# A PROCEDURE TO DETERMINE HEAD-IN-PILLOW DEFECT AND ANALYSIS OF CONTRIBUTING FACTORS

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**ABSTRACT**

Head-in-Pillow (HIP) defects are a growing concern in the electronics industry. These defects are usually believed to be the result of several factors, individually or in combination. Some of the major contributing factors include: surface quality of the BGA spheres, activity of the paste flux, improper placement / misalignment of the components, a non-optimal reflow profile, and warpage of the components. To understand the role of each of these factors in producing head-in-pillow defects and to find ways to mitigate them, we have developed two in-house tests.

- ***Approach 1:*** In this approach a BGA rework station was used. A 35mm x 35mm, SAC305 PBGA package was placed on the test board. Rework profiles with different temperature gradients and varying solder paste formulations were used to create HIP defects. This test method showed the effect of: (i) Components, (ii) $\Delta T$ across the test board and (iii) Solder paste chemistry on HIP defect.
- ***Approach 2:*** In this approach a custom designed test set-up was used to place a single SAC305 solder sphere on a molten lead-free solder paste deposit. Spheres were placed at different times and temperatures to create varying HIP defect rates. This test method showed the effect of: (i) Sphere oxidation, (ii) Reflow profiles and (iii) Solder paste chemistries on HIP. Further, a detailed comparative study of a number of lead-free solder pastes was also completed.

Conclusions from these test methods are detailed herein. In particular, the focus was on the experiments run to understand the critical role of the flux chemistry on HIP defects. Initial results show that the paste flux chemistry plays an important role in producing and mitigating HIP defects. A quantitative comparison of the paste performance is also presented. In addition, the role of the reflow profile optimization for each of the pastes will be discussed. The main objective of this paper thus is to identify the root causes of the HIP defect and to investigate potential material and process solutions to minimize HIP.

Key words: Lead-free assembly, Head-in-pillow defect, process optimization, solder paste activity, oxidation (of BGA spheres) and BGA warpage.

## INTRODUCTION

Head-in-Pillow (HIP) defects are becoming major concerns for the electronics assembly industry. This defect is produced during the reflow of an assembled board when the printed paste deposit coalesces but sphere doesn't collapse and merge with the paste. Molten paste appears to wrap around the sphere but the two remain separate during the cooling process though physically and electrically in contact. HIP defects appear as a depression in the paste ("the pillow") with sphere ("the head") resting therin, hence the name. HIP defects are also referred to as Head-on-pillow, ball in socket or ball in cup defects.

There are number of factors contributing to the formation of HIP defects. Some of the major contributing factors include:

1. Poorly chosen reflow profile that either exhausts the flux activity before reaching the melting point, or insufficient peak temperature / time above liquidus.
2. Flux activity insufficient to completely coalesce paste deposit and BGA sphere.
3. Excessive warpage of components that increases the gap between the paste deposit and the solder sphere surface during reflow either for the peripheral spheres ("Smile") or the central spheres ("Frown").
4. Excessive surface oxidation of spheres.

## ASSEMBLY PROCESS MAP FOR HIP

Several papers have recently been published that list the failure modes of head-in-pillow defects (1 - 3). Few papers list the set-up that is used to create and test the HIP defect (3). Based on this literature search (1 - 5) and extensive in-house experiments (discussed further) we have developed a process map of a typical assembly process with potential for exacerbating this defect. This process map is shown in Table 1. Four aspects of the assembly process are considered – materials, stencil printing, component placement and reflow profile. Factors contributing to the HIP defect are divided into two categories: Critical factors (marked as blue in the table) and secondary factors that can accentuate the defect in interaction with other critical or secondary factors.

- Contributing factors in the materials category include – PCB, Component, BGA spheres and solder paste used. Solder paste, component warpage and BGA sphere oxidation are some of the most critical factors that contribute to the HIP defect. Each of these factors is further explained in Table 1.

- Stencil printing category includes two key factors – stencil used and printing process parameters. Stencil design (including the thickness, aperture design) plays a key role.
- Component placement includes positional accuracy as well as placement force. This step can contribute in combination with other factors in causing the HIP defect.
- Reflow is another key category. A non-optimal reflow process can directly affect - the paste performance, oxidation of the BGA spheres, and PCB warpage, all of which are key factors in HIP defect formation.

