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INVESTIGATION AND DEVELOPMENT OF TIN-LEAD AND LEAD-FREE SOLDER PASTES TO REDUCE THE HEAD-IN-PILLOW COMPONENT SOLDERING DEFECT

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ABSTRACT

Over the last few years, there has been an increase in the rate of Head-in-Pillow component soldering defects which interrupts the merger of the BGA/CSP component solder spheres with the molten solder paste during reflow. The issue has occurred across a broad segment of industries including consumer, telecom and military. There are many reasons for this issue such as warpage issues of the component or board, ball co-planarity issues for BGA/CSP components and non-wetting of the component based on contamination or excessive oxidation of the component coating. The issue has been found to occur not only on lead-free soldered assemblies where the increased soldering temperatures may give rise to increase component/board warpage but also on tin-lead soldered assemblies.

In order to reduce this affect work was done on a set of tin-lead and lead-free solder pastes which were developed with flux formulations in the solder paste having higher heat resistance which did not lose their flux activation properties as quickly and quicker wetting which helped to reduce the head-in-pillow defect. The results of the evaluation are presented with test methods to analyze the head in pillow defect not only on BGA component test vehicles but also more fundamental studies to assess BGA/CSP solder ball interactions with the developed versus control solder pastes. As well as reviewing some of the other causes of the Head-in-Pillow defect such as printed solder paste volume, component placement and reflow profile used, an assessment will be done on the industry standards which need to be updated or developed for component and board co-planarity in the as-received and reflowed conditions.

Key words: Lead-free, Tin-lead, Head-in-Pillow, Warpage

INTRODUCTION

The head-in-pillow (HIP) soldering defect occurs as a result of the incomplete merging of the BGA/CSP component sphere and the molten solder paste during reflow (Figure 1). The typical situation causing this defect involves the following:

i) During the preheat and soak stages of the reflow process, the BGA/CSP sphere and the flux become oxidized.
ii) At the early stages of reflow, the solder paste starts to melt, with bleed out of the flux and further oxidation of the BGA/CSP bumps with a gap between the reflowed solder paste and ball.
iii) The flux is then consumed as the solder melts.
iv) During the peak reflow stage, the oxide film on the BGA/CSP sphere surface does not melt with the reflowed solder paste which has a flux layer with almost no activation.
v) This along with the fact that the time above liquidous is limited before cooling, causes the head-in-pillow defect.

Figure 1: Head in Pillow component soldering defect

Some of the causes of the separation of the BGA/CSP sphere from the solder paste during reflow are related to component package warpage and inconsistent BGA/CSP ball sphere size, with component package warpage being especially problematic during lead-free soldering with the higher lead-free soldering temperatures. An improper reflow profile may also cause HIP defects if excessive warpage of the component and/or the PCB results. During reflow there may also be lifting of certain BGA/CSP spheres from the paste deposit due to the wetting forces acting during reflow.

Vaccaro et al. [1] showed that large component warpage could be caused by moisture in the part and the use of higher peak lead-free soldering temperatures. This would mean that even though the component may be qualified to a certain Moisture Sensitivity Level (MSL) rating for lead-free soldering according to IPC/JEDEC J-STD-020 [2], it still may cause issues in production due to excessive component warpage. For a 37.5mm square part, an increase in die size from 5mm x 5 mm to 11 x 11mm could help to reduce the component warpage during the lead-free reflow operation due to the additional stiffening from the larger die size.

Lathrop [3] also indicated that one of the main factors influencing BGA coplanarity was component laminate warpage due to underfill and over molding operations on the package side. Lin et al. [4] conducted a study on PoP (Package on Package) components using the Shadow Moire technique to understand the influence of package warpage during lead-free reflow assembly from 25°C to 260°C and then back down to 25°C. Various factors had an influence on warpage including die size, mold compound thickness and mold compound CTE (coefficient of thermal expansion), substrate material, thickness and copper layer ratio which could then be optimized to reduce component package warpage.

The difficulty with this defect is that it is usually very difficult to detect during inspection and functional level testing. There is partial contact between the reflowed solder paste and the ball sphere but no real metallurgical bond. Thus, when the component is subject to mechanical or thermal stress in the field, Head-in-pillow defects lead to failure.

Head-in-pillow soldering defects have also been found to be a result of a large temperature gradient (delta T) across the BGA component during reflow [5] causing un-uniform melting of the component spheres into the paste. Shadow Moire techniques have also been employed to understand the warpage of the component during reflow with the reflow profile used in the Shadow Moire testing machine adjusted to simulate the production reflow oven profile. The warpage effect of the component during the reflow profile can cause the head-in-pillow defect so it is important for component warpage/coplanarity behavior during reflow to be understood and controlled by the component supplier during component design to prevent issues occurring in production.

