julia Xu, Rebbeca Dehlin, Dzemila Durakovic, Naser Ismaili, Mats Karlsson, Binas Nisic and Jesper Wittborn

[11] Picture source: IPC-A-610G, Acceptability of Electronic Assemblies [2]