A Novel Approach to Experimentally Create and Mitigate Head-in-Pillow Defects

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Abstract
One of the solder joint failures encountered frequently during Printed Circuit Board Assembly (PCBA) is due to Head-in-Pillow (HiP) defects. The primary cause of HiP defect is due to the warpage of the component during the reflow process. The ultimate solution for solving HiP is to eliminate component warpage however that is very difficult to accomplish in all packages due to various material and construction constraints. Hence, there is a need to find other approaches to solve this problem. One effective solution would be to investigate a solder paste that can mitigate HiP defects.

The theory investigated here presumes that had the BGA spheres maintain contact with the main card solder paste the HiP defect would not occur. Therefore it is during SMT reflow that package warpage raises the BGA sphere(s) up off the applied solder during flux activation and reflow. The BGA sphere only returns to contact the melted/coalesces solder paste during cooling when the package has begun to return to its initial flatness. At this point either the flux is exhausted and is unable to form the joint or the flux itself has created barrier between the two solder features, BGA sphere and PCB solder bump created from the reflow paste on pad.

The Head-in-Pillow defects parts per million (DPPM) level would require a DOE sample size in the thousands therefore this study devised a method to create Head-in-Pillow defect in a controlled lab environment. This method eliminates the use of expensive problematic BGA components and instead applies control over reflow conditions and timing of the contact between the solder ball and the melted solder paste. The SRT BGA rework machine was used to effect programmable control of the time and temperature profile and sphere contact timing.

A baseline SRT process was established using a solder paste common to multiply production line exhibiting HiP defects. The baseline profile was modified until the baseline solder paste consistently created HiP defects. Using these same programmed SRT parameters eight other no-clean solder pastes from different vendors were evaluated. A high resolution video camera was used to record the entire reflow process and track the occurrence of the HiP joint. The performances of all the pastes were analyzed to determine the best solder paste to mitigate HiP defects. The results of this study were incorporated into production and were further validated through the elimination of the HiP joint defect. This test method provides engineers a means to evaluate a solder paste effectiveness in mitigating HiP defects.

Introduction and Background:
Head-in-Pillow (HiP) is a defect that occurs due to the non-coalescence between the solder ball of a component and the solder paste printed on the pad during the reflow process. This defect resembles the appearance of a head placed on the top of a pillow as illustrated in Figure 1 and is also sometimes referred to as "ball-in-socket" joint [1]. HiP joints maintain partial contact between the printed solder paste and the BGA ball and can escape X-ray inspection and pass electrical tests (functional and In-Circuit tests). However, as these joints are poorly formed at best they pose a significant risk of infant failure in the field. Hence the elimination of this defect is paramount in maintain high production yields and field reliability.

The mechanism for HiP defect formation is fairly understood. It occurs in four stages during the reflow process as shown in Figure 2. Initially when the BGA is placed on the solder paste, all the solder balls make contact with the solder paste. As the temperature increases, some BGA packages warp due to Coefficient of Thermal (CTE) mismatch, causing the corner balls of the BGA to lose contact with the solder paste. This stage happens somewhere during the soak zone of the reflow process depending on the warpage characteristics of the package. Since the solder ball is not in contact with the solder paste the solder balls becomes oxidized due to the absence of flux. Once the reflow temperature reaches the melting point of the solder, both the solder paste and solder ball melt, however the sphere and paste still are not making contact with each other. At some point during the cooling stage, when the package reverses back to its original shape, the solder ball makes contact with the solder paste . At this stage, if the flux is not active enough to break the oxide layer present on the solder ball before the solidification process, there will be non-coalescence between the solder paste and solder ball resulting in a HiP defect.

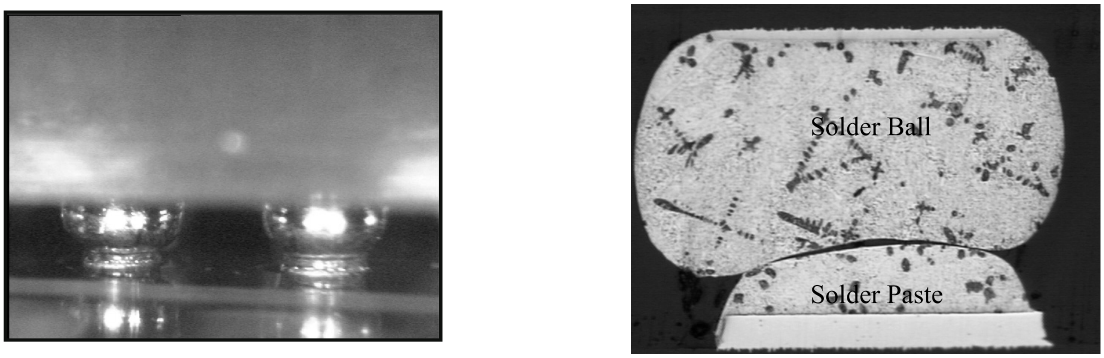


Figure 1: Sideview and Cross-Section Images of a Head in Pillow Defect

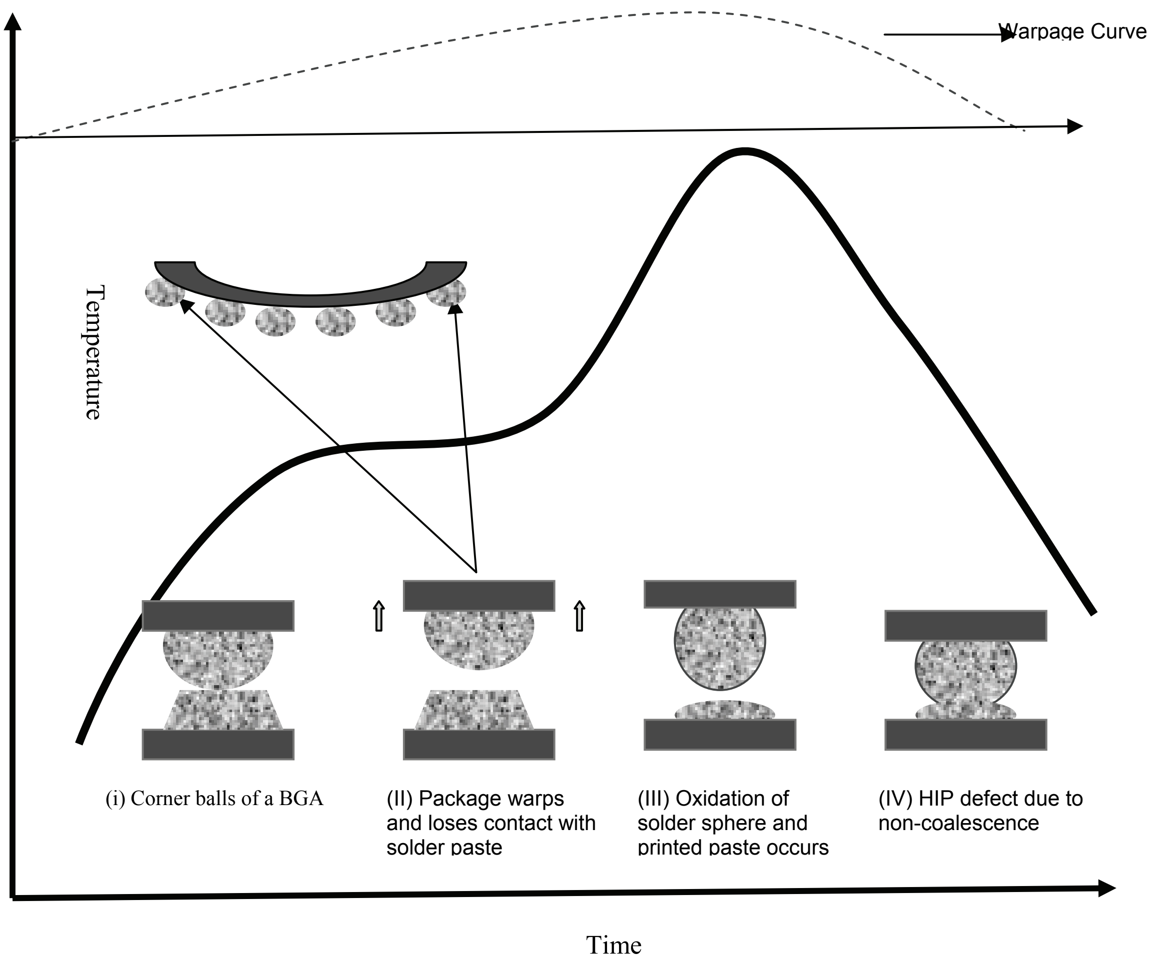


Figure 2: Mechanism of Head in Pillow Defect Formation

There are several factors that causes HiP defect as shown in fishbone diagram, Figure 3. The most effective solution for solving HiP defects would be to reduce warpage as much as possible. The JEDEC specification allows a maximum component warpage of 8 mils, however, during package reflow that warpage can increase. Recently, new "At Temperature" co-planarity specifications had been adopted. In printed circuit board assembly (PCBA), it was found that the selection of solder paste is a significant factor that can influence the formation of HiP defects. A solder paste designed specifically for

HiP can effectively mitigate HiP defects. Some key properties of the solder paste that helps in mitigating HiP defects are discussed later.