An attempt has been made to create a comprehensive list of all the key and secondary factors that will contribute to the HIP defect. By undertaking appropriate preventive measures for each of the assembly steps listed in Table 1, the HIP defect can be mitigated to a large extent.

## HEAD-IN-PILLOW APPARATUS DESIGN

To investigate the factors affecting the head-in-pillow defect, two approaches were used:

A. BGA REWORK STATION
B. A CUSTOM HIP TEST

**Table 1:** Assembly Process Map for HIP Defects

| ASSEMBLY PROCESS STEPS | | CRITICAL & SECONDARY HIP CAUSES |
|---|---|---|
| MATERIALS | Printed Circuit Board | PCB Warpage |
| | | PCB Oxidation |
| | | PCB Surface finish |
| | | Pad design (NSMD vs SMD) |
| | Component (excluding BGA sphere) | **Warpage of semiconductor component** |
| | | Substrate thickness |
| | | Die thickness and size |
| | | Mold Compound, CTE mismatch of die, component and die material |
| | | Ratio of die to component size |
| | BGA Sphere | **Oxidation of the BGA sphere** |
| | | **Alloy additives / Dopants** |
| | | Type of BGA Alloy |
| | | Variation in sphere size / coplanarity |
| | Solder Paste | **Solder paste chemistry / Activity of the paste flux** |
| | | **Solder paste volume / deposits** |
| | | **Solder paste wettability** |
| | | Paste alloy |
| | Stencil | **Aperture Design (Reduced vs. 1:1)** |
| | | Stencil thickness and solder paste volume |
| | | |
| STENCIL PRINTING | Stencil | **Aperture Design (Reduced vs. 1:1)** |
| | | Stencil thickness and solder paste volume |
| | Print Process Parameters | Print pressure, Print speed, etc. |
| | | |
| PICK AND PLACE | Component Placement | Improper component placement / misalignment |
| | | Pick and place parameters (placement force) |
| | | |
| REFLOW | Non Optimal Reflow Parameters | **Soak Time, Peak Temp., TAL, Cooling Rate, etc.** |
| | Reflow environment | Nitrogen vs. Air |
| | Mixed System Assembly | Different alloys (paste and BGA sphere) in an assembly process |
| | | |

**A. BGA REWORK STATION:** A BGA rework station was used to create and analyze HIP defects. A 35mm × 35mm SAC305 PBGA component was placed on a custom designed test vehicle. A special fixture was designed to hold the test vehicle together with the PBGA component, as shown in Figure 1. The rework station used in this experiment was Zhumao ZM-R5860 BGA Rework Station. Details of the test vehicle, stencil, component and assembly are as follows:

| **Table 2.** Process Details | |
|---|---|
| Test vehicle dimensions | A 50mm × 50mm coupon with a provision for 35mm × 35mm package placement |
| Stencil | 4 mil laser cut stainless steel |
| Component | 35mm × 35mm PBGA package with 1.0mm pitch |
| Solder pastes (SP) used | SPA (Standard chemistry)<br>SP B (Reduced HIP chemistry) |

**Assembly Details:** Two solder pastes (A and B) were printed on the test vehicle using a 4 mil stencil. To set and monitor the initial process, thermocouples were placed on the test vehicle at the centre and at the corner of the PBGA locations. Two reflow profiles (straight ramp and high soak) were then developed for this testing and are shown in Figure 2. A PBGA was vacuum picked, pre-heated and then placed on the test vehicle. Time and temperature were controlled for the placement of the component in the reflow profile.

