As originally published in the SMTA International Conference Proceedings.

HEAD – AND – PILLOW SMT FAILURE MODES

Dudi Amir*, Raiyo Aspandiar*, Scott Buttars*, Wei Wei Chin**, and Paramjeet Gill**
Intel Corporation
Hillsboro, OR, USA*
Kulim, Kedah, Malaysia**

ABSTRACT
With the electronics manufacturing industry moving to lead free soldering and with Ball Grid Array (BGA) packages becoming thinner and having finer ball pitches, there is an increase in the incidences of a SMT non-wet type of defect known as head-and-pillow (HnP). This defect is hard to detect after SMT assembly and most likely will fail at the customer. There are a number of causes for this type of defect. They can be categorized into process issues, material issues, and design related issues. This paper will examine these different causes for the head-and-pillow non-wet defect after surface mount assembly and the mechanism to create this defect. The paper will also describe the critical factors that are affecting head-and-pillow. It will discuss how to identify the root cause and give potential solutions to prevent the defect and have a robust SMT assembly process.

Key words: Head and pillow, failure mode, non wet, reflow soldering, oxidation, warpage, mis-placement .

INTRODUCTION
The electronics industry is trending toward environmentally friendly manufacturing, smaller and thinner packages and increase of board density. All of these increase the challenges of board assembly. As a result of these challenges, there is an increase in the incidence of a SMT non-wet open joint defect called head–and-pillow (HnP). This defect is known by many other names such as head on pillow, head in pillow, ball in cup, ball in socket, and hidden pillow. They all refer to the same phenomena that is defined as a joint that is comprised of two metallurgical distinct masses formed from BGA balls and reflowed solder paste with incomplete or no coalescence. Figure 1 shows a typical cross section of the head and pillow defect.

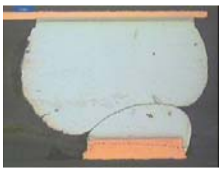


Figure 1. HnP defect

As seen in Figure 1, the BGA ball is sitting on the solidified paste, but it did not form a contiguous solder joint. It is hard to detect this defect using standard test methods since with a little or no pressure it may pass in-circuit test and 'escape' to the customer. Since this defect most likely will fail or give an intermittent connection after some customer use, it is important to understand the defect mechanism and prevent it from happening.

The objective of this paper is to highlight the contributing factors to the HnP defect, to explain how they form and best known solutions to prevent them. The paper has categorized the cause for HnP defect into three different areas: process issues which relate to SMT and the board assembly process; material issues which relate to the material used during the assembly process such as solder paste, package material, and the BGA ball; and lastly, design issues that relate to board and package.

The HnP defect is not an easy problem to solve since it is influenced by a number of different factors. This paper attempts to highlight the important factors causing HnP in order to assist engineers and technicians with HnP root cause analysis.

HEAD-AND-PILLOW DEFECT CREATION
A description of how the head-and-pillow defect forms is depicted in Figure 2. First, the BGA ball is placed on the solder paste which has been printed on the printed circuit board (PCB) lands (Figure 2a). As the BGA on the PCB enters the reflow soldering oven, and its temperature increases, the flux in the solder paste starts to activate and reduce the oxides on the solder paste particles as well as the part of the solder ball it touches. There may or may not be contact between the solder ball and the solder paste at this stage (Figure 2b).

Next, a gap develops between the ball and the solder paste due to some factor, such as dynamic warpage of the package and/or PCB. The solder on the PCB land melts and flux covers its surface. The solder ball also melts and its surface, which typically has little or no flux covering it, starts to oxidize, assuming an air atmosphere in the oven (Figure 2c). When the BGA package collapses the ball once again makes contact with the molten solder paste mass. At this time, if the ball and the molten solder paste mass coalesce together, then a good solder joint is formed. But, if there is insufficient flux activity to remove the oxide coating on the surface of the ball, or there is some contamination on the solder ball or molten solder paste mass, these two will not coalesce (Figure 2d). This will result in an HnP solder joint defect when the package cools down to room temperature and both the solder ball mass and the solder paste solidify (Figure 2e).

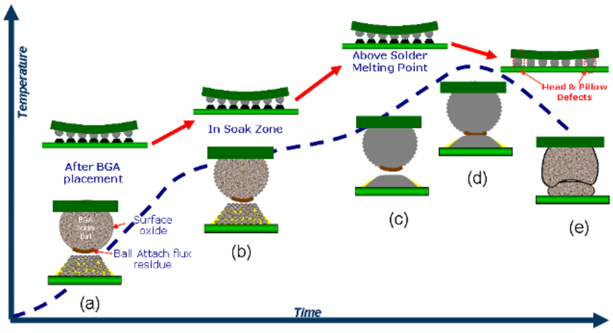


Figure 2. Depiction of the Head - and - Pillow Defect Formation Mechanism.

The essential root cause for the generation of the HnP defect from this mechanism is the existence of the gap between the molten solder ball and the molten solder paste deposit on the PCB, as depicted in Figure 3. If this gap does not form during the reflow soldering process, then the HnP defect will not form, unless there is either contamination present on the solder ball, such as ball attach residue, or on the solder paste surfaces, or excessive oxidation of the solder ball or solder paste is present.

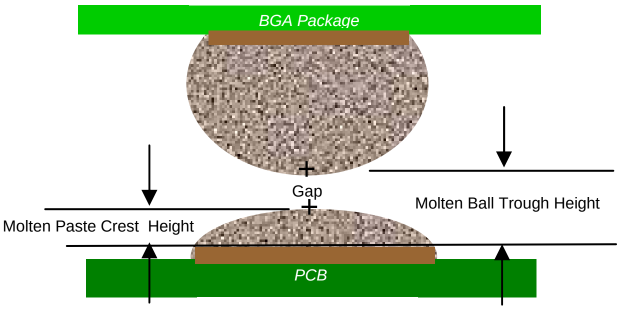


Figure 3. Illustration of the gap between the solder ball and the solder paste that precedes the formation of most HnP BGA solder joint defects.

In these cases, the molten solder of the ball and the solder paste deposit are not able to come in contact with each other. An insufficient reflow temperature will also cause the same signature of a HnP defect since either the solder ball, or the solder paste, or both, have not reached the liquidus temperature and become fully molten to coalesce and form a metallurgically sound solder joint.

PROCESS FAILURE MODES

Solder Paste Volume

The solder paste consists of two critical components which are metal solder powder and flux. Both play an important role to ensure good solder joint formation during SMT reflow.

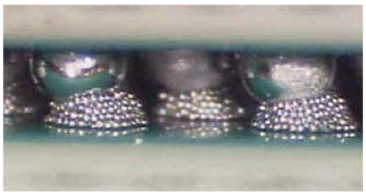


Figure 4. BGA balls and paste contact

The solder powder provides a contact medium between the board pad and BGA solder ball while the flux removes the oxide and protects the molten solder in the joint formation process. Contact between the ball and the paste is necessary in order to get maximum oxide removal during reflow, as shown in Figure 4.

The solder powder deposition is controlled with respect to stencil aperture design, while the flux amount is controlled to a certain ratio during the manufacturing of the solder paste itself. Hence, stencil design is the most significant factor in order to control the printed solder paste volume.

Good stencil design (aperture opening area, and aspect ratio of the stencil aperture to stencil thickness) is critical to ensure good release and transfer efficiency. A square aperture design deposits higher volume compared to round aperture design (see Figure 5).