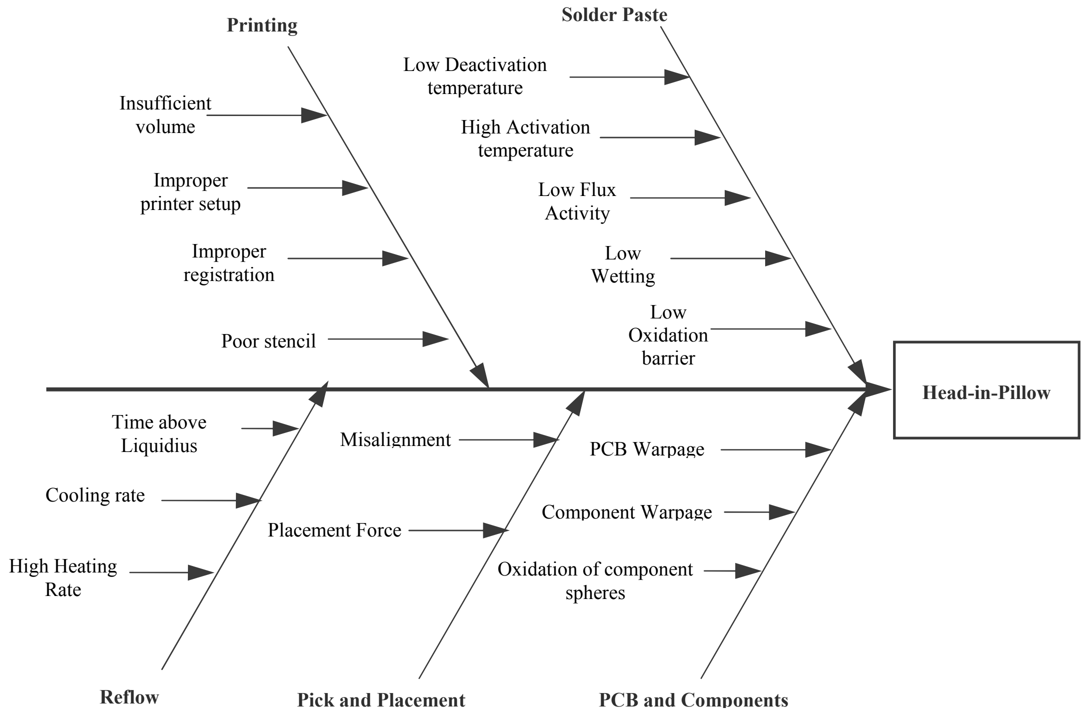


Figure 3: Fishbone diagram for HiP defect

A few studies have been conducted on HiP defects previously [1, 2, 3, 4]; however there is not a methodology that will simulate the package warpage in a reflow process. In this study, a novel approach to create HiP experimentally using a rework machine was developed. The purpose of developing this methodology is to evaluate solder pastes that can effectively mitigate HiP defects. The outcome of this study will help solder paste suppliers to design solder paste to mitigate HiP defects. Additionally it will also provide OEMs and CMs a test method and guideline to evaluate solder pastes for mitigating HiP defects.

Experimental:

Experimental Methodology: The schematic setup for this experiment is illustrated in Figure 4. As shown in this figure, a BGA rework nozzle was used to place a single solder ball on a single test pad with solder paste printed on the pad. The BGA rework equipment was also used to reflow the solder ball and solder paste, while controlling the movement of the solder ball with respect to the solder paste on the pad. The purpose of controlling the movement is to mimic the movement of the corner balls of a BGA as they warp during the reflow process.

A single pad from the test vehicle shown in Figure 5 was used as the test pad for the experiment. The pad was 24 mils in diameter with OSP surface finish. A mini stencil of 6 mils thickness was used to print solder paste on the test pad. The solder paste was measured to ensure it doesn’t exceed tolerance of +- 1 mils. A no clean SnPb solder paste with a known history of HiP defects was used as the baseline paste. The next process was component preparation. A single wafer from a BGA connector was removed from the housing manually. All the pins on this wafer were removed except the center pin. A custom fixture was developed to hold the solder ball to the pick-up tube of the rework equipment. The wafer was held by vacuum during the reflow process. To control the height at which the solder ball makes contact with the solder on the PCB pad, a metal shim was placed on the PCB surface directly underneath the holding fixture. This ensured a consistent contact height, irrespective of board warpage.

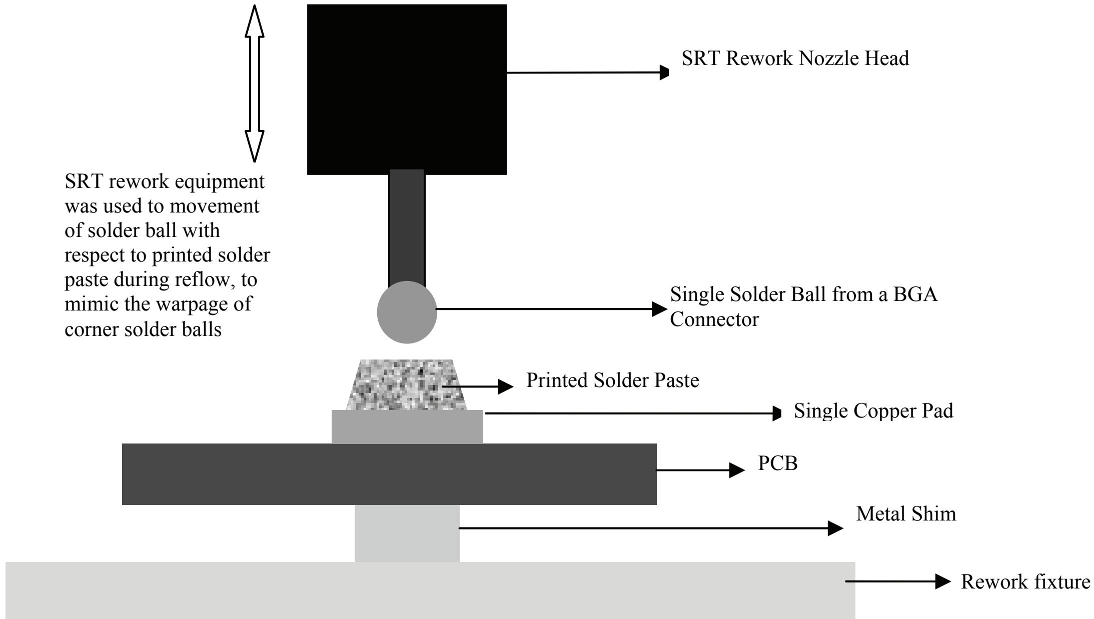


Figure 4: Experimental Setup

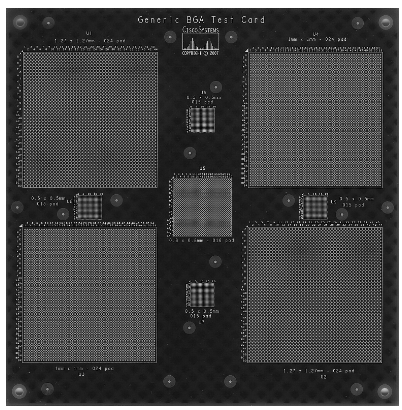


Figure 5: Test Vehicle

A typical SnPb thermal profile was developed with the parameters listed in Table 1. Then the board was mounted on the rework machine and the solder ball was mounted to the pickup tube of the rework equipment. The solder ball was then aligned to the center of the solder pad. This is a critical step as any misalignment will cause HiP defect irrespective of the solder paste used and skew the results.

The most challenging part of this study was to find the right conditions that will create HiP defect. Several trial runs were performed to establish a process and identify the critical test parameters. Two possible scenarios were considered:

a) The solder ball is in contact with the paste initially, then it's moved up during the preheat stage and makes contact again during the cooling stage.
b) There is no initial contact between the solder ball and the paste and the ball makes contact with the paste at some point during the cooling stage. This is a worst case scenario compared to the previous scenario.

With scenario A, no HiP defects were created. However HiP defects were created using scenario B at conditions C1 and C2 shown in Figure 6.

C1. Initially there is no initial contact between the solder ball and the paste. Then at 200 ° C during the cooling down phase, the solder ball is pulled down slowly (1 mil/second) so that it makes contact with the solder paste.

C2. Initially there is no initial contact between the solder ball and paste. Then at 190 °C during the cooling down phase, the solder ball is pulled down slowly so that it makes contact with the solder paste. This condition is similar to C1 but there is less contact time before solidification.

The pickup tube was positioned at about 16 mils above the PCB surface as shown in Figure 7 at the start of the sequence. When the test condition is reached, the solder ball was released by turning the vacuum off as shown in Figure 7. The entire sequence was recorded by video which will clearly track the occurrence of HiP defect. After reflow the joint was inspected with a microscope to confirm the HiP defect. An example of a good joint and HiP joint is shown in Figure 8.