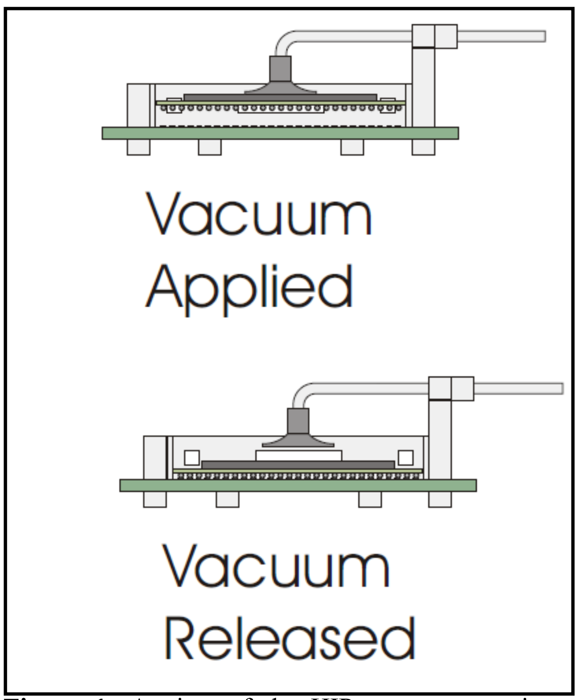


**Figure 1:** A view of the HIP test set-up using a BGA Rework station

In this assembly process, high ΔTs were noted between the centre and at the corner of the PBGA. This helped in creating HIP defects. As expected paste A and paste B behaved differently and gave varying HIP results. Results of the HIP testing with the two solder pastes are shown in Table 3 and Figure 3 a-e below. Percent HIP are calculated by dividing 36 opportunities at the center block of the PBGA component.

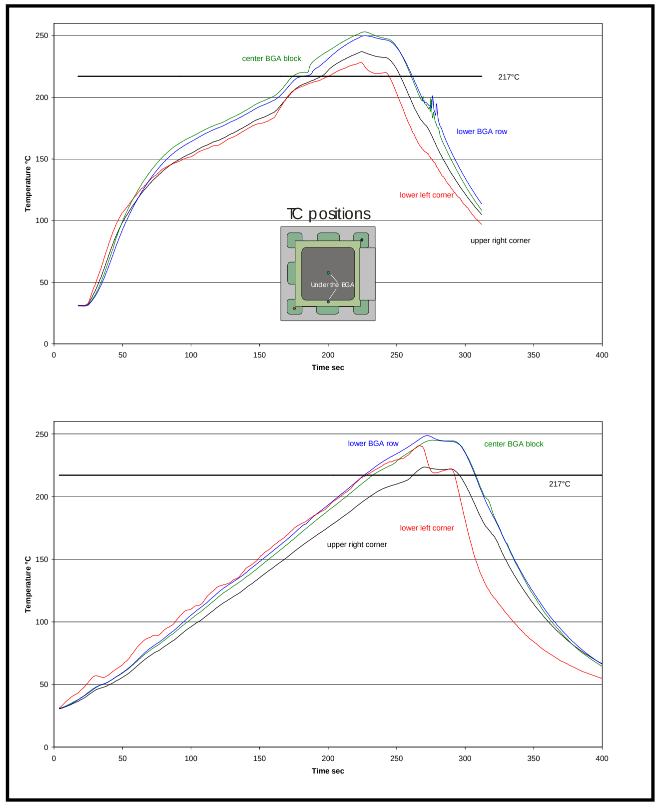


**Figure 2:** High Soak and Straight ramp reflow profiles

| **Table 3. HIP Test Results** | | | | |
|---|---|---|---|---|
| Solder pastes | Profile 1 | Profile 2 | Average HIP | % HIP |
| SP A | 33 | 23 | 28 | 77.7 |
| SP B | 1 | 1 | 1 | 2.8 |