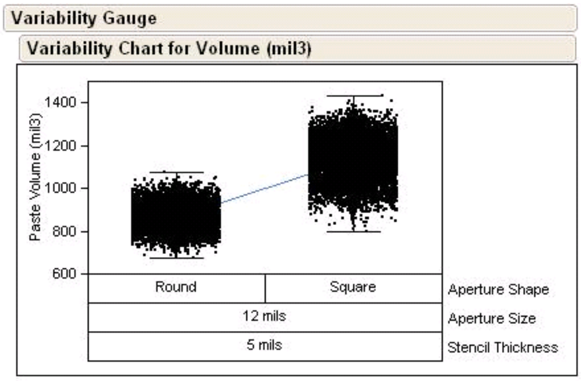


Figure 5. Paste volume by stencil design

Solder paste inspection equipment is typically designed to calculate the amount of metal powder deposited on boards while assuming the flux is directly correlated to this amount.

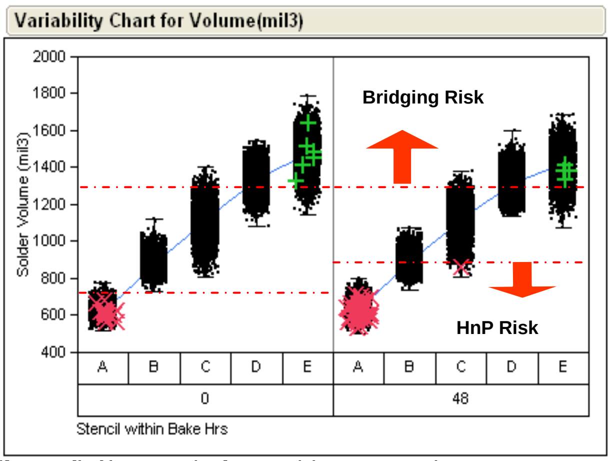


Figure 6. Case study 1 on solder paste volume

Figure 6 shows data from five incremental aperture designs used to vary printed solder paste volume. The results shows HnP observed at low paste volume (red crosses) while bridging is observed (green crosses) at high paste volume. In this experiment, baking of components also shows higher HnP fallout and a smaller process window as a result of an increase in the oxide thickness on the BGA solder ball.

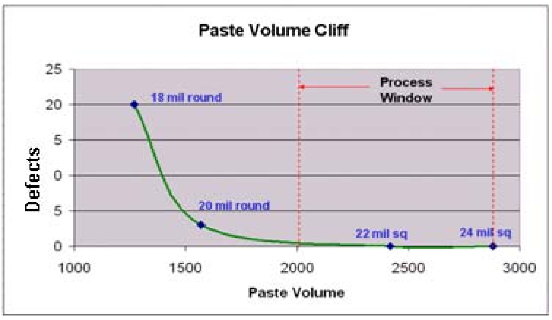


Figure 7. Case study 2 on solder paste volume

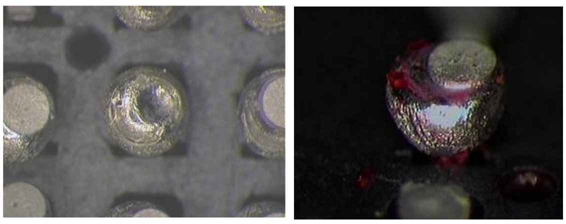
Fig 7 shows paste volume cliff for HnP /Bridging defects and the safe process window for paste volume. It is necessary to select an aperture design which is well centered within the process window and has margin on the low side against head and pillow and margin on the high side against bridging.

The printed solder paste volume defines the crest height of the molten solder on the PCB land during reflow. A high crest height of the molten solder paste mass increases the likelihood that it will contact the solder ball. (see Figure 3).

The amount of paste is only a modulator for HnP, it is not a primary factor. It is a secondary factor. When a HnP problem exists, having low paste volume is known to increase the incidences of HnP, and a high paste volume decreases the incidence of HnP.

Component Mis-Placement

Component mis-placement has been implicated in being a cause of HnP defects. Observations of solder joints after the Die-and-Peel (DnP) failure analysis procedure indicate, as shown in Figure 8a below, that the dimple in the ball was off-center and, as shown in Figure 8b below, even the good solder joints appear to be misaligned.



(a) (b)

Figure 8. (a) Off-center dimple in the ball of an HnP defect and (b) off-center land in the ball of a good solder joint after DnP test.

To determine whether mis-placement of the component can be the primary root cause of HnP solder joints, 6 samples of test vehicle boards were assembled with BGA sockets through the reflow soldering process, with some of these sockets intentionally misplaced in controlled amounts on the PCB land patterns. 5 sockets were soldered per board, with one of the 5 being placed accurately (the control sample), two placed with a positive off-set with respect to the reflow direction by 125 microns and 250 microns, respectively and two placed with a negative off-set with respect to the reflow direction by 125 microns and 250 microns, respectively.

DnP results from this study indicated that zero HnP defects were formed. As shown in Figure 9, cross-section photos indicate that, good joints have formed despite the intentional mis-placement of the sockets. Hence, component mis-placement may not be a primary root cause of the HnP defect.

Figure 9. Optical Microscope photo-graphs of cross-sections for the misplaced BGA sockets on a test vehicle board. The off-sets for the various sockets are shown in the photos.

However, component mis-placement may be a `secondary` root cause. If there is significant component and/or PCB warpage that reduces the overlap required between the molten solder ball and molten solder paste, then mis-placement of the component may have a secondary effect in causing the HnP defect. This scenario is illustrated in Figure 10. When there is significant warpage and misplacement, a gap between the solder ball and the solder paste can be created during the reflow soldering process and lead to HnP, as shown in Figure 10a. However, if the warpage is minimal than even misplacement of the component would not necessarily create a gap, as shown in Figure 10b.

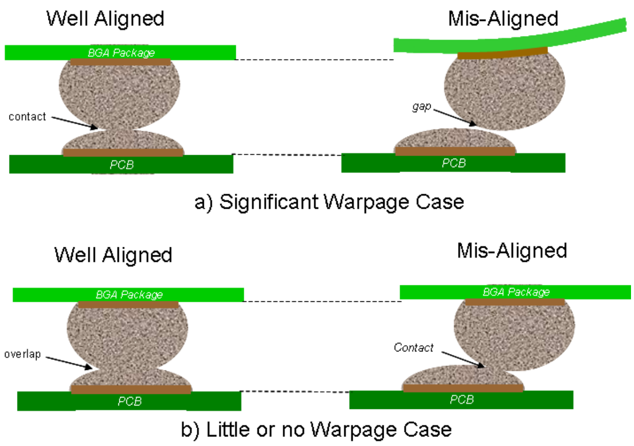


Figure 10. A scenario where significant warpage of the component and board can lead to Mis-placement of the component causing an HnP defect

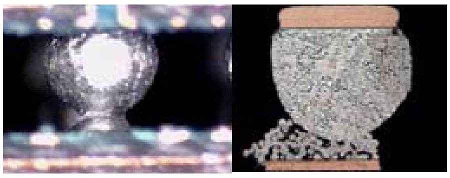
One other potential cause for creating the gap between the molten ball and molten solder paste for area-array solder joints is the mis-alignment illustrated in Figure 10a, caused not by component mis-placement but by the coefficient of linear expansion mis-match between the component and the board. This typically occurs for first level interconnects between the silicon die and an organic substrate [1]. This expansion mis-match is not a major concern for second level interconnects such as that for BGA components or sockets.

Incomplete reflow

This failure mode can be described as a solder ball or solder paste that did not melt completely during the reflow process. Usually it is the BGA ball that is not completely molten, since it is the slowest one to heat during reflow.

The root cause for HnP for incomplete reflow mode is incorrect reflow profile. The profile is too cold to completely melt the BGA balls and the balls don't have enough thermal energy to coalesce with the paste. It also could be a result of reflow excursion or oven malfunctioning.