Table 1: Thermal Profile Parameters

Preheat time (between 100°C and 150°C)	65 sec
Soak time (between 150°C and 170°C)	120 sec
Solder Joint Peak Temperature	220°C
Time above Liquidus	88 sec

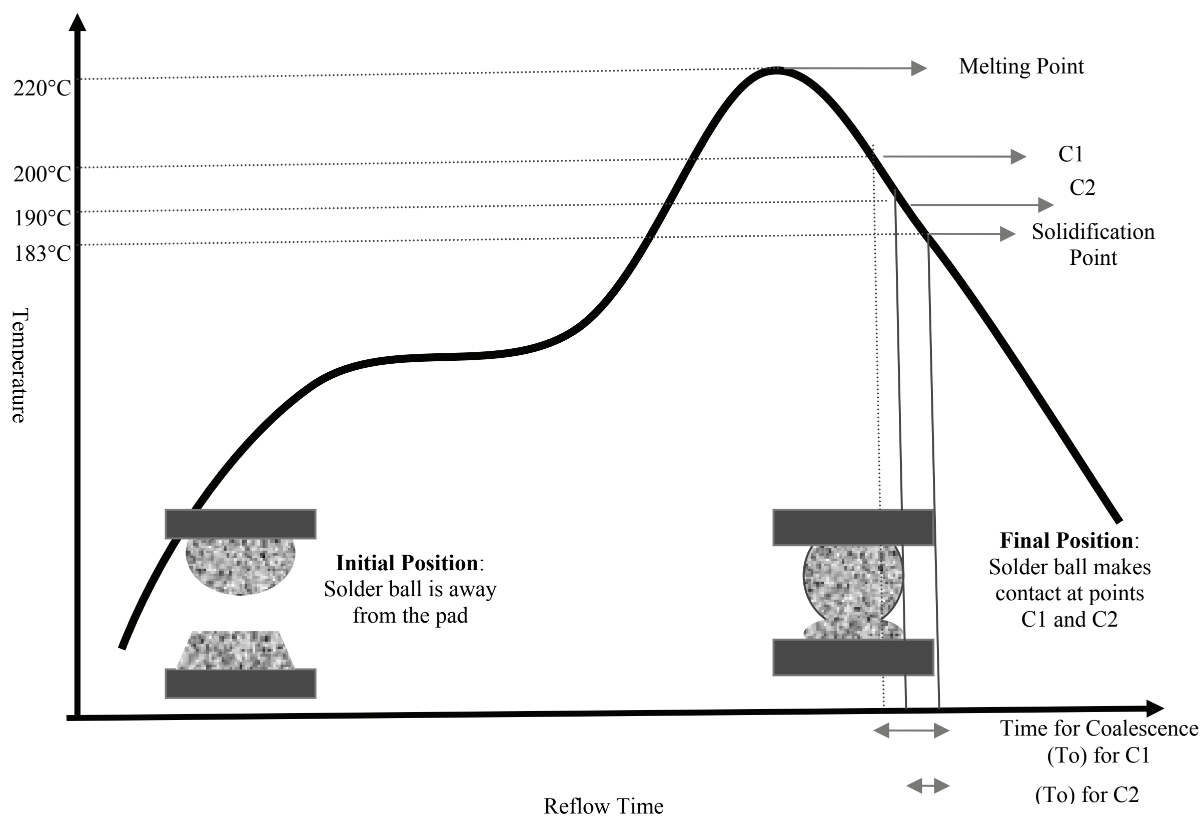


Figure 6: Conditions for HiP Defect

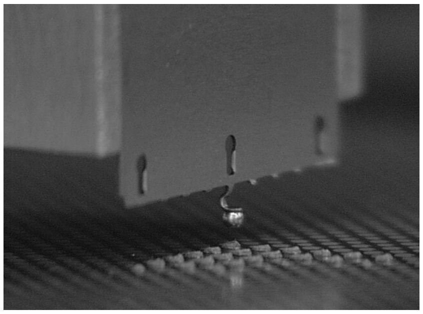
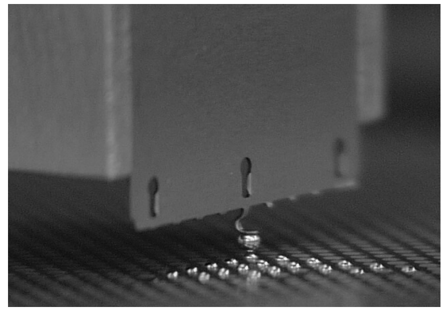
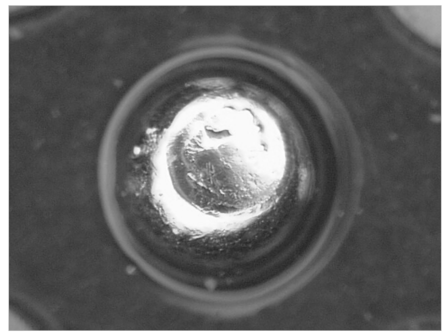


Figure 7: Solder ball position at preheat stage



Solder ball during cool down stage making contact with solder paste.

Figure 8: Good Joint.



HiP Joint

Solder Paste Candidates: A total of eight SnPb no-clean solder pastes were evaluated with base conditions C1 and C2. A total of 10 sample trial runs were performed for each solder paste. The nine solder pastes were from nine solder paste suppliers and were selected based upon their recommendation. All the solder pastes were designed specially to mitigate HiP defects. Table 2 enumerates the solder paste candidates and their properties for mitigating HiP defects. This data was provided by the paste suppliers. It's important that the qualifying pastes should not create other problems while trying to solve HiP defects. So they were selected only after they satisfied the selection criteria listed below:

- Should pass the SIR testing of Telcordia GR-78. The test should be performed at a lower temperature of 205°C instead of 215°C, to ensure that the residues are fully deactivated even at a lower temperature, as otherwise it may pose a reliability risk.
- Should pass the Ionic Contamination test of IPC- J STD-001.
- Should pass the standard printing and solderability tests.
- Should not produce defects such as voiding, tombstoning, bridging etc.
- Should have good pin probing characteristics.
- The flux of the solder paste should be compatible with the wave soldering fluxes.

Results and Discussion:

First a total of trial runs were performed using the baseline solder paste A at condition C1. Each trial run was recorded by video and time for coalescence (T_0) was noted. Ideally the T_0 should be constant but in reality its values for each trial run. Therefore the wetting was classified into four levels based on the T_0 value and each is given a weighted average. The total weighted average for each solder paste is calculated by summation of individual trial run average.

1. Immediate coalescence (Fast Wetting): The solder ball immediately coalesces after contact with the solder paste. This denotes the best performance and given the highest weighted average of 0.75.
2. Slow wetting: The solder ball and paste coalesces between 1-10 seconds. This outcome is given a weighted average of 0.20.
3. Very Slow wetting: The solder ball and paste coalesces after 10 seconds. This outcome is given a weighted average of 0.05.
4. HiP Defect: If the solder ball doesn't coalesce at all it results in a HiP defect. It's given the least weighted average of 0.

The results for condition C1 is graphically shown in Figure 9 and the total weighted average is listed in Table 3.

Table 2: Solder Paste Candidates

Solder Paste	Properties for mitigating HiP defects (Data from Paste Supplier)
A (baseline)	This paste has a history of HiP defects.
B	- The flux retains more of its activation after prolonged reflow profiles. One cause of Head in Pillow (HiP) is the movement of the BGA away from the paste deposit (the BGA component smiles). If the flux activation is used up in the reflow profile and the BGA balls returns to the paste deposit without having collapsed, non-wetting of the BGA will result in the HiP defect. This paste was designed to remain active under longer thermal profiles than any other tin/lead pastes that the paste supplier make (in fact, it can withstand a Pb free soak profile; up to 3 minutes from room temperature to peak in air, even longer in Nitrogen). - Low paste volume can also add to the chances of a HiP defect. As an example: if there is a 5 mil thick deposit of paste, and the sphere is placed 3 mils deep into the paste, the sphere could move up 2 mils and still be in contact with the paste (pre-liquidus). For example, if the paste deposit is 3 mils thick, you then have less vertical motion tolerance. Lower print volume = higher chance for HiP defect. This paste can help reduce HiP because it provides outstanding printing and consistent board to board and pad to pad repeatable print volumes. This is due to the excellent release characteristics of the solder paste from the stencil.
C	Excellent activity and residues that do not flow away from the joint. The flux also wets up which reduces the oxidation of the ball.
A	Removes oxidation barrier and high paste transfer efficiency. This paste is also a HF paste
D	The flux system is thermally stable and has a thermally driven activator package to reduce surface oxides during the liquidus phase of reflow, thus promoting increased wetting and complete solder joint formation.
E	This paste has a modified SnPb alloy with longer pasty region. So this alloy allows melting over a longer timeframe which should assist wetting during/after warpage.
F	Enhanced wetting speed.
G	Consistent high print volumes and reduced speed of pad wetting and maximum speed of ball wetting, resulting in rapid ball collapse mitigating the effect of co-plainarity differences

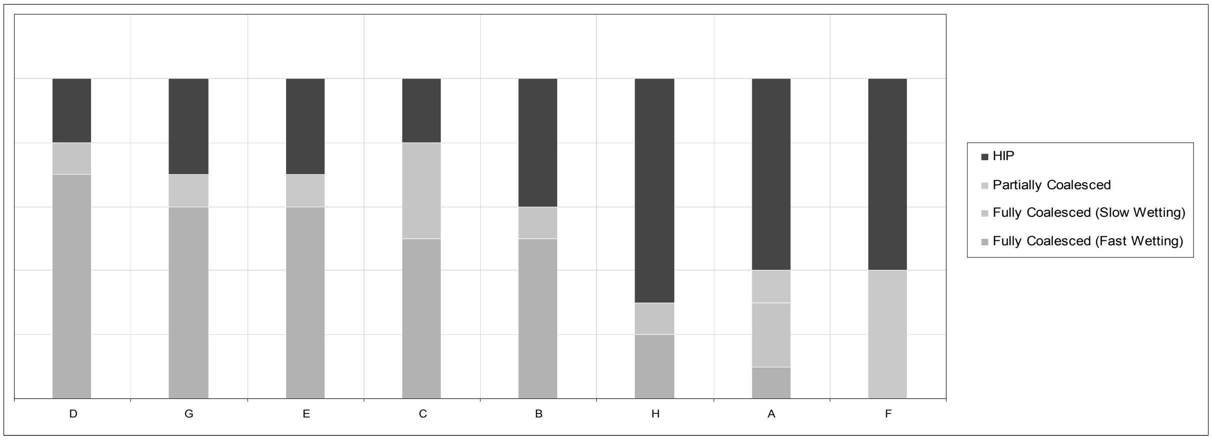


Figure 9: Results for Condition C1

Table 3: Ranking of Solder Paste from Condition C1

Ranking	Solder Paste	Weighted Score
1	D	5.45
2	G	4.55
3	E	4.55
4	B	4.35
5	C	3.95
6	H	1.7
7	A	1.2
8	F	0.2

The top four solder pastes from Table 3 were further evaluated using condition C2. Five trial runs were conducted for this phase. The results are shown in Table 4 and graphically illustrated in Figure 10.