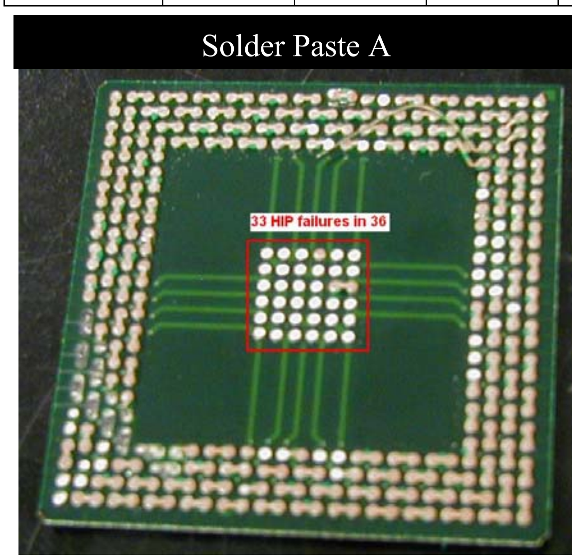


**Figure 3a:** PBGA component showing 33 HIP defects

**Figure 3b:** PBGA component pryed from the test vehicle

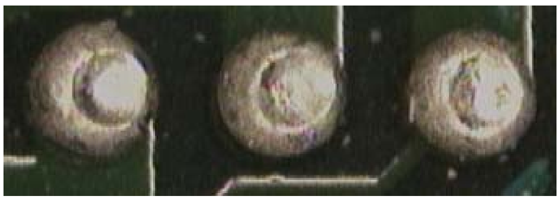

**Figure 3c:** Obvious HIP defects

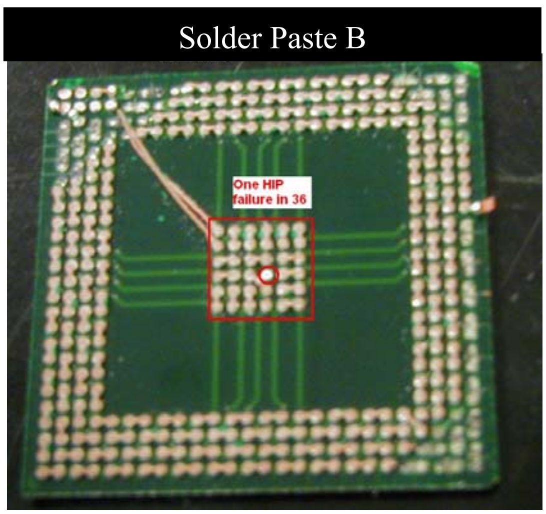


**Figure 3d:** PBGA component showing 1 HIP defect

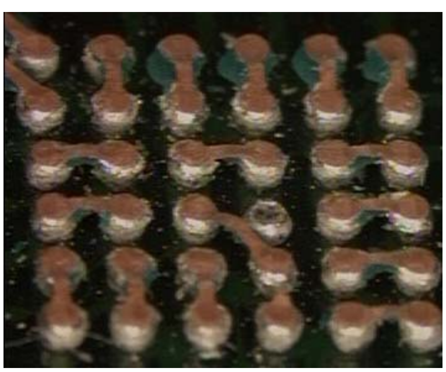

**Figure 3e:** PBGA component pryed from the test vehicle

These test results corroborated that solder pastes can be designed/formulated for the desired activity that will have varying effect on the HIP formation. Solder pastes that are properly optimized can drastically reduce the HIP defects in combination of the reflow profiles used.

**B. ALPHA CUSTOM HIP APPARTUS:**

To systematically investigate the factors affecting the head-in-pillow defect formation, a new apparatus has been designed. This apparatus allows for further elaboration of the HIP defect creation as compared to the BGA rework station discussed above. This test apparatus consists of:

- ***Precise Temperature controlled rapid rise heater:*** This heater is used to heat the test substrate used in the study. Number of ramp and soak steps can be used to set the reflow profile similar to that seen by typical circuit boards in a reflow oven.
- ***PCB placement:*** On top of the heater is an aluminum plate with a precisely defined area for placing a test board with the BGA388 design. The test board can be repeatedly placed at exactly the same location every time (see figure 4). The heater assembly is on a manual x-y stage enabling the test board to be aligned with the solder sphere to be placed.
- ***BGA Sphere Pick up head:*** A specially designed pick up head picks and places a sphere on a paste deposit. The apparatus can be programmed to place spheres at a defined height in / over a solder paste deposit (see figure 5). Placement of the sphere at a given time or temperature enables experimentation and creation of HIP defects.
- ***Video recording:*** A high magnification, high resolution video camera monitors the whole reflow process, paste coalescence and solder ball collapse in-situ.

In a conventional reflow oven, BGA components warp due to the differing CTE's of the various materials in the component package. This warpage causes some of the solder spheres on the component to become separated from the paste deposits in which they were placed. In this scenario solder spheres are not in contact with the paste deposit during parts of the reflow cycle. This usually happens during the heating segment of the reflow. During the later parts of the reflow cycle, the component returns to its original shape, bringing spheres back into contact with the paste deposit. In some situations these spheres do not completely melt and merge with the reflowed paste, resulting in a head-in-pillow defect. Thus, to create head-in-pillow defects with this apparatus and study the factors influencing them, we place heated spheres on paste deposits at a predetermined time during the reflow cycle to simulate BGA warpage. Before placement the sphere is picked by a vacuum pick up head which is maintained at a predetermined temperature that is slightly below the melting point of solder alloy (see figures 4 and 5). The sphere pick-up head is attached to a precise motorized linear stage which is controlled by the same software. Once the sphere comes to the preset placement position the vacuum is switched off automatically, releasing the sphere. Temperature and time are recorded with each frame captured. Figure 5 includes a frame of recorded video where the sphere pick-up head has just moved to the placement position.