This defect was reproduced in a DOE using a colder profile when the reflow temp was only 7 deg C above the eutectic temp. This defect mode has seen a recent increase in occurrences with lead free assembly since component manufacturing are starting to use alternatives alloys to SAC 305 for increasing reliability performance of their packages. An example for an alternative alloy is SAC 105 which has less silver. Another example is a ball alloy with added element such as nickel, magnesium or other. The alloy changes are impacting the reflow melting point and many of them require a reflow profile adjustment. In many cases the assembly houses using the package are not aware of this change and incomplete reflow HnP can occur.



(a) (b)

Figure 11. Incomplete reflow HnP defect

Usually this defect mode will show a BGA ball that did not collapse (see Figure 11a). The solder may appear grainy and in extreme conditions would not coalesce (see Figure 11b). The cross section may show different grain structure between BGA and solder paste indicating that one, or both, did not reach proper reflow temperature. Preventing this defect requires good reflow profile process control and understanding the paste and BGA ball reflow requirements.

Reflow Profile Parameters

The reflow profile parameters have strong impact on HnP sensitivity. The ideal case at reflow is that all the components on the board should reflow at the same time. However, all boards during reflow have some level of temperature variation between different components on the board and within a single component. The temperature difference between the coolest to the hottest point is defined as delta T (dT). dT on the board is driven by the board design, layout and laminate material, the type of component on the board and the component material.

There are two scenarios in which dT will impact HnP. Scenario 1 relates to a lightweight BGA. If we have temperature delta between the two sides of the BGA, one side will reflow sooner than the other and can cause the component to tilt as shown in Figure 12.

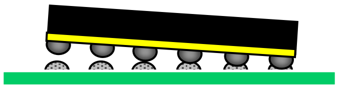


Figure 12. Tilted BGA

The paste will melt at the first corner, tilt the package, expose the other side to high temperature. Oxidation will increase on the exposed balls since it has no protection from the paste flux which itself is loosing its activity. The package will pulled back to flat by the paste wetting to the ball, and how quickly its pulls back depends on the wetting force of the paste. By the time this happens HnP defects may develop in some area of the package because there isn't enough active flux to reduce the oxides on the balls surface.

Figure 13. dT test board

A test board was used to simulate high dT across a 15x15 mm lightweight BGA package. To create dT across the BGA, two FR4 pieces were attached on the bottom side of the board such that they were under half of the BGA land pattern (see Figure 13). These FR4 pieces will shield the heat to the BGA from the bottom. dT of 8 deg C was achieved at 217 deg c. DOE results showed HnP rate of 35% compared to 0% without the FR4 pieces and a dT of 2 deg C.

The second scenario when dT impacts HnP is for large BGAs ,which have a large temperature difference between the inner and the outer balls. The paste will melt first on the outer balls. Since no packages are flat, some balls will not be in contact with the paste until the inner balls all melt and the package collapses.

The time difference between when the two extreme balls (inner & outer) become liquidus is critical and it is called liquidus time delay (LTD). As this time delay increases, the same impact as we saw in scenario 1 happens. It increased the time the exposed balls are oxidizing since there is no flux to protect them, and by the time full package collapse occurs, the flux has lost most of its ability to do it's job and results in HnP for some joints. Also the true TAL (ball is liquidus and in contact with liquidus paste) which the outer balls will see is much smaller than the profiler software indicates.

Figure 14 illustrates a profile of a large BGA 50x50 mm. The profile LTD is 23.6 seconds while dT is 9.3 deg at peak and 22 deg at 220 °c. The true TAL is define as the TAL after the package collapses until the first ball become solid. It is calculated from Figure 14 to be 40.5 seconds while the software TAL is 72 sec.

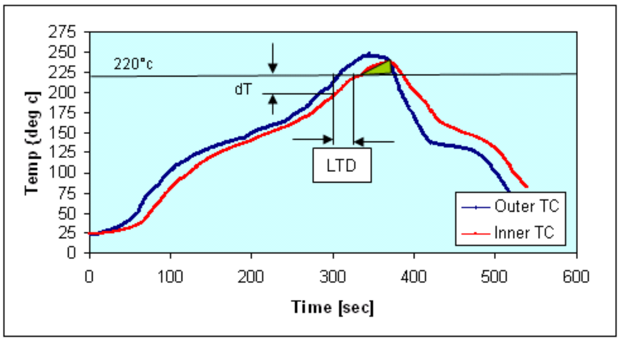


Figure 14. BGA liquidus time delay

The LTD that delayed the package ball from collapsing is reducing the TAL window and stressing the paste under high temperature while the package stays elevated. Both of these parameters, the LTD and the true TAL which we also call effective TAL, are important parameters to understand and assess the risk for HnP during SMT. LTD will impact the paste degradation in high temperature and the true TAL will impact the contact time between the ball and the paste. Figure 15 can give a general idea of acceptable values for these parameters to prevent HnP. The data in the chart consists of a number of different packages that are mounted with different profiles in an air reflow environment. Each condition that had HnP defect is marked in HnP zone.

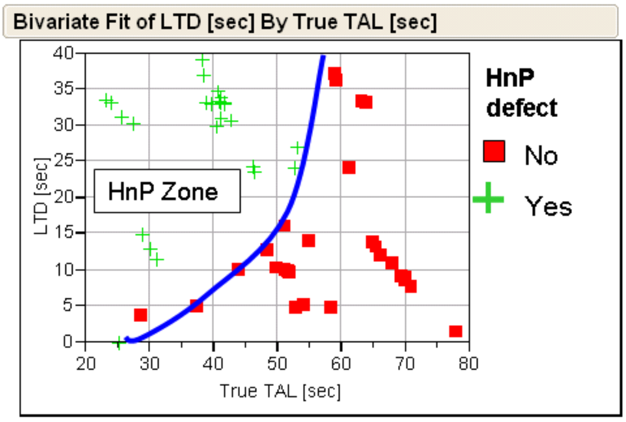


Figure 15. LTD and true TAL

Be aware that this curve in Figure 15 is illustrating a particular paste type that was tested and had an intercept point on the true TAL axis of 25 seconds. The 25 sec is the paste limitation to create a good joint when there is no delay time. This curve is expected to move with different paste types. The curve also will move to the left with N2 environment where the process window for HnP increases.

<u>Peak temperature and time above liquidus (TAL)</u>
Some of the reflow parameters that have impact on HnP are peak temperature & TAL. When dealing with HnP defects increasing TAL and peak temperature can decrease the defect level by adding more time for the package to contact the paste after full collapse and coalesce. The paste properties should be able to tolerate this increase otherwise it would not help.

A DOE was run to check reflow process window. The results from this DOE showed that low TAL and low peak temperature profile gave rise to HnP defect this is shown in Figure 16 and table 1.

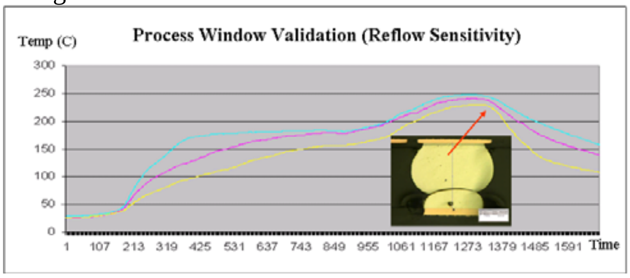


Figure 16. Process window validation

Leg	Reflow	Peak Temp °C (230-250)	Soak [sec] (60-120)	TAL [sec] (30-60)	Coplan Range	SMT Yield
1	Low Temp	231.7	61.1	28.5	3.97 – 6.46 mils	98% (49/50)
2	High Temp	247.1	119.4	59.6	3.55 – 6.94 mils	100% (50/50)
3	Medium Temp	239.3	90	47.3	3.71 – 6.83 mils	100% (25/25)

Table 1. Process window validation

<u>Soak time</u>
One other reflow parameter that could have an impact on HnP is soak time. The impact depends on the type of paste used and its behavior in high temperature. The DOE described below shows significant impact of soak time on HnP for a particular LF paste. The DOE used 3 different reflow profiles with different soak times (Short medium and long), which are shown in Figure 17. Short soak was the most suitable for reducing HnP defect for the type of paste that was tested.