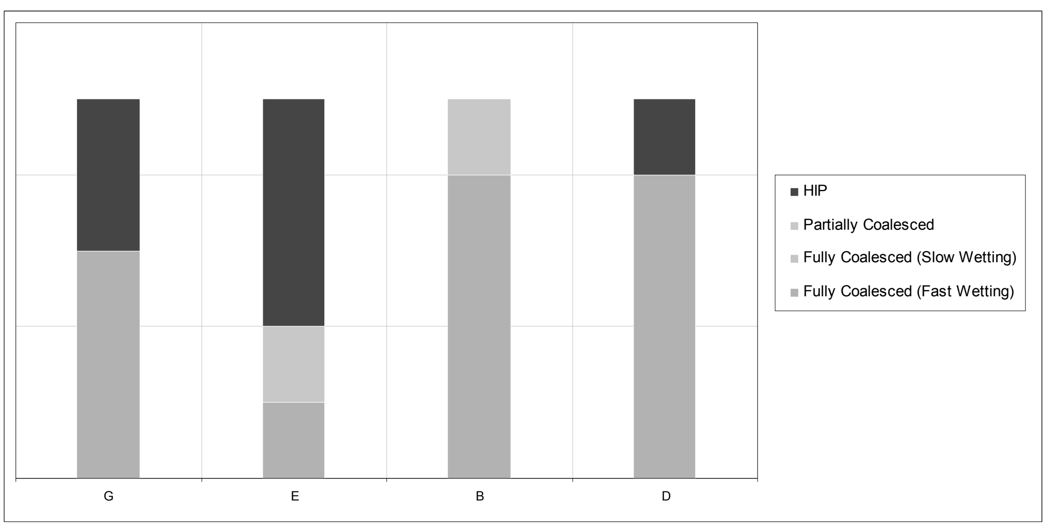


Figure 10: Results for Condition C2

Table 4: Ranking of Solder Paste from Condition C2

Rank	Solder Paste	Weighted Score
1	B	3.05
2	D	3
3	G	2.25
4	E	0.8

The results of this study were validated by assembling a Test Vehicle with components that has a known history of HiP defects. The performances of the top four candidates were compared with the baseline solder paste 'A'. A sample of 8 boards was assembled without preconditioning and with preconditioning for each solder paste. The preconditioning was performed by baking the boards in air for 48 hours. The purpose of preconditioning to is to induce oxidation thereby improving the occurrence of HiP defects. After assembly the joints were inspected for HiP defects using 5DX inspection. The top four solder candidates performed significantly better than the baseline solder paste which confirmed the validity of the experimental methodology developed in this study.

Summary:

HiP is a serious defect in the electronics industry since they escape the initial inspection but show up as failures in the field before the warranty time of the product. They can occur in the following scenarios. 1) There is no contact between the solder paste and solder ball through the reflow process until solidification. 2) There is no contact only until the peak temperature but the solder ball is unable to wet the solder paste due to oxidation or exhaustion of flux.

Among the several solutions for mitigating HiP defects, one of the most significant factors would be the effect of solder paste and its flux system. In this study, an experimental methodology was developed to evaluate solder pastes that will help in mitigating HiP defects. The solder pastes candidates selected using this methodology performed significantly better than the baseline solder paste for mitigation of HiP defects.

Acknowledgements:

The authors wish to acknowledge Ken Hubbard from Cisco Systems for his great guidance and ideas. We would also like to thank the contributions of Quyen Chu from Jabil AMT group who provided the assembly and equipment support for this study. We would also like thank all the paste suppliers who took part in this study enthusiastically. Contact Information: gusubbar@cisco.com

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Outline

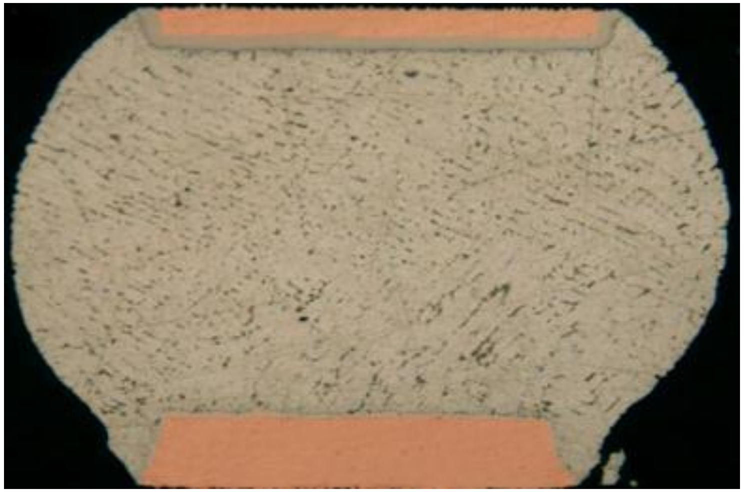
- Motivation
- What is a Head-in-Pillow (HiP) joint?
- Why are they a concern?
- What is the mechanism for the formation of HiP joints?
- What are the causes for HiP joints?
- How can we detect HiP joints?
- HiP Risk Mitigation
- Problem Statement
- Experimental Methodology
- Results and Discussion
- Conclusion and Key Takeaway

Motivation

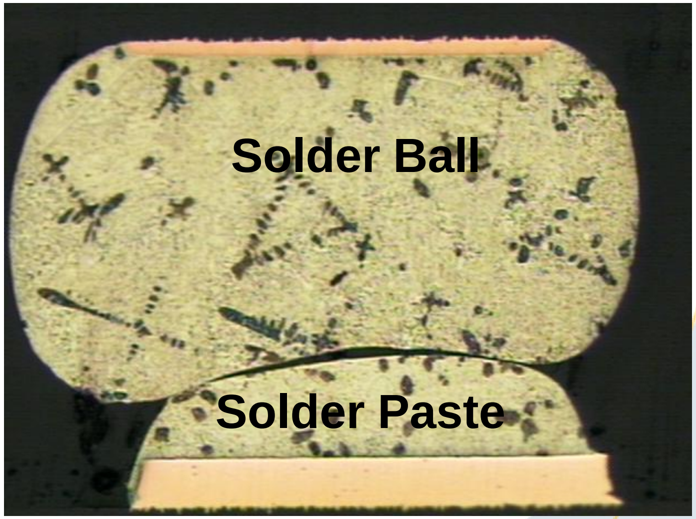
- Failure of products at customer site.
- X-Section revealed HiP joints.
- Primary cause traced to warpage of components.
  - Depend on timing of warpage.
- Controlling warpage completely is very difficult.
- Find other solutions for mitigation HiP defects
- Solder paste is an effective solution for mitigating HiP joints.
- Evaluating solder pastes with DoEs is difficult.
- Lack of methods to create HiP joints in the industry
- So need develop an methodology to create HiP joints

Head in Pillow (HiP) Joint

- Definition: Non-coalescence (Non wetting) between the solder ball and the solder paste during reflow.
  - Also referred to as “Ball and Socket” defect.
  - Not an ‘open’ joint as there is weak intermittent contact.
  - Occurs mostly on corner balls at low DPMO.

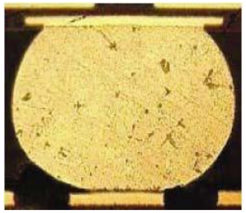


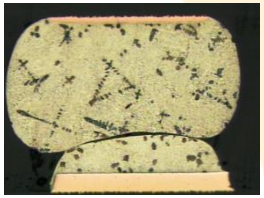
X-Section of a Good Joint

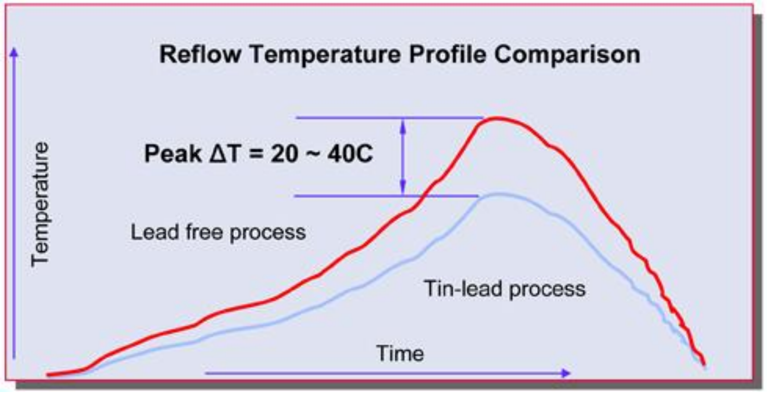


Why HiP is a Concern?