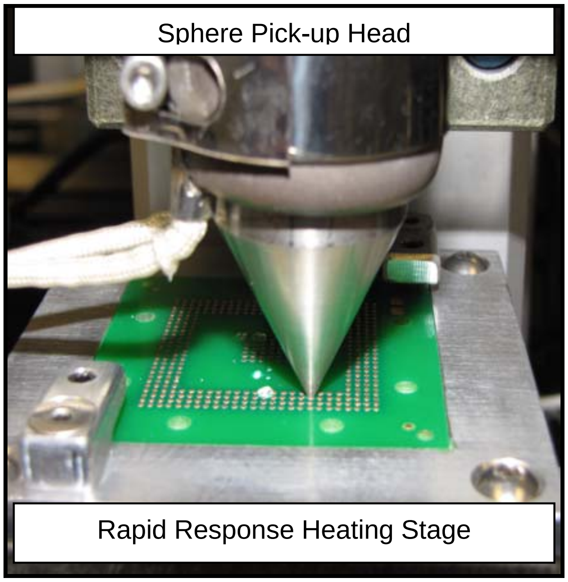


**Figure 4:** A view of the HIP test apparatus

**SETTING AND VERIFYING REFLOW PROFILE**

Control of the reflow profile is critically important in producing and mitigating head-in-pillow defects. A proper choice of the reflow conditions can greatly reduce and possibly eliminate the defect. Therefore, precise control and the capability to modify the profile are important factors for successfully investigating the HIP defect. Our apparatus can reproduce any reflow profile encountered in a typical SMT assembly process.

In addition to control, the repeatability of a particular reflow profile is essential to accurately assess the tendency of HIP defects to form. Our apparatus can generate a heating profile with repeatability / reproducibility at least as good as a conventional reflow oven. Figure 6 shows six measured temperature profiles superimposed. In all six runs, the temperature at any given time is reproduced within 5 degrees. This repeatability is comparable to a typical reflow oven. Similar validation runs were conducted each time a new profile was tested.

**RESULTS AND DISCUSSION**

The first set of experiments was run to compare two pastes (labeled Paste 1 and Paste 4). Knowing the chemical composition of the pastes, it was understood that Paste 1 was more active than Paste 4. In this test, the paste was printed on the circuit board using a 4 mil thick stencil with aperture size matching 1:1 with the pad diameter. The board was placed on the heater and reflowed. The reflow profile included a soak time of 2 min at 160°C before ramping up to a peak of 225°C. The relatively long soak and low peak temperature were intentionally chosen to increase the likelihood of HIP defect formation. The hold time at 225°C was long enough for the solder balls to collapse completely. The solder ball, held at 180°C, is dropped at a pre-determined time. Solder spheres used in this experiment were pre-conditioned at 200°C in air for 24 hours to further oxidize the sphere surfaces and increase the tendency to