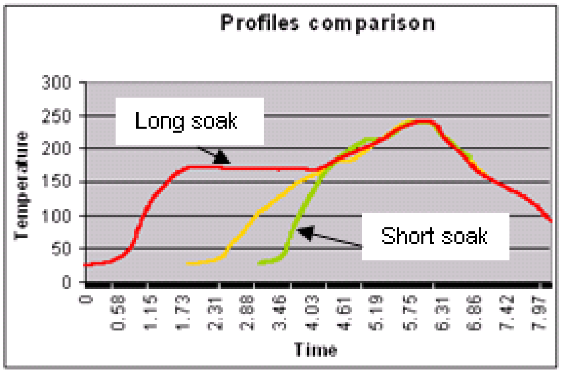


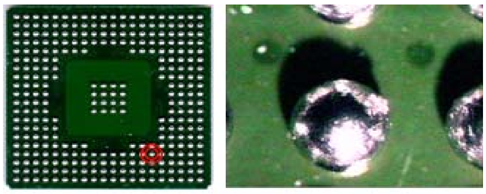
Figure 17. Soak time profile comparison

Leg	Time between 150-175°c	Time between 175-217°c	TAL 217°c	Peak [°c]	H&P
Short soak	13 sec	56 sec	65 sec	242	7%
Medium soak	33 sec	56 sec	67 sec	241	22%
Long soak	162 sec	63 sec	60 sec	241	100%

Table 2. Soak time DOE

Contamination
The description of this defect mode is a solder ball that did not wet to the paste due to presence of foreign material on the ball or the paste. This defect is an excursion where an unusual substance like NaCl, Si or other is present. The presence of an unusual substance can be a result of process contamination during package

assembly, package handling and packing material. One example is a HnP excursion that happened on a mother board. Visual inspection showed foreign material on some balls before SMT. Energy Dispersive X-ray spectroscopy (EDX) analysis detected Si (silicon) as a foreign material. Customer analysis indicated that sticky tape made of Si was used to mark the reworked units. The tape left some residue on the balls and prevented wetting during reflow, as shown in Figure 18. As a result a new rework marking procedure was implemented eliminating the sticky tape.



(a) (b)

Figure 18. Foreign material on ball

When too much flux is used in the ball attach process, it may not all be consumed during this process. Excess flux may become carbonized, remain on the surface of the ball and then result in a HnP solder joint. These carbon deposits may appear as dark patches on the surface of the solder ball and can be seen using a microscope as shown in Figure 19.

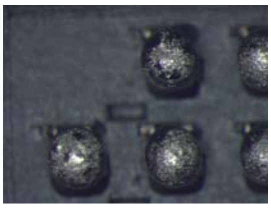


Figure 19. Dark patches on balls

EDX analysis shows a strong carbon signal. This is illustrated in Figure 20.

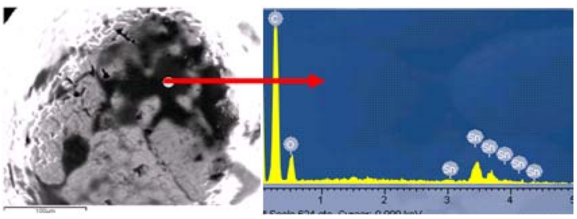


Figure 20. Dark patches material analysis

Flux reside is often found at the base of the ball, near the package land, and is not a concern. If the residue is found on the tip of the solder ball, where it will contact the solder paste then it is a contributor to HnP formation.

Contamination is one of the modes where a gap between solder and BGA ball during reflow is not necessary in order to create a HnP defect.

MATERIAL RELATED FAILURE MODES

Solder Paste Key Properties

The solder paste properties are important to accommodate the lead-free soldering assembly challenges. Flux chemistry of these lead-free solders must have adequate properties to form a good solder joint. This paper will illustrate 3 key paste properties which affect the HnP defect. These include solder paste stability with time and temperature; solder paste wettability on Cu; and solder balls and the oxidation resistance of the solder paste.

<u>Solder paste stability with time and temperature</u> [3]

The stability of solder paste material is dependent on its temperature and time exposure. A premature reaction could occur within the flux of the solder paste during its shipment/storage/printing. This leads to a weakened capacity for the flux to clean the solderable surfaces during air reflow. In order to understand the stability of solder paste, viscosity and pH tests of accelerated aged solder pastes were carried out. Results indicated that solder paste's viscosity increases and pH decreases when they are aged. Overall results showed `Solder Paste A` is more stable than `Solder Paste B` as the former has smaller degree of material property changes (viscosity and pH) under the aging conditions, as shown in Figure 21.

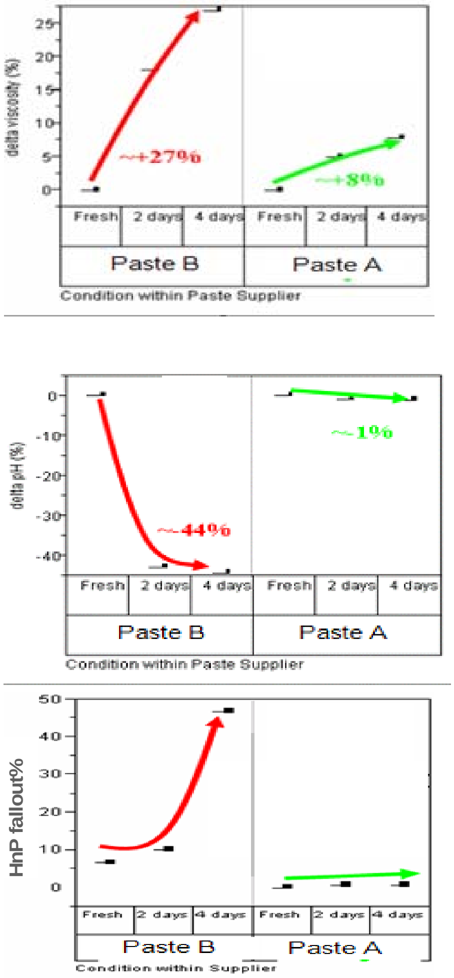


Figure 21: Comparison between solder paste A and B at 29ºC for 4 days, changes in viscosity & pH recorded together with HnP fallout

This result suggested that the premature reaction will lead to the increase in solder paste viscosity. Reduction of the oxides on the solder metal particle surfaces by the flux will form metal salts as a by-product and lead to an increase of solder paste viscosity. Premature reaction will lead to decrease in the pH due to the release of H^+ ion. In the context of solder paste, the covalently bonded activator in solder paste is dissociating to release H^+ when the reaction takes place This reaction is hypothesized as a dehydrobromination process to produce HBr. Thus, a higher degree of change in viscosity and pH are indicators of a premature reaction. This results in HnP defects due to insufficient flux capacity during reflow soldering in air atmosphere. A strong correlation was established between the stability of solder paste and the rate of formation of the HnP defect. `Solder Paste A` which is more stable over time and temperature had a lower HnP defect fallout rate over the temperature and time tested than `Solder Paste B`.

Wettability of solder pastes on copper and solder

Shorter wetting time for a solder paste on copper implies that it is favorable for wettability. This is because the flux is more effective in removing surface oxidation layers and results in better interaction. A shorter wetting time normally reflects a faster fluxing reaction. Therefore, solder pastes that have a low wetting time have good wettability.