- Which defect is worse?
  - ‘Open’ or HiP Joints?
- HiP are very difficult to detect
  - Pass electrical inspection.
  - Shows as infant failures after shipped to customers.
- Incidence rates more in Pb-free assembly.
  - Higher temperatures increases warpage
  - Increased oxidation due to more Sn content of SAC

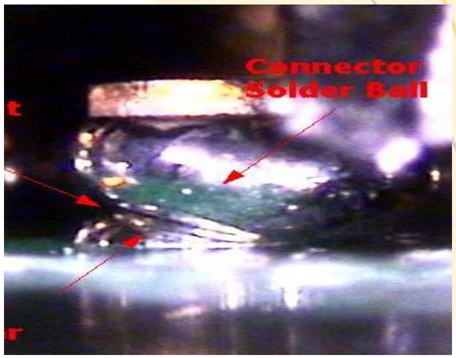




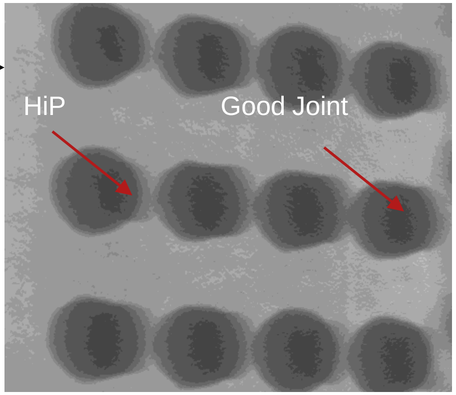


Detection Tools

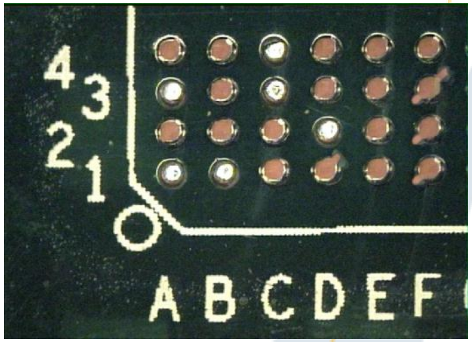
- Optical Side view inspection
  - Only good for corner joints



- 2D Oblique X-Ray Inspection
  - Very tedious method

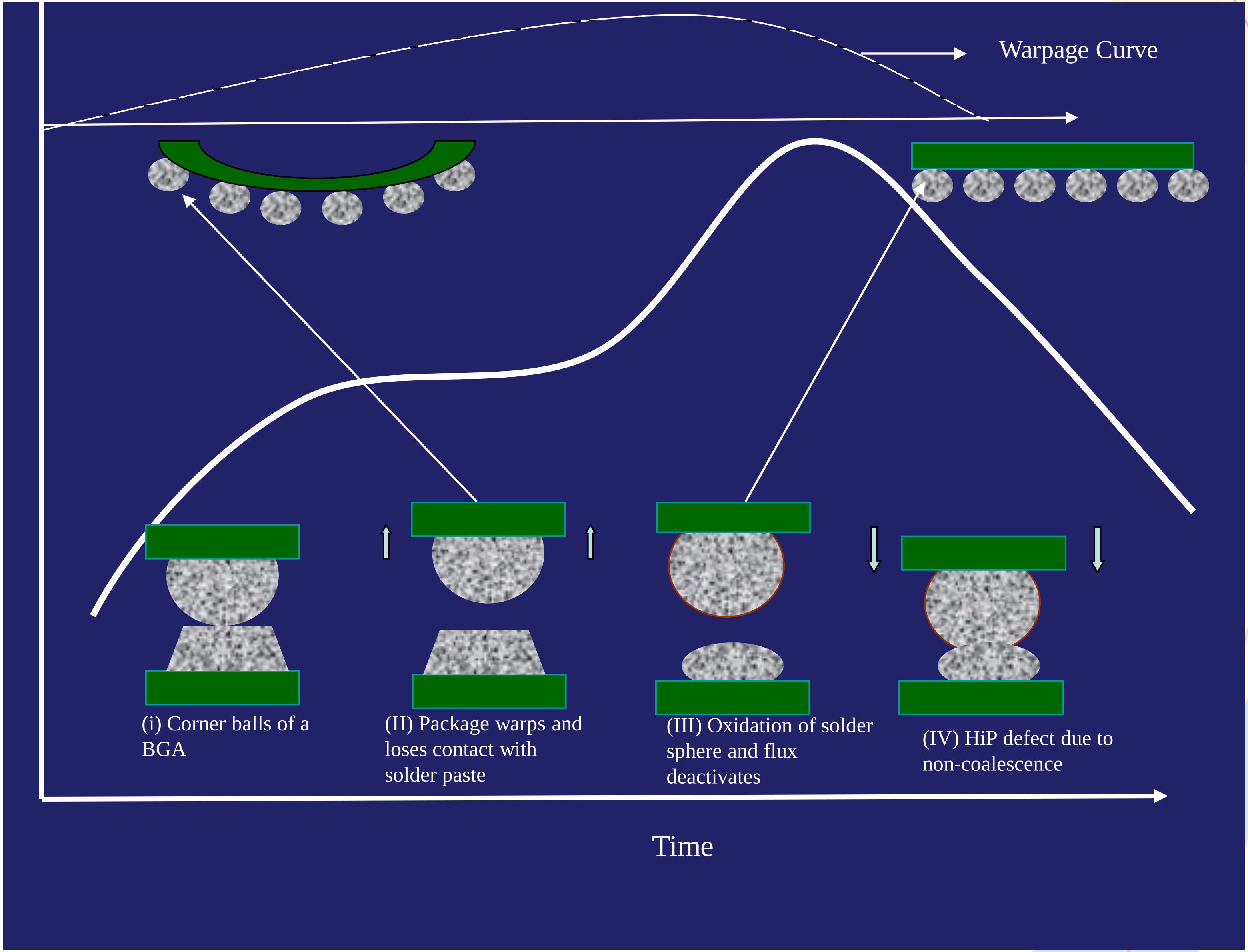


- 5DX Automated Inspection
  - Edge Recognition
  - Risk of false calls and escapes