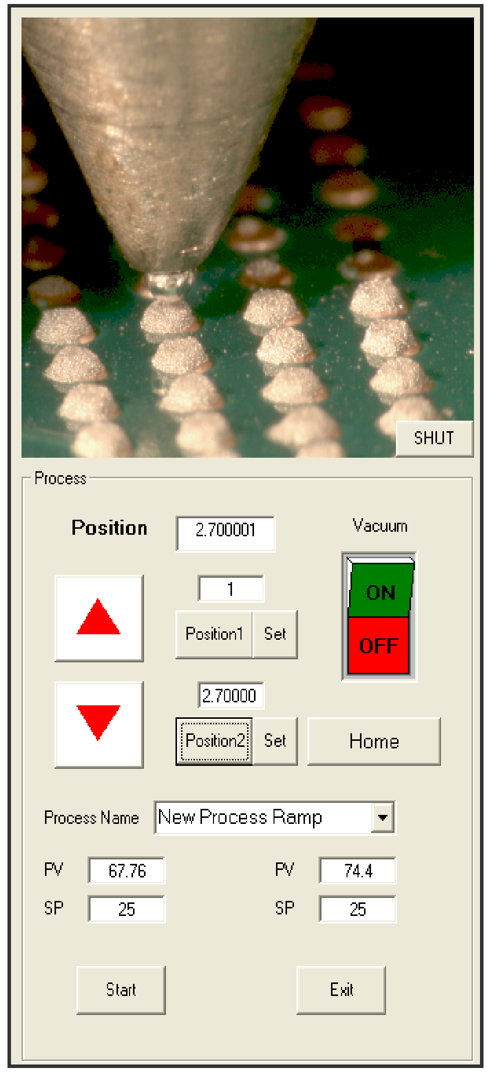


**Figure 5:** Front panel of the computer control interface

form HIP defects, enabling discrimination between the pastes being tested. The ball drop time was exactly the same for all the runs with both pastes. Video recording began just before ball drop and continued until the end of reflow. From the recorded video time and temperature, the time taken for the paste to coalesce and the sphere to collapse is determined. The sequence of events for both the pastes is shown in figure 7. Actual measured data is shown in Table 4.

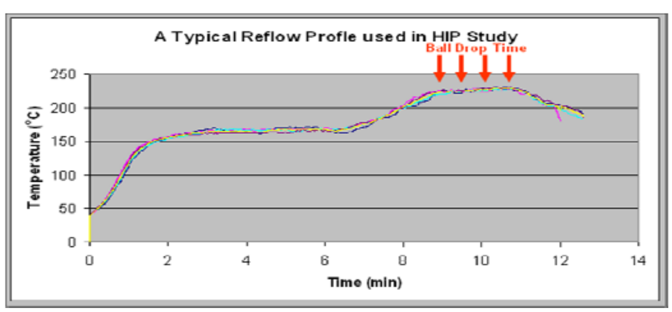


**Figure 6:** One of the profiles used in the HIP study. Temperature reproducibility is within 5-6°C, which is comparable with a typical reflow oven.

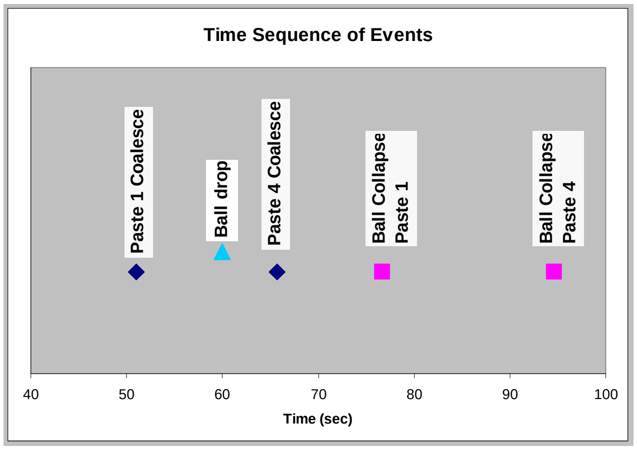


**Figure 7:** Sequence of events is shown in this study of pastes.

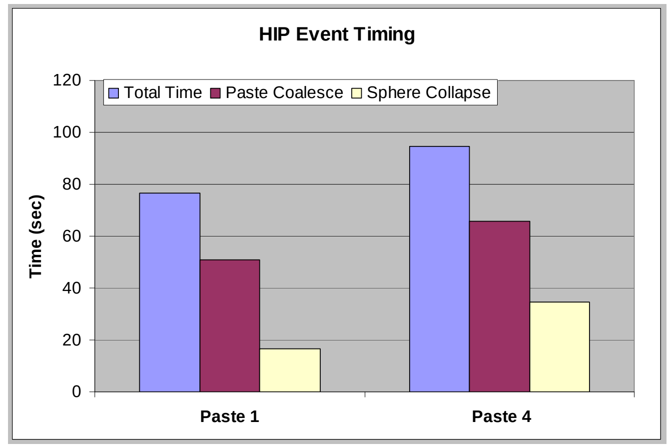


**Figure 8:** Comparison of coalesce and sphere collapse times.

Paste 1 started to coalesce around 51 sec while Paste 4 coalesced around 66 sec. Therefore, in this case, Paste 1 was already in liquid form when ball was dropped while Paste 4 had still not completely reflowed. The ball dropped on to Paste 1 collapses completely around 77 sec, while with Paste 4 it takes roughly 95 sec for the same. Both of these observations are consistent with the fact that that the flux used in Paste 4 had lower activity than that in Paste 1.