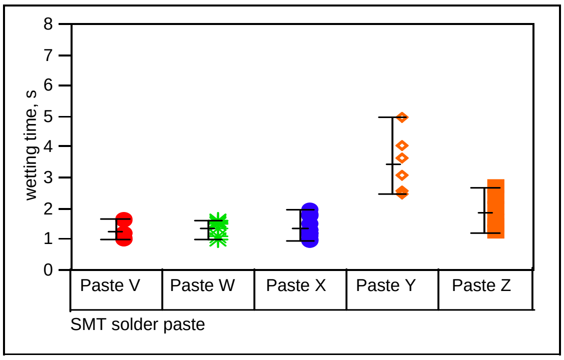


Figure 22: Wetting time results for multiple solder pastes using a wetting tester

Good wettability of the solder paste to the solder balls is another key property to ensure the solder paste is able to wet on to the solder ball and form solder joints. To understand wettability of solder paste to solder ball, the following experiment was conducted. A BGA package was inverted and solder paste was printed on the solder balls. The package was then reflowed in an air atmosphere and inspected. Ideally, the solder paste should coalesce with the solder ball. If it did not coalesce, then a small solder ball would be observed on top of the larger BGA solder ball. This indicates poor wetting (higher wetting angle). Photo graphs of the solder balls formed after reflow are shown in Figure 23.

The solder ball formation can be correlated to the HnP fall out rate by reflow soldering the BGAs with the same paste using the same reflow soldering parameters. This was done and the results are shown in Figure 24. They indicate that higher solder balling % will lead to higher HnP fallout rate.

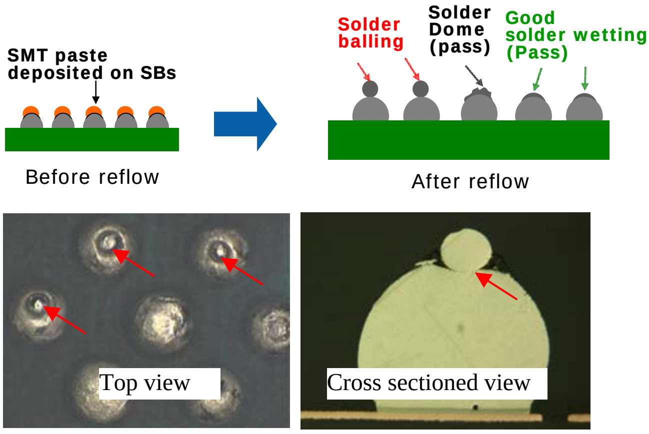


Figure 23: Wetting test on solder balls and solder balling images.

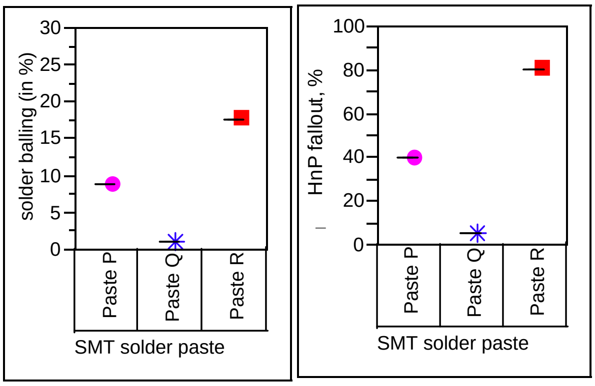


Figure 24: Higher solder balling % shows higher HnP fallout rate.

Oxidation resistance of solder pastes

Oxidation resistance of solder paste is important part of the flux system. A flux that is unable to protect solder powder, will cause high oxidation at outer surface of paste deposits. This oxide layer becomes a barrier on the solder paste for joint formation and thus increases the tendency to form HnP. The mechanism of oxidation resistance effect on HnP is depicted in Figure 25.

A Stencil with multiple aperture opening sizes was used to print various solder pastes on OSP copper coupons. These coupons were then reflowed in an air atmosphere. The resulting solder deposits were inspected for the strawberry effect (non-coalescence of the solder particles on the outer surface). If there is strawberry effect on the solder deposits from a particular solder paste, then it implies that solder paste does not have good oxidation resistance. Figure 26a depicts the results of this experiment. Results indicate that the strawberry effect increases with reduced solder paste deposit volume for all solder pastes tested. Further, two solder pastes W and Z, have an increased strawberry effect with decrease in aperture relative to the other three, thus indicating that these two paste have lower oxidation resistance. Solder Pastes W and Z also result in a higher % of HnP defect, as shown in Figure 26b.

These results suggest that to form a good joint, a solder paste should exhibit adequate oxidation resistance in addition to good wettability.

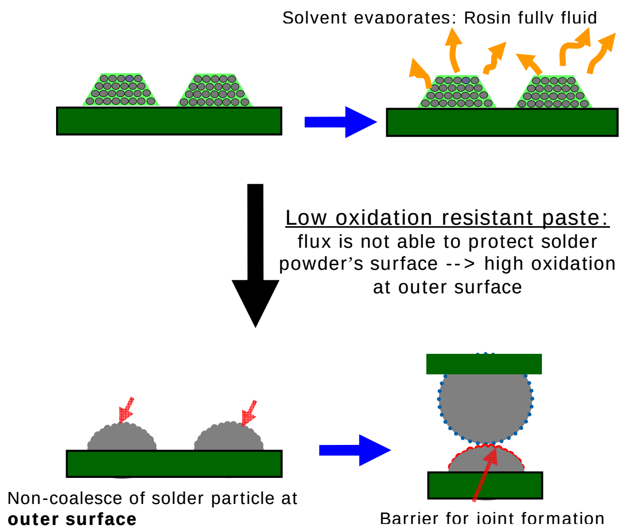


Figure 25: Mechanism of Oxidation resistance affecting HnP.

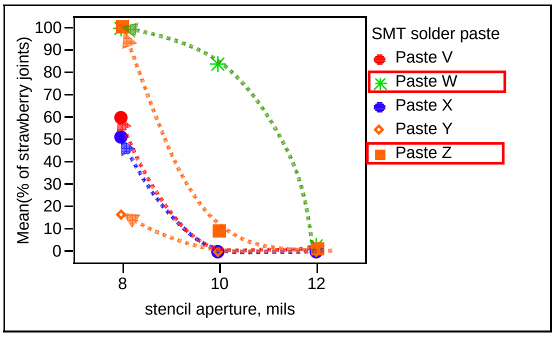


Figure 26a: % of non-coalesce solder paste with decreasing stencil aperture.

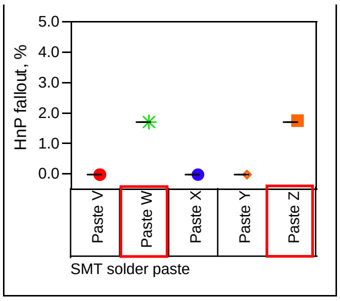


Figure 26b: % of non-coalesce solder paste leads to risk of HnP

Solder Ball Oxidation

The tin in SAC solders will oxidize in air in preference to the other two significant elements, Ag and Cu present in the alloy as shown in the Ellingham diagram [2]. The Ellingham diagram for $Sn/Sn0_2$ also indicates that Sn will oxidize in air at all temperatures of interest to soldering. This tin oxide has to therefore be removed, physically or chemically from the surface of the solder ball before it can coalesce with the molten solder paste.

The flux in the solder paste has the job of reducing the tin oxide to metallic solder during the reflow soldering process, preferably before the solder ball becomes molten. However, if there is separation of the solder ball from the solder paste during the reflow process before the solder ball has melted, as shown in Figure 2, the oxide on the solder ball will not be reduced and would even further oxidize when it melts in the reflow zone within the reflow oven. When the solder ball eventually contacts the flux from the solder paste mass, then and only then will the flux be able to reduce the oxide from the surface of the solder ball.