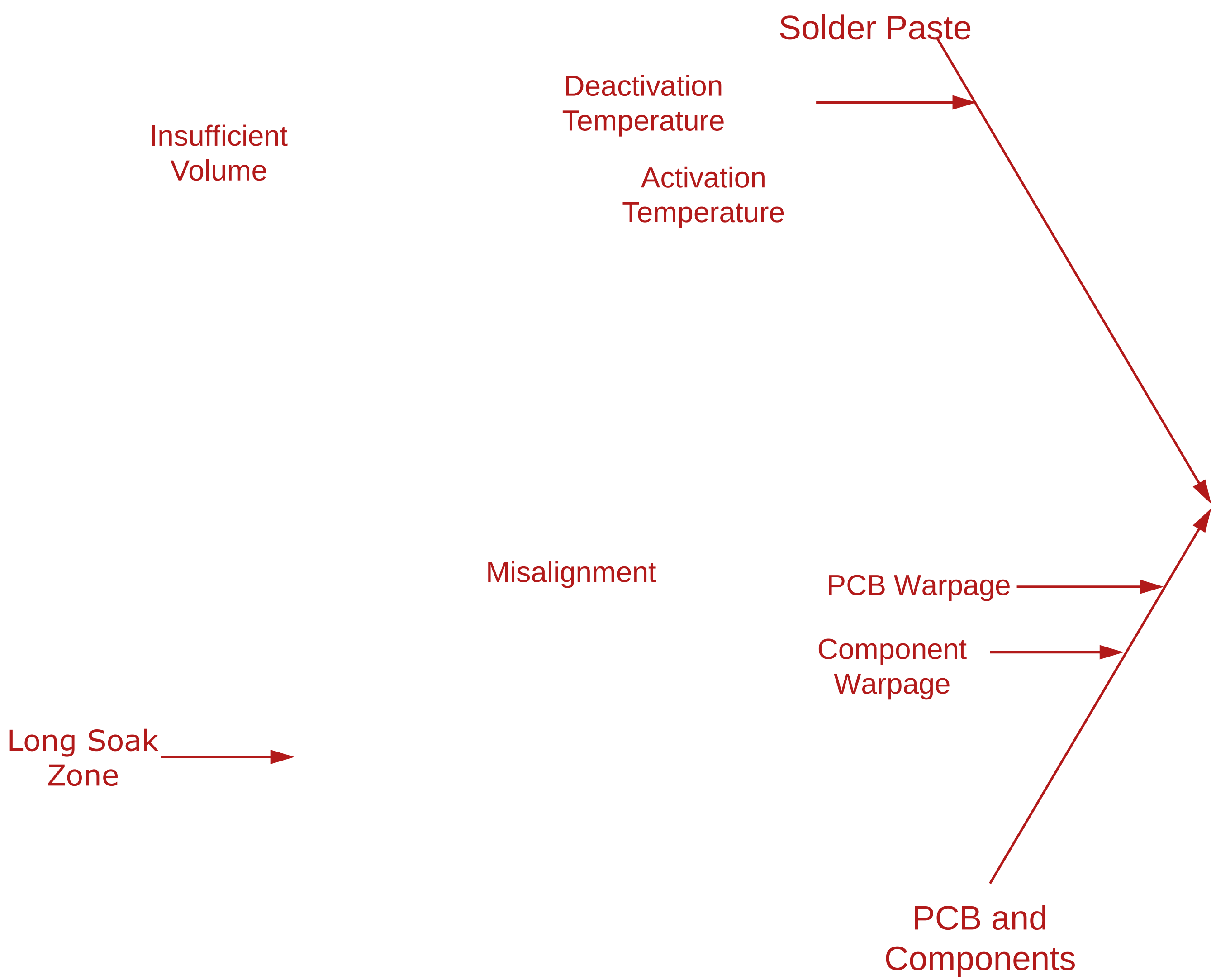


- Pry analysis

HiP Mechanism

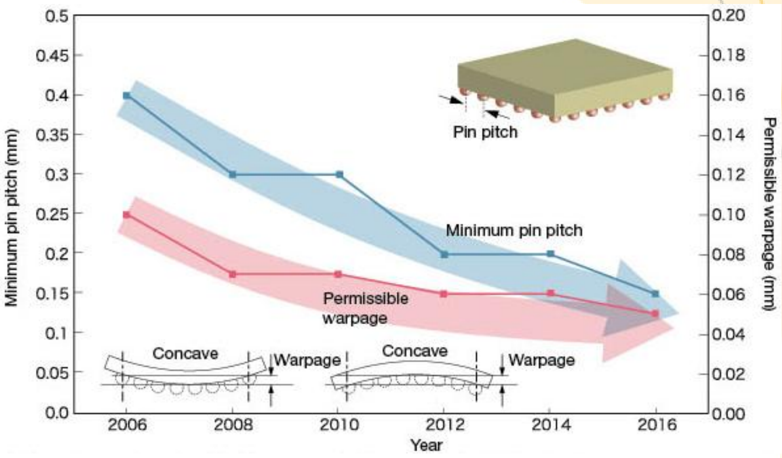


Fishbone Diagram



Mitigation Steps

- Reducing warpage in components
  - Can't be eliminated due to material constraints
  - Warpage expected to decrease

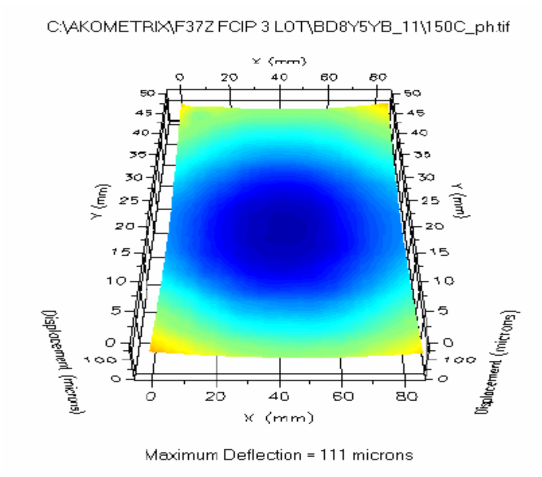


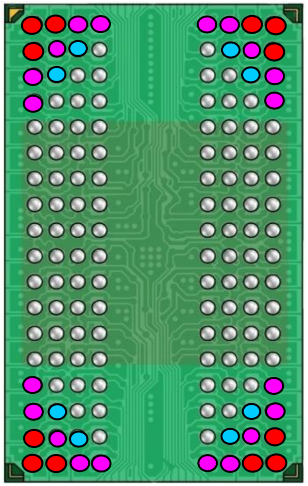
Ref: JEITA Roadmap

- Using solder paste with the following properties
  - 1: Active flux for prolonged reflow profiles
  - 2: Flux with higher oxidation barrier
  - 3: Flux that wets up reducing oxidation
  - 4: Solder paste with excellent release characteristics
  - 5: Flux with fast wetting time
  - 6: Consistent high print volumes
  - 7: Reduced speed of pad wetting and maximum speed of ball wetting, resulting in rapid ball collapse
  - 8: Thermally driven activator package to reduce surface oxides during the liquidus phase of reflow
  - 9: Longer pasty region

Mitigation Steps - Materials

- Bulls eye stencil (increase aperture on corner pads)





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= Circular +.001”

= Circular +.002”

= Circular +.003

- Flux dipping of solder balls
- Using Nitrogen during reflow process
- Reflow: Hotter and longer soak coupled with a quick transition into the solder’s liquidus phase

Problem Statement

- Develop conditions that can create a HiP defect experimentally.
- Investigate for solder pastes for mitigating HiP defects.
  - Solder pastes should have good printing and wetting
  - Pass SIR test at 205 C.
  - Pass Ion Chromotography test.
  - Not create other defects.
- Determine the properties of solder paste that mitigated HiP defects.

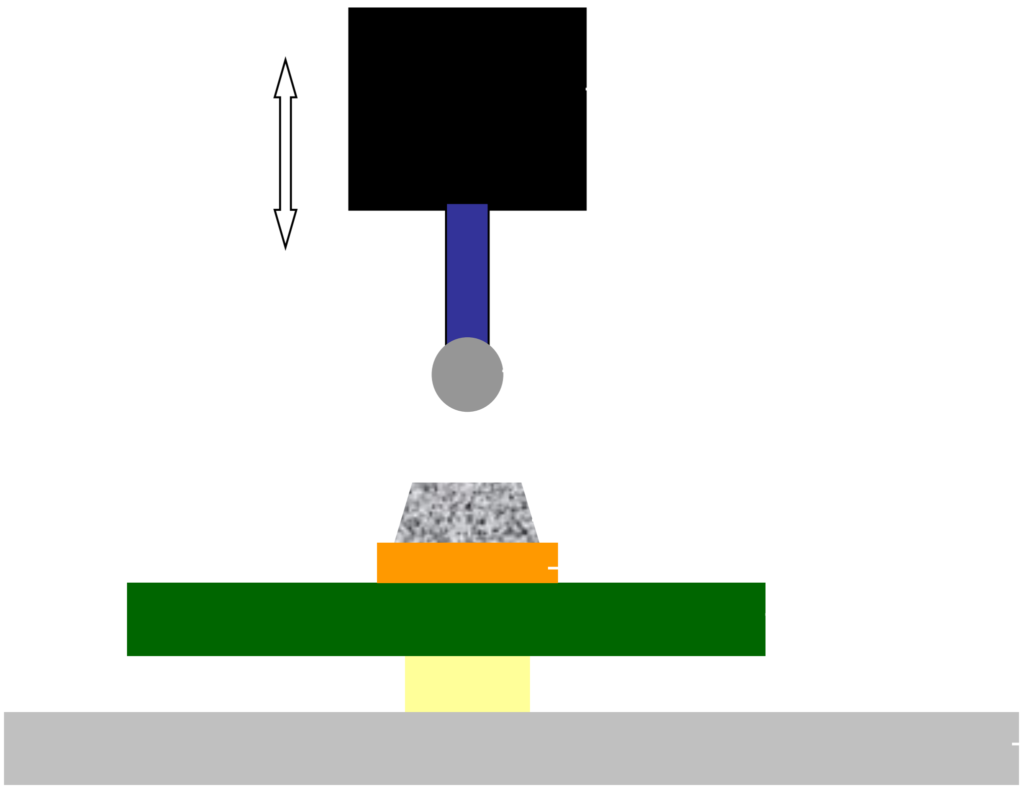
Solder Paste Candidates

Solder Paste Candidates	Properties from Slide 8
A	Baseline Solder Paste with history of HiP defects
B	1,6
C	3,5
H	2,4,6
D	8
E	9
F	5
G	6,7

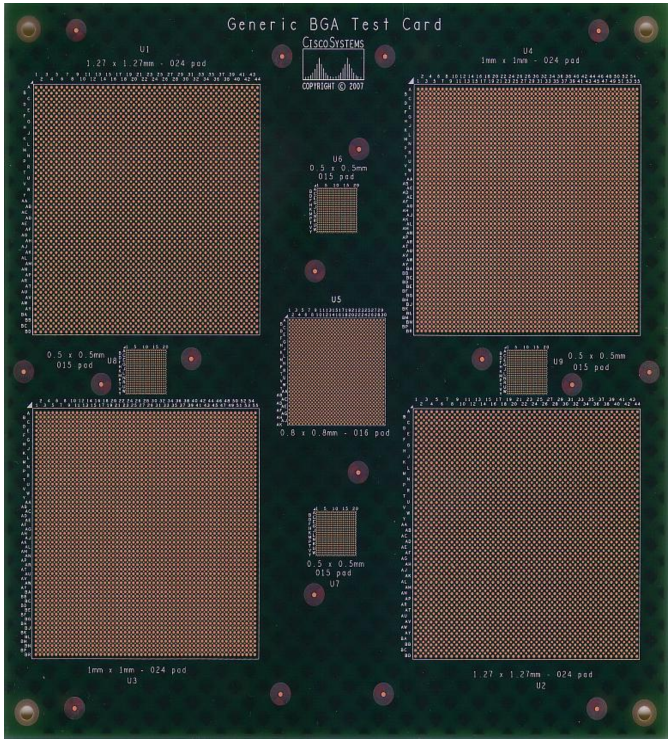
Experimental Methodology

- BGA rework equipment was used to place a single ball on a pad.
  - Solder paste was printed on the pad and reflowed.
- Gap between solder ball and gap was controlled to mimic the warpage of corner balls during reflow process.
- Each test run was also recorded on video. This helped determine the time it took for the solder ball to coalesce after making contact.
- A no clean SnPb solder paste with known history of HiP joints was used as the baseline paste.