**Table 4:** Time for the paste to coalesce and sphere to collapse

| Paste | Time for paste Coalesce | Time to Sphere Collapse (sec) | | |
|---|---|---|---|---|
| | | Total | From Ball drop | From Paste Coalesce |
| Paste 1 | 51 | 76.7 | 16.7 | 25.7 |
| Paste 4 | 65.7 | 94.7 | 34.7 | 29 |

Alternately, one can calculate the time for the solder to collapse from the time ball is placed on the paste. This data is shown in the 4th column of Table 4. Still another option is to calculate the time for solder ball collapse starting from the paste coalescence. This data is shown in the last column of Table 4. All of these measurements show a slower wetting with Paste 4 as compared to Paste 1. The same data is shown graphically in figure 8.

Results shown above clearly indicate that the paste activity has a major impact on coalescence and wetting time. A slower wetting paste is less likely to sufficiently penetrate the surface oxide on the solder sphere in a short TAL profile. Suppose in this case our reflow profile starts cooling around 90 seconds, then Paste 4 would not have collapsed the sphere and would have resulted in a HIP defect.

In the second set of experiments the effect of a delay in the solder ball placement on the solder joint formation was investigated. This was to simulate the effect of component warpage, its resultant effect on the HIP defect and role of the solder paste in mitigating the defect. Component warpage during reflow will result in separation between individual solder spheres and their associated print paste deposit during heating portion of the reflow. At some point during the cooling, the warpage is reduced and the solder ball comes back into contact with the solder paste once again. If the flux in the solder paste has retained sufficient activity when the solder ball comes in contact with it, the solder ball will collapse, and no HIP defect will be formed. If the paste has lost considerable activity during the heating profile then by the time the solder ball comes in the contact position, the flux may be unable to sufficiently penetrate the oxide layer on the solder sphere, resulting in a HIP defect. Therefore, a study of the effect of the delay in sphere placement from the time the paste reaches the peak temperature will provide insight into the behavior of the paste. A robust paste should show small variation in the paste activity over time at high temperature. A non-optimal paste will show poor thermal stability and lose its activity quickly at high temperatures. In many cases, the activity loss is so much that the paste will not reflow the sphere at all. Four different pastes were used in this experiment.

Figure 8 shows the fraction of the sphere collapse as a function of the time delay in placing the solder sphere. Both the paste and sphere alloys are SAC305. The peak reflow temperature is 226°C. Once again the spheres were oxidized in air at 200°C for 24 hours. Paste 1 and Paste 2 show little change in sphere collapse up to a 30 sec. placement delay while Paste 3 shows a 30% drop, and Paste 4 shows a 66% drop in sphere collapse fraction. After 60 sec. delay, all the pastes show little to no ability to collapse the oxidized spheres. That means that in worst case situation, severe enough warpage leading to excessively long delayed contact between spheres and paste, will result in an HIP defect being generated for all the pastes. In middle range, Paste 1 and Paste 2 have low probability of producing an HIP defect as compared to Paste 3 and Paste 4.