However, to reduce the oxide from the surface of the molten solder ball and have this molten solder ball coalesce with the molten solder paste mass to form an acceptable solder joint, requires that a) enough of the active acid of the flux still be present to reduce the oxide to metallic tin and water vapor and b) both the solder ball and the solder paste mass be still molten when this reduction of tin oxide has taken place. Hence, the more oxide thickness present on the solder ball, the more difficult it would be to reduce it during the reflow soldering process, especially if the contact between the ball and the paste is lost during this process.

To confirm that excessive oxidation of the solder ball was indeed a concern for generation of HnP defects, three different BGA packages, denoted by Package A, P, and E, were baked in air for 24, 48 and 72 hours, and then reflow soldered under identical conditions.

Results of this study are shown below in Figure 27. It is clearly apparent that with increase in baking time the HnP defect rate increases. However, this increase varies with the package type and one of the packages, Package E, does not show any significant HnP defect formation even after 72 hours of baking in air prior to surface mount reflow soldering.

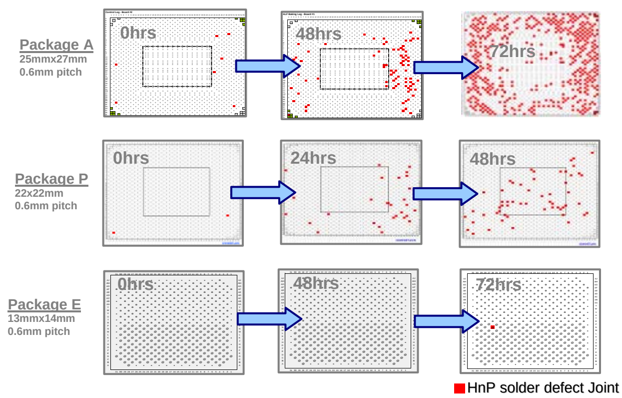


Figure 27. Impact of baking time in air on the propensity to form HnP defects after reflow soldering for three different BGA packages

To confirm that there was more oxide generated on the surface of the solder ball during the baking operation, the oxide thickness on the solder ball surface was measured for all three packages after the various baking times in air. Figure 28 shows the plot of oxide thickness with HnP defect rate for all three packages.

For two of the three packages types measured, Package A and P, increasing oxide thickness does result in an increase in the HnP rate with this rate flattening out in a plateau above ~15 nm of oxide thickness. However, for Package E, the increase in oxide thickness has no discernible increase in the HnP defect rate. Package E had minimal warpage at high temperatures, and the loss of contact between the solder ball and solder paste would not have occurred. Hence, the solder paste flux would be able to reduce the oxide from the solder balls and protect it from further oxidation.

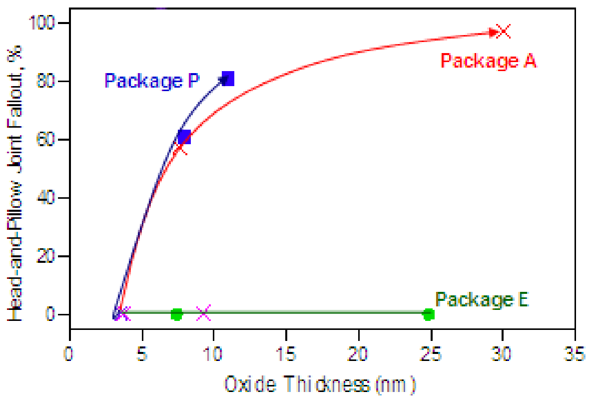


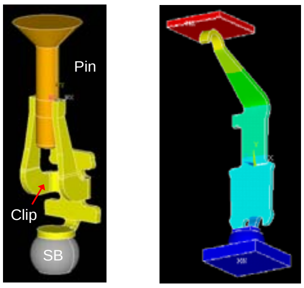
Figure 28. Variation of HnP Solder Joint Fallout rate with Oxide thickness on the solder balls for three different BGA packages

These results therefore ascertain that more oxide on the surface of the solder ball can cause an increase in the HnP defect rate, but may not be a major driving factor for the HnP defect. The warpage of the package that results in separation of the solder ball and the solder paste before the reflow zone in the oven is the main key factor for HnP defect formation.

Paddle Insertion in BGA Sockets

<u>Paddle stitching description</u>

The socket body is formed using a molding process which provides opening in the body for the metal contacts which the paddle is a part of. These are then press fit into the socket opening using a stitching process which resembles a sewing machine action and thus is the origin of the process name.



(a) PGA Contact (b) LGA Contact

Figure 29. Socket Contact

<u>Ball/Paddle relationships to socket standoffs</u>

It is critical that the solder ball extends beyond the socket standoff to ensure that the solder ball will contact the solder paste. This is referred to as solder ball standoff gap. Since the solder ball is attached to the paddle on the contact it essential that the stitching height be sufficient to allow for this, as shown in Figure 30.

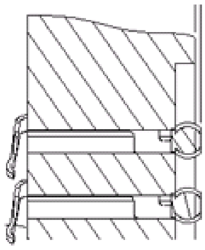


Figure 30. Solder Ball Standoff Gap

<u>Paddle height variation</u>

It is important that the paddles are stitched at the same height to maintain coplanarity of the solder balls. If the height varies with adjacent paddles, this can result in elongated solder joints, and in some cases a head and pillow solder joint, as seen in Figure 31.

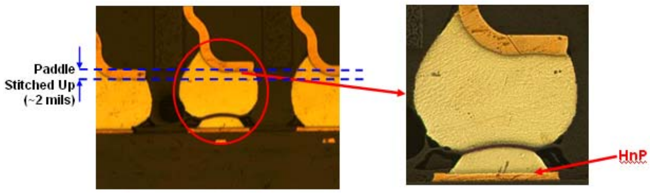


Figure 31. Socket HnP

<u>Handling damage impact on paddle height</u>

Inconsistent paddle height can result from the stitching process itself but often is a result of handling damage. This often happens when sockets are placed into a tray by hand. The contacts can be pushed further up into the socket body when just a few of the solder balls contact an object like the edge of the tray and the force is then concentrated on these balls. This can happen after an inspection for coplanarity and the socket is manually placed back into the tray. Other manual handling steps to watch out for is replacing miss-picked sockets back into the tray or when transferring from one tray to another.

Dynamic Warpage

Some package attributes affect its dynamic warpage behavior at high temperature. The main cause is Coefficient of Thermal Expansion (CTE) mismatch between substrate and silicon at high temperature. The rate of expansion of the substrate is higher compared to Si. With the presence of underfill material restraining the substrate expansion, it starts to warp. The warping effect will cause the solder ball to be lifted up from the solder paste on the board which increases the oxide growth on the surface of the ball as flux is absent. Some other attributes which modulate the dynamic warpage are die thickness, package form factor, underfill material CTE, package substrate layer count & substrate Cu distribution.

Shadow Moire Interferometry is recognized as a conventional and commercially available optical technique that determines the out of plane displacement or warpage from a surface contour. Shadow Moire Interferometry has been widely applied in the electronics packaging industry to study the warpage with relatively low displacement sensitivity with a large field of view. It gives 3D and 2D signature of the package during reflow as seen in figures 32 and 33.