Experimental Setup



Test Vehicle Design



PCB Pad Design Details

PCB Pad Dimension	**0.024" Diameter**
Solder Mask Opening	**0.027" Diameter**

Stencil Aperture Design Details

Stencil Thickness	**0.006"**
Stencil Fabrication Method	**Laser-cut**
Stencil Aperture Shape	**Circular**
Stencil Aperture Opening	**0.025" Diameter**
Area Ratio	**1.04**
Solder Paste Volume Target	**3,065 cubic mils**

Component Details

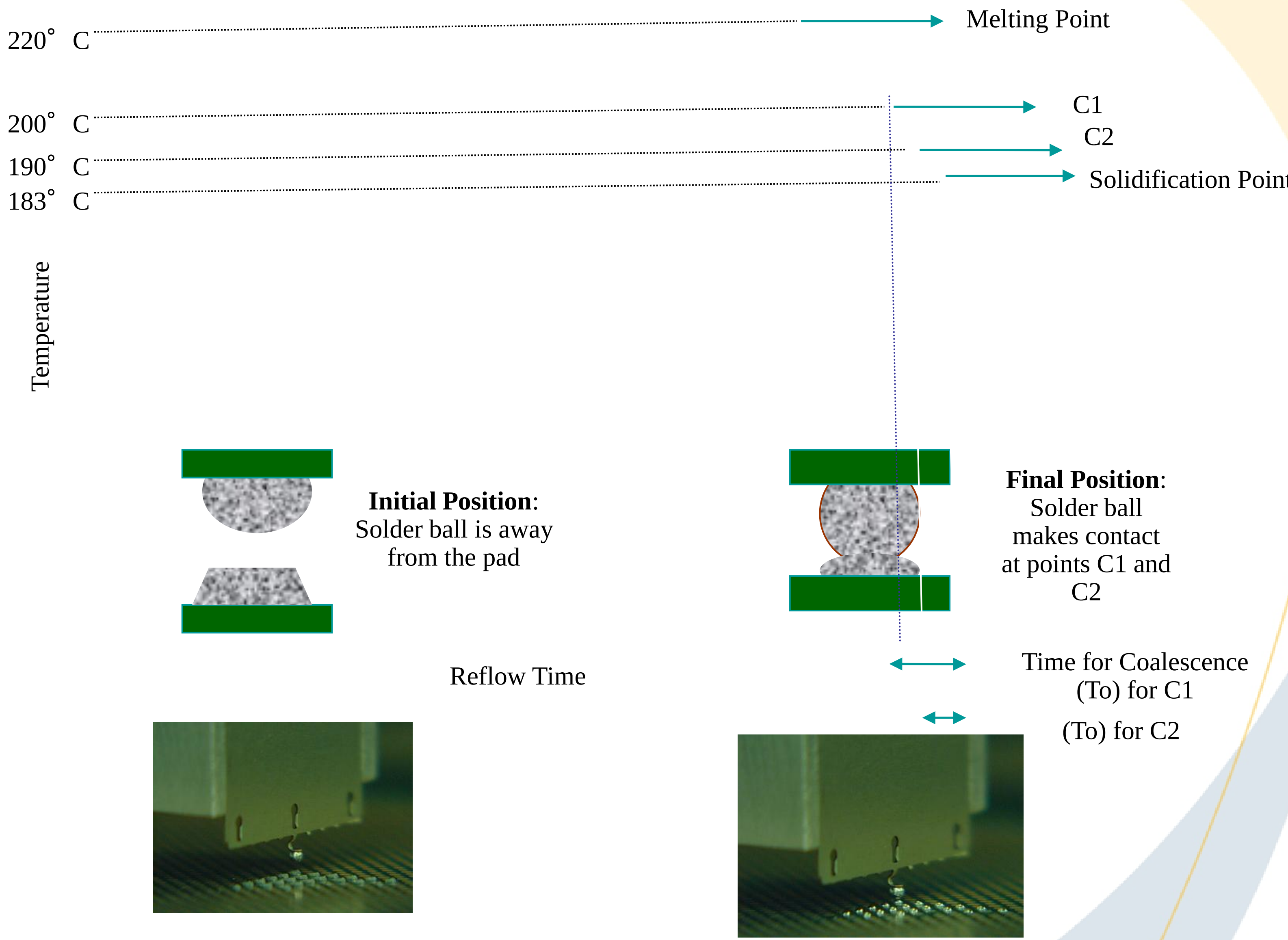
Solder Ball Alloy Composition	**Eutectic Sn/Pb**
Solder Ball Size	**0.028" Diameter**
Solder Ball Height	**0.024"**

PCB Dimensions:	**6.5" x 6.5"**
PCB Thickness:	**0.093"**
Layer Count:	**8 Layers**
PCB Surface Finish:	**High Temperature OSP**

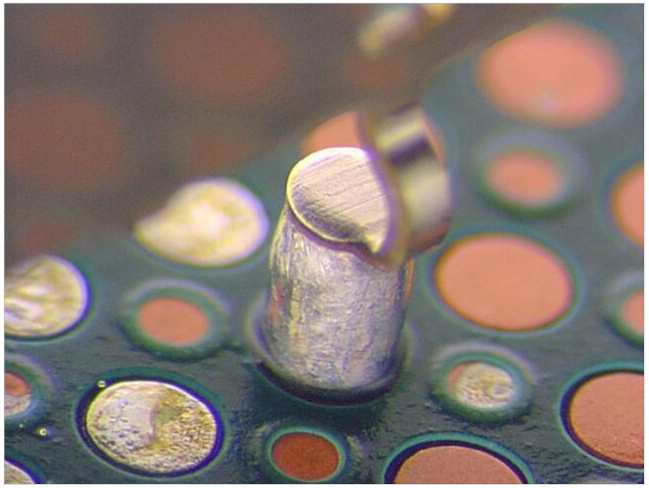
Trial Runs for Creating HiP Joints

- A) Ball and paste contact initially, then ball moved up during the preheat stage and makes contact again during the cooling stage.
- B) No contact initially but ball makes contact with the paste at some point during the cooling stage.
  - Worst case scenario compared to the scenario A.
- No HiP defects for A. However HiP defects were created using B
  - **C1:** Contact at 200 ° C during cooling phase
  - **C2.** Contact at 190 ° C during the cooling phase
    - This condition is similar to C1 but there is less contact time before solidification.