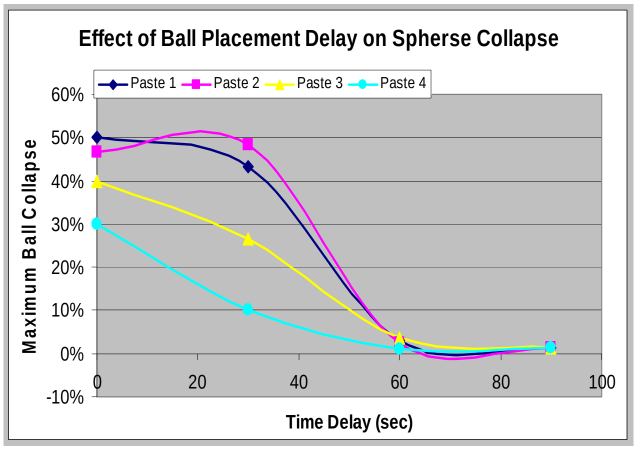


**Figure 8:** Dependence of sphere collapse on the time delay between the paste coalescence and the ball placement.

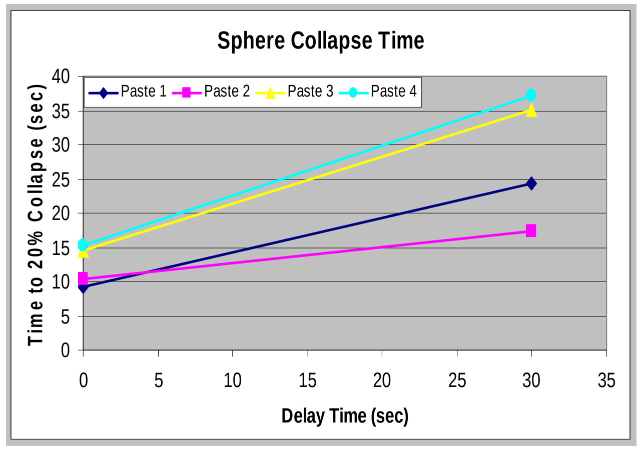


**Figure 10:** Dependence of the time for 20% sphere collapse on the delay in ball placement.

Further, Figure 9 shows the images of Paste 1 for the time delay experiments. If the solder paste is kept at high temperature the paste activity decreases with time; time to collapse thus increases. Pastes optimized for robust activity and wetting will significantly reduce the occurrence of HIP defects.

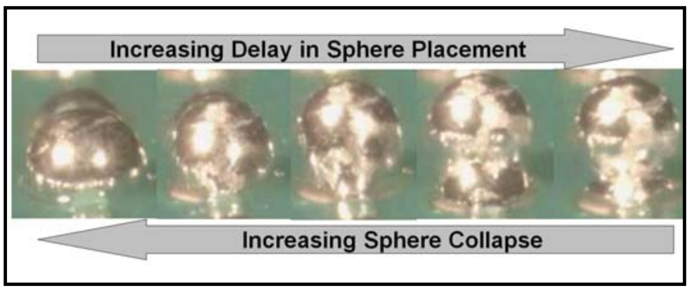


**Figure 9:** Collapse of solder sphere as a function of sphere placement time (time delay in placement in creating HIP defect)

An alternate way of looking at the same data is to compare the time to a fixed percentage of sphere collapse for all the pastes as a function of the delay time. Figure 10 shows time to 20% collapse of the sphere for all four pastes for 0 and 30 sec. delay. For Paste 1, the time increases from about 9 sec. to 24 sec., for paste 2 from ~8 sec. to 16 sec. while for Paste 3 and Paste 4 it increases from ~14.5 sec. to ~36 sec. Paste 2 shows good stability, hence less likely to form HIP defects, while Paste 3 and Paste 4 show a large increase in time to collapse thus making them more likely to produce HIP defects.

## SUMMARY

To investigate the root causes of head-in-pillow defects, a new apparatus has been designed, built and tested. This apparatus is designed to record the solder joint formation process in-situ using different solder pastes, BGA spheres and different reflow profiles to show their effect on HIP defect creation. It has been demonstrated that the activity of the solder paste flux package is an important variable in determining the speed with which a solder sphere is merged with its associated paste deposit during reflow and hence an important factor in the HIP defect level for a given assembly process. It has also been shown that pastes tend to lose activity at different rates if kept at high temperature. A paste that loses activity quickly will have a narrow process window beyond which it is more likely to produce HIP defects.

## REFERENCES


1. "Head-And-Pillow SMT Failure Modes", Amir, D., et al., SMTA, San Diego, 2009.
2. "Head-On-Pillow Defect – A Pain in the Neck or Head-On-Pillow BGA Solder Defect", Chris Oliphant, Bev Christian, Kishore Subba-Rao, Fintan Doyle, Laura Turbini, David Connell and Jack Q. L. Han, APEX 2010
3. "A Novel Approach to Experimentally Create and Mitigate Head-in-Pillow Defects" Guhan Subbarayan, Scott Priore and Sundar Sethuraman, APEX 2010.
4. "Addressing the Challenge of Head-In-Pillow Defects in Electronics Assembly", Scalzo Mario, APEX 2010.
5. "Telecommunications Case Studies Address Head-In-Pillow (Hnp) Defects and Mitigation through Assembly Process Modifications and Control", Russell Nowland, Richard Coyle, Peter Read and George Wenger, APEX 2010.