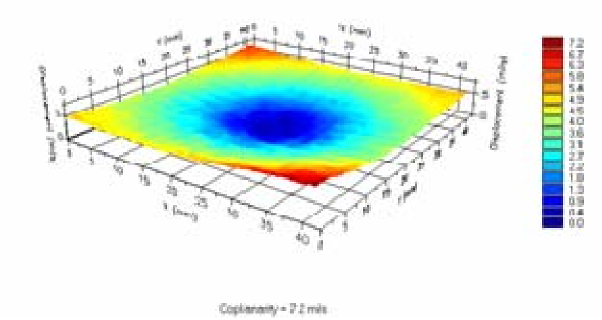


Figure 32. BGA warpage 3D chart

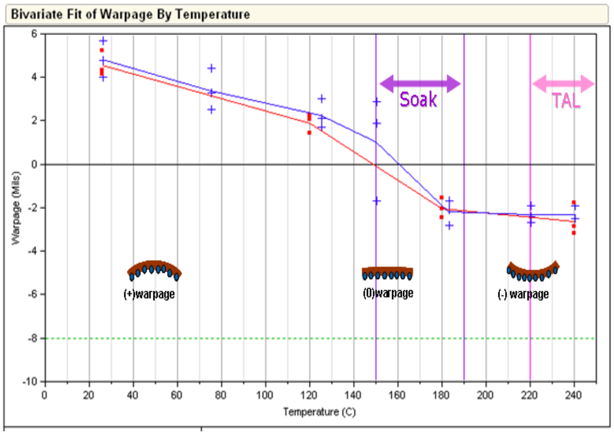
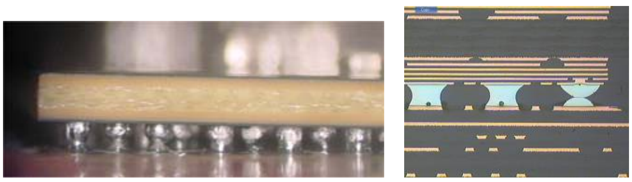


Figure 33. BGA warpage during reflow

Understanding the package warpage behavior at reflow temperatures is crucial in order to identify the associated risk to it. For a typical Flip Chip BGA package, the room temp shape is convex (frown) and it will transition into concave (smile) at high temp. This shows the risk of having a gap between the solder balls and board pads/paste in the corner regions. As a result, HnP defects will occurs at the package corner with stretched joints seen next to it. Figure 34a shows HnP on corner joints and stretched joints. Figure 34b shows a cross section of HnP at the corner and two stretched adjacent joints.



(a) (b)

Figure 34. BGA warpage HnP

Figure 35 shows the correlation of room temperature coplanarity to high temperature warpage. Generally, flip chip BGA packages with low coplanarity exhibit high warpage during reflow.

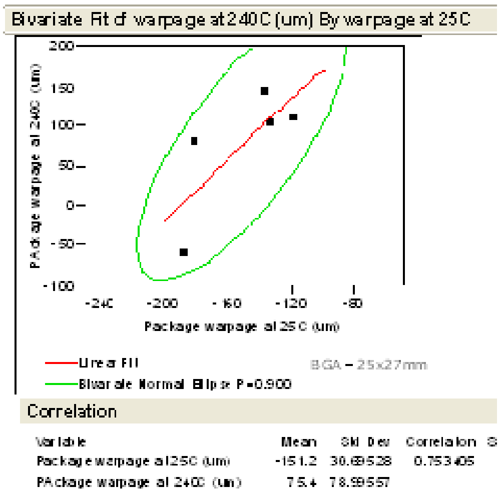


Figure 35. Warpage correlation between room & reflow temperature

One solution to mitigate the HnP defect rate caused by package warpage is to over-print solder paste on the PCB lands. This will reduce the gap between the solder paste deposit and the solder ball of the warped package and provide extra flux to clean the ball once the gap is closed.

Solder Ball True Position

There are two specifications for solder ball true position. The first is the solder ball location with respect to the socket body. The second is the position of the solder balls with respect to one another. This serves to locate the socket to the PCB and therefore it is necessary to insure that the relative position of the solder balls is controlled as tightly as possible to maximize solder ball joint strength. A poorly controlled solder ball location could result in a tilted solder ball shape which would be less reliable in use and shipping conditions and increase the likelihood of HnP formation. Because this is important for solder joint quality the ball to ball true position specification is tighter of the two. That is why the socket placement equipment should use the solder balls and not the socket housing to determine placement.

Figure 36 shows a typical call-out of the solder ball true position in a mechanical drawing of a BGA socket.

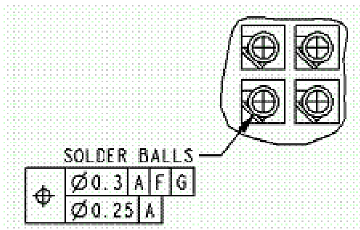


Figure 36. Typical call-out for solder ball true position in a mechanical drawing for a BGA socket.

Package Coplanarity

Thin substrate packaging is one of the solutions for miniaturization of electronic products. These thinner packages provide a reduction in overall package z-height. Unfortunately, the introduction of thinner packages often produces higher room temperature package coplanarity measurements, often exceeding the JEDEC Specification for these package types. Data from one case study presented in figure 37 shows packages with extremely high coplanarity which are not meeting the JEDEC requirement did not produce any HnP defects.

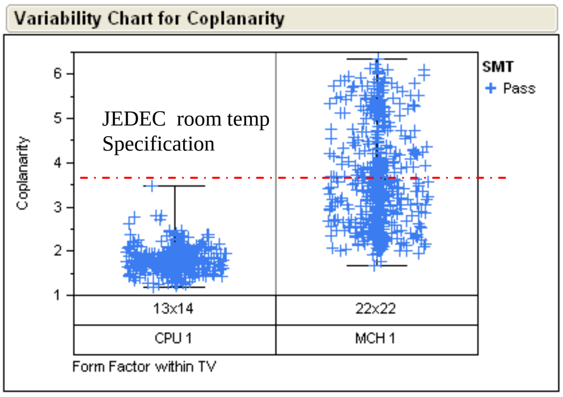


Figure 37. Coplanarity and SMT yield

Even when a small ball is present, no HnP were detected as shown in Figure 38. The substrate was relatively flat in this example.

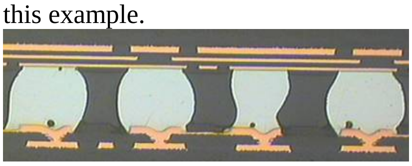


Figure 38. Small ball after SMT

Hence, data shows that room temperature coplanarity is not a main factor in HnP. Other modes are most likely to impact HnP defects.

Board warpage and sag

Boards warp during reflow can increase the gap between the paste on the board and the balls on the package. Usually there is more than one ball with head and pillow defect in this failure mode. Also, the adjacent joints look stretched. Board sagging, due to gravity, is usually a secondary effect and cannot cause HnP defect by itself.

When the board is too thin and not supported during reflow, board warpage can be a primary cause for HnP. A small test board of size 136x139mm with 4 different thicknesses was used to investigate this. The board was processed with and without a pallet. A HnP defect rate cliff was found with 0.024” thick board without pallet. The dominant defect was HnP as shown in Figure 39. The board warpage was measured during reflow by performing shadow Moiré analysis for each board thickness.

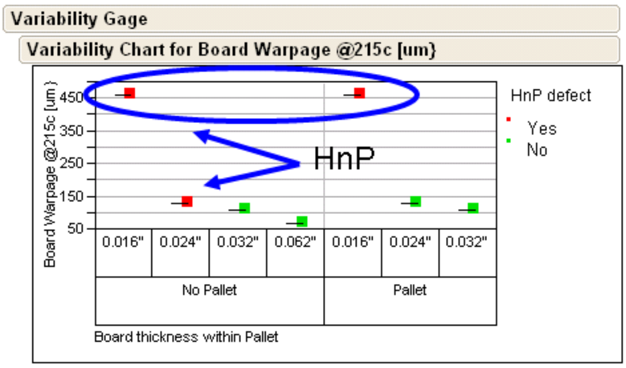


Figure 39. Board warpage DOE

Figure 40 shows a picture of a BGA socket whose corner has HnP defects. The board is warping down creating a gap between the paste and the balls.

Figure 40. Board warpage

A close up picture of this corner shows HnP on a number of adjacent joints, as seen in Figure 41.