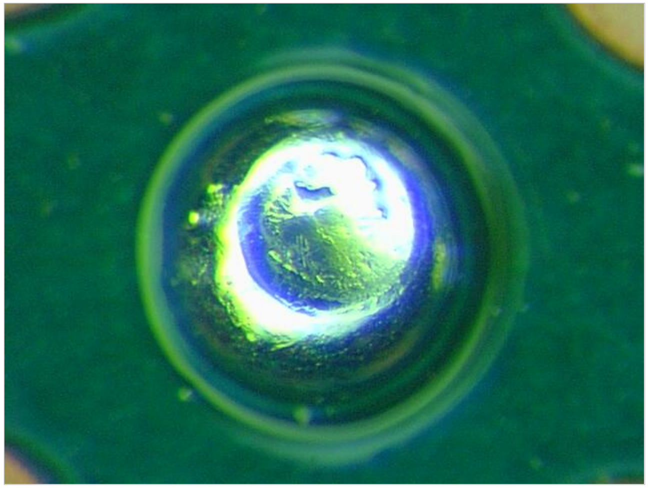
HiP Conditions



HiP Identification



Example of a Good Joint



Example of HiP Joint

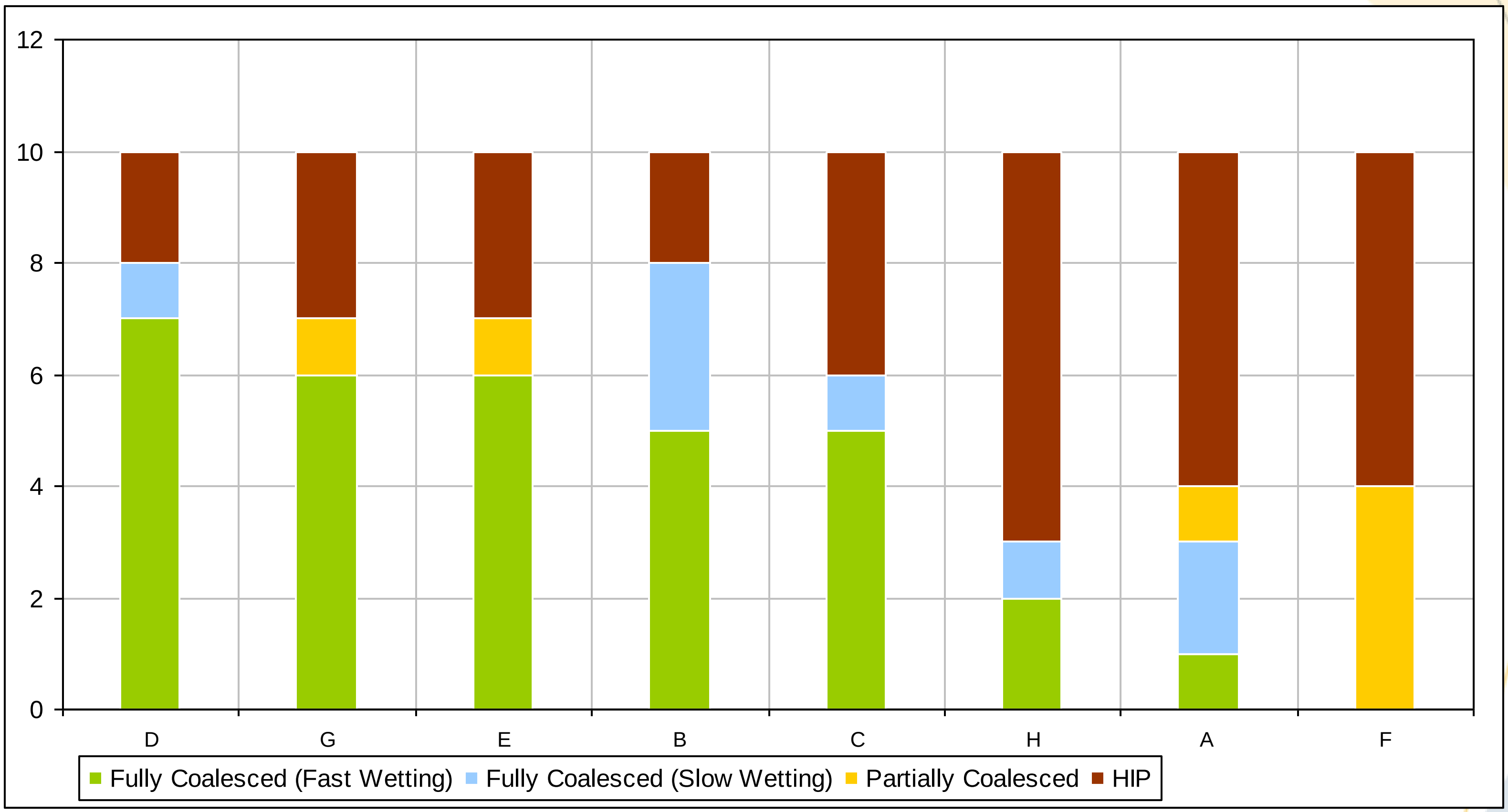
Classification of Wetting

- Fast Wetting: Immediate coalescence
  - Best performance and given the highest weighted average of 0.75.
- Slow wetting: Coalesces between 1-10 seconds.
  - Weighted average = 0.20.
- Very Slow wetting: Coalesces after 10 seconds
  - Weighted average = 0.05.
- HiP Defect: No coalesce.
  - Weighted average = 0.

Hip.wmv

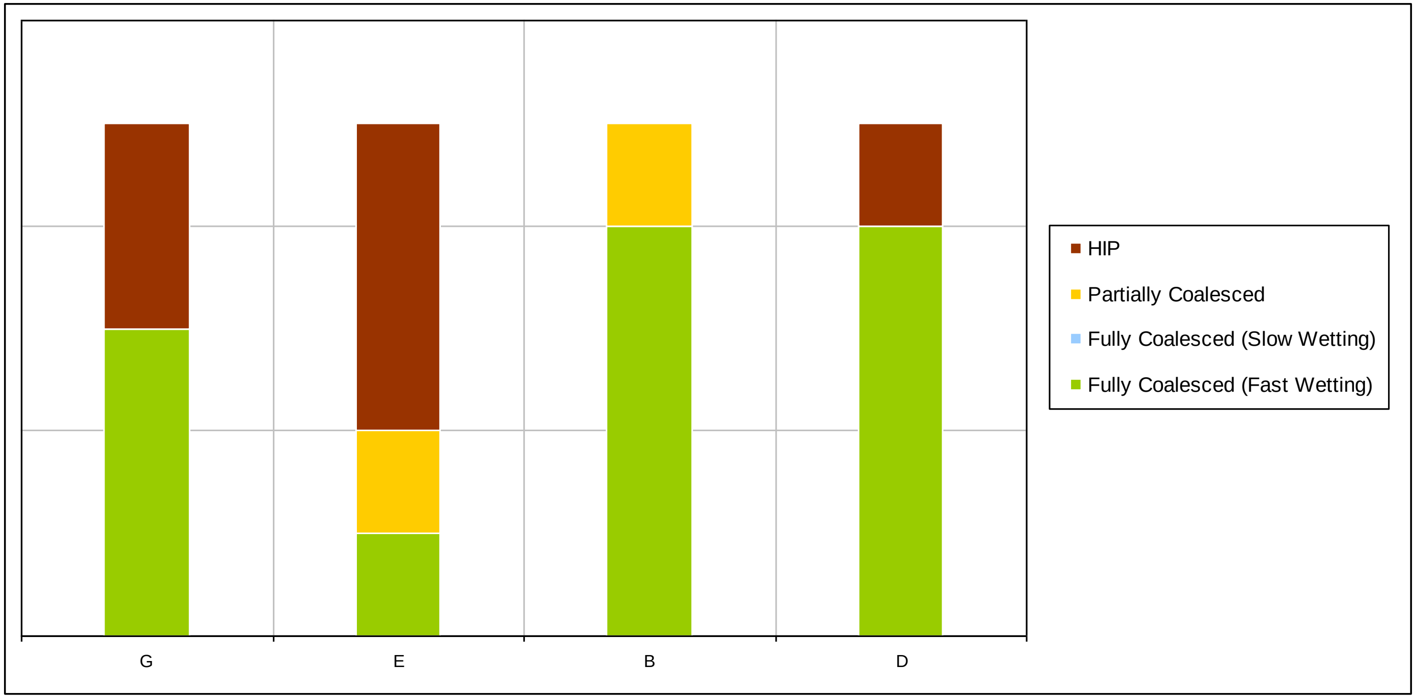
Fast.wmv

Results for Condition 1



- Top four solder pastes D,G,E,B selected for Condition C2

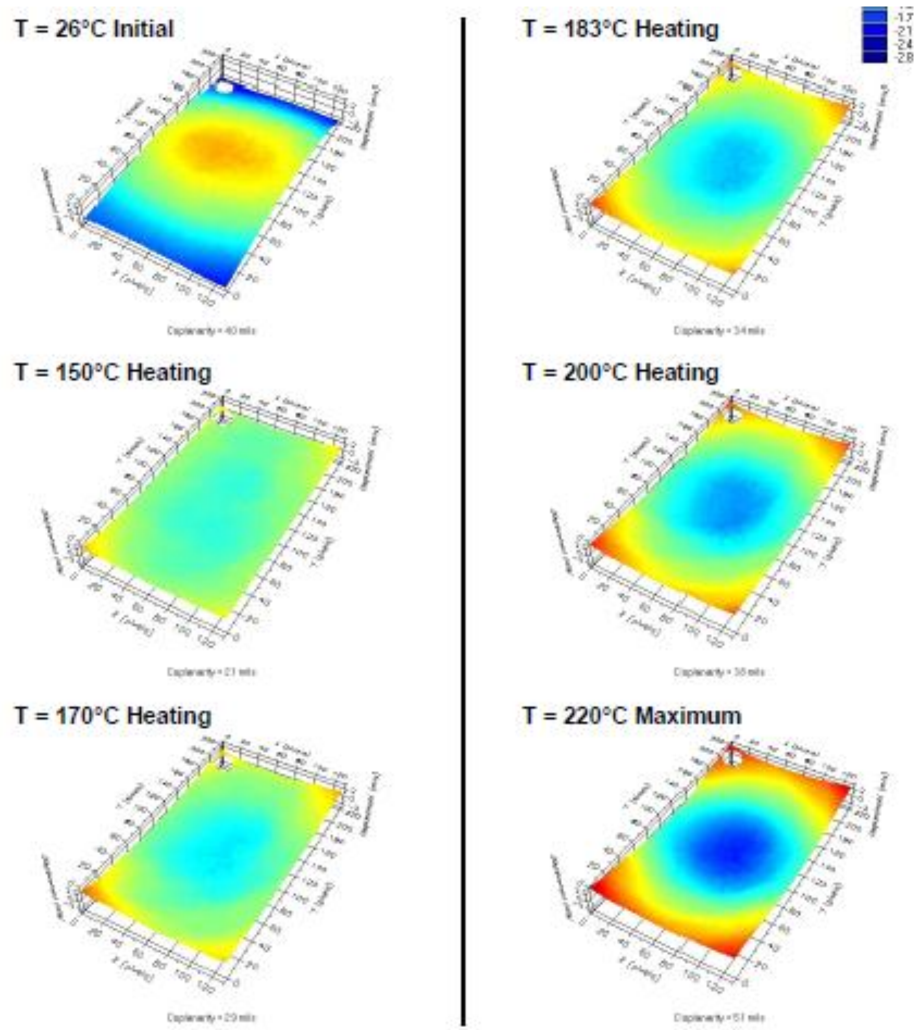
Results for Condition C2



Rank	Solder Paste	Weighted Score
1	B	3.05
2	D	3
3	G	2.25
4	E	0.8

Verification Build

- A memory FBGA 144 with known history of HiP defects was assembled.



Verification Build

- Top four candidates (B,D,G,E) were compared with the baseline paste ‘A’.
  - Without preconditioning
  - With preconditioning.
    - The preconditioning was performed by baking the boards in air for 48 hours.
- Sample size = 16
- After assembly the joints were inspected for HiP defects using 5DX inspection and confirmed using Dye and Pry analysis.
- Top four solder candidates (B,D,G,E) performed significantly better than the baseline solder paste.
- Top 3 solder pastes implemented in production and have reduced HiP defects drastically.

Summary and Key Takeaway

- HiP is a nightmare as it causes infant failures after shipped to customers.
- HiP occurs when there is no contact until the peak temperature but contact during cooling stage.
  - Inactive flux when there is contact.
- The test method developed was found to be effective in mitigation HiP defects.
- Solder pastes can mitigate HiP defects effectively with following properties:
  - Flux that can withstand longer reflow profiles.
  - Flux that wets up
  - Flux with high wetting speed
  - Good oxidation barrier

Questions?

Acknowledgement and Contacts

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