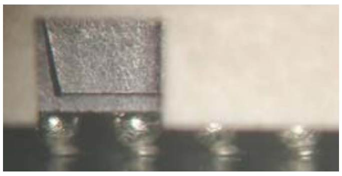


Figure 41. HnP due to board warpage

In order to prevent HnP due to board warpage a board support is needed during reflow. The data shows that a pallet can be successfully eliminate HnP defects up to 130 μm of board warpage. The board warpage limit for HnP without pallet is found to be 110 μm. These numbers will vary slightly depending on the package used and its own warpage behavior.

DESIGN RELATED FAILURE MODES

Board Design

Board design has a secondary impact on HnP. It was found that different boards have different sensitivity to the HnP defect when using the same package. This sensitivity is driven by thermal delivery, board stack up and internal copper layers under the pad. All of these have an impact on temperature differential between pads. This can cause time delay for the paste to melt increasing oxidation when a gap between the BGA ball and the paste exist. Figure 42 shows a high speed camera image of a pasted BGA site while reflowing. The first frame, Figure 42a, shows the pasted site being heated; the second frame, Figure 42b, shows that some of the pads melted and the paste coalesces while others did not melt. The third frame Figure 42c, shows that all but one pad melted and coalesced. The one that didn’t melt had a buried via. There was a melting time delay of 5 seconds across all pads.

(a) (b) (c)

Figure 42. Paste melting delay

Another example of copper density is shown in Figure 43. In this example, there was a 15% HnP defect rate difference on the same board fabricated by two board suppliers. The sensitivity to HnP found out to be related to anti-pads that were trimmed by one supplier and completely left out by another. This additional copper plane surrounding the via changed the heating rate causing melting time delay difference. These are nonfunctional pads that were invisible to the assembly house and the board designer.

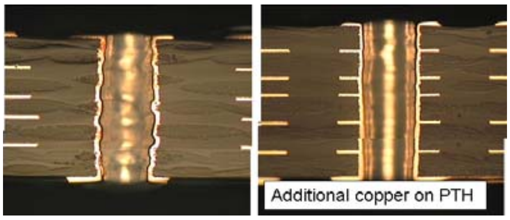


Figure 43. Paste melting delay

Most BGAs have interstitial vias under them. Via capping under BGA can impact the temperature differential between outside and inside balls. When the vias are non-capped, more heat can flow to the center of the package. Profile measurement shows 2-3 deg change on inner balls' temperature when using a non-capped via design, thereby decreasing dT.

Sensitivity to HnP was seen between solder mask define (SMD) pads and metal defined (MD) pads. Usually SMD pads end up with a larger pad diameter which will cause a smaller solder crest after reflow, as shown in Figure 44.

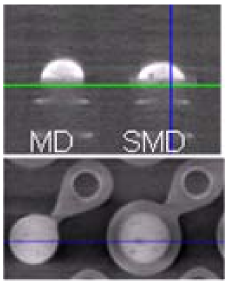


Figure 44. Crest height

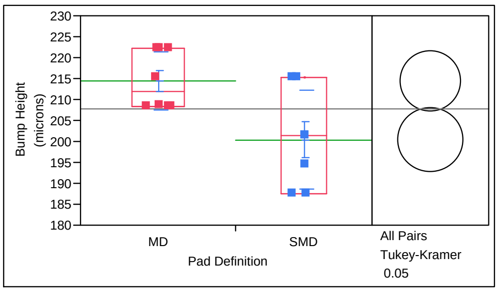


Figure 45. Solder crest height data

The pad sensitivity means that HnP will most likely occur on SMD pads and not on MD pad. Data shows ~87% more HnP on SMD pads. Although there is sensitivity to SMD pads for HnP defects, the pad design itself is not considered a primary cause.

Package Standoff

Figure 46 illustrates a BGA package with standoffs on the bottom. The standoff gap on a BGA is important during reflow for HnP defect. It is defined as the distance between the bottom of the package standoff to the tip of the solder balls.

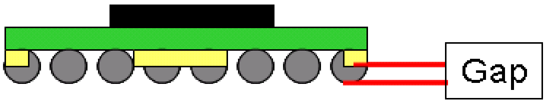


Figure 46. BGA with standoff

Some BGA packages have a standoff due to design requirements for shock, bridging or a controlled Z height to ensure minimum height after reflow. Some BGAs also have passive components on the bottom of their substrate to enhance the package electrical performance. In both cases during reflow the collapse of the solder balls may be limited.

Limiting the ball collapse during reflow can be crucial when package warpage exists. Any limited collapse will cause a larger joint height between the high warpage area on the package (usually the edges) and the paste on the board. In an extreme case, the ball and paste might not touch after collapse, and no joint will form.

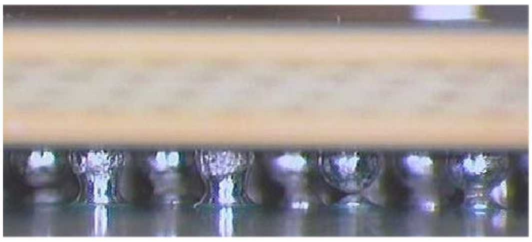


Figure 47. HnP and stretched joints

Usually this type of failure mode will exhibit HnP defect and stretched joints at the high warpage area. It is very similar to the warpage mode signature. If you get this failure mode signature and your package has a standoff, then the HnP root cause is the standoff. The defect will go away if the standoff is reduced or eliminated. Figure 47 shows a BGA with two stretched joints and two HnP defects caused by package standoff.

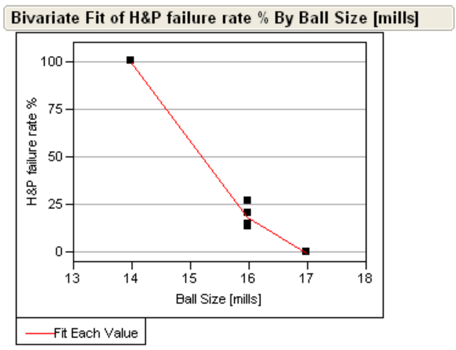


Figure 48. Ball size with standoff

A DOE was conducted to determine the impact of standoff on HnP. The standoff gap to the ball was changed by using different size balls on a BGA. In the DOE, the HnP defect rate moved from 100% to 0% over a 3 mils ball diameter range as shown in Figure 48. That range was sufficient to turn on and off HnP.

CONCLUSION

HnP is not an easy defect to solve since there are many failure modes that can cause this defect. This paper describes all known failure modes that can create and modulate HnP. Understanding these modes can be used to solve an existing HnP problem or avoid it from happening completely. In many cases, the HnP problem is very complex and consists of more than one failure mode at a time. The best problem solving approach would be to identify which are the primary failure modes that need to be addressed to solve the problem and how to make the assembly process more robust and not as sensitive to these modes. Using a nitrogen atmosphere in the reflow oven is an effective way to mitigate most of these problems and reduce or eliminate HnP on some of the failures modes. But, it will certainly not solve all HnP issues.

REFERENCES

1. Z.P.Xiong, H.P.Sze, K.H. Chua, `Bump Non-wet issue in large-die flip chip package with eutectic Sn/Pb solder bump and SOP substrate pad`, Proceedings of the Electronic Packaging Technology Conference, 2004, pp. 438-443
2. L.S.Darken and R.W.Gurry, Physical Chemistry of Metals, Mc-Graw Hill, New York, 1953.
3. W.W.Chin, C. C. Chong, L.H. Ng, C.S.Tay, `Air Reflow of Lead Free Soldering for Fine Pitch BGA', Proceedings of SMTAi Conference, 2006, pp. 100-106

ACKNOWLEDGMENTS

Many people from Intel contributed to HnP work. The authors would like to give special thanks to Satyajit Walwadkar, Srini Aravamudhan.