Based on this issue, a set of experiments was conducted to develop both tin-lead and lead-free solder pastes to help to reduce the affect. As already discussed, some of the stages in Head-in-Pillow formation are:

1. Inconsistent ball size of the BGA/CSP sphere or a extended time-lag in melting of the solder ball and paste causing solder balls to detach from the solder paste during reflow.
2. As they are apart from one another, the solder paste and solder balls get oxidized.
3. As the reflow time progresses the solder balls start to drop back into the solder paste.
4. The solder paste and solder balls come back into contact.
5. Oxidized surfaces on both ball and paste sides hinder complete merging, causing the defect.

Based on these stages fluxes were developed for tin-lead and lead-free solder paste that retained their high activation level during the reflow/cooling stage which helped to remove the oxidized film formed.

Comparing tin-lead (Sn37Pb) with lead-free (Sn3Ag0.5Cu) solder pastes, the lead-free paste would have a higher melting temperature and be more vulnerable to oxidization with the increased temperature during pre-heat and reflow. For these reasons, wetting failures for lead-free solder such as un-molten solder, non-wetting to components, and head-in-pillow defects would occur more often.

The tin-lead and lead-free solder pastes were developed to accommodate high pre-heat, and prevent/ reduce the head-in-pillow defects caused by component warpage and oxidation (Figure 2). The solder pastes developed addressed certain areas including flux activation level, heat-resistance, and paste printability with the experiments and results reported in the following sections.

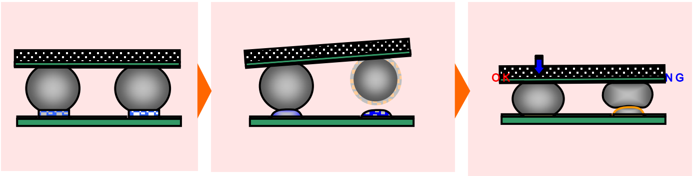


Figure 2: Head-in-pillow defect (Warpage, oxidization)

EXPERIMENTAL

To prevent and reduce the head-in-pillow defects a series of experiments were done to understand and address this issue. There were various areas explored which are discussed in the following sections.

Adjustment of Flux Fluidity

To reduce the oxidization of the solder paste the flux fluidity was adjusted to have the flux protect the solder more from heat during the pre-heat stage.

Heat Resistivity Improvement of Flux

The flux was developed so that the activation level of the flux was increased during pre-heat by improving the heat resistivity of flux. Based on this the flux would be better able to remove oxidized films on the BGA/CSP component sphere.

Nitrogen Versus Air Reflow Test

As head-in-pillow defects were typically caused by oxidization of the BGA/CSP component and deterioration of flux, the occurrence of the defect could be decreased by reducing the oxidization of the BGA/CSP component using flux that could help to remove oxidized film while choosing a more heat-resistant flux.

Reducing BGA/CSP component oxidation could also be achieved in a nitrogen environment which would help to reduce oxidation. In case the nitrogen environment could not be used because of nitrogen cost issues, more emphasis on flux development could be employed.

The primary development in flux formulations for tin-lead and lead-free solder pastes was to remove the oxidized film on the BGA/CSP component and to improve the heat resistance of the flux.

SnPb Head in Pillow Paste Development

The initial work over the last four to five years was to remove head in pillow defects when using tin-lead solder pastes as this was the initial customer problem to help to reduce head-in-pillow component soldering defects in tin-lead soldering. The following section describes the development work in this area.

Test Method on Chip Components Using Tin-lead Solder Paste

To simulate the phenomenon, an oxidized component was placed on top of the previously reflowed and oxidized tin-lead solder paste and then the combination was reflowed. The evaluation consisted of using three solder pastes: Control SnPb Paste A, Control SnPb Paste B and Improved Head in Pillow SnPb Paste C. The method developed used the following steps:

i) Oxidization of chip component - 150℃ for three hours (2125C [0805] chip size, 90Sn10Pb component coating)

ii) Oxidization of the reflowed solder paste- 150℃ preheat for 1 minute followed by 230℃ reflow for 1 minute. The reflow profile used is shown in Figure 3.

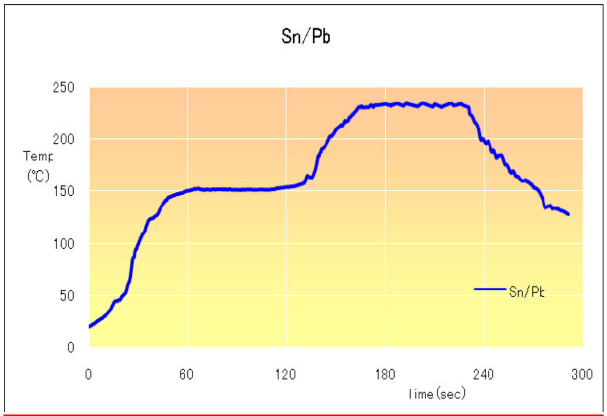


Figure 3: Reflow profile used to oxidize the tin-lead solder paste (Time over 183°C = 120 seconds)

After oxidizing the chip component and the reflowed solder paste, the chip component was placed on the reflowed solder paste as shown in Figure 4. It would have been preferred to use molten solder paste to replicate the head-in-pillow defect more accurately but due to experimental difficulties, reflowed solder paste was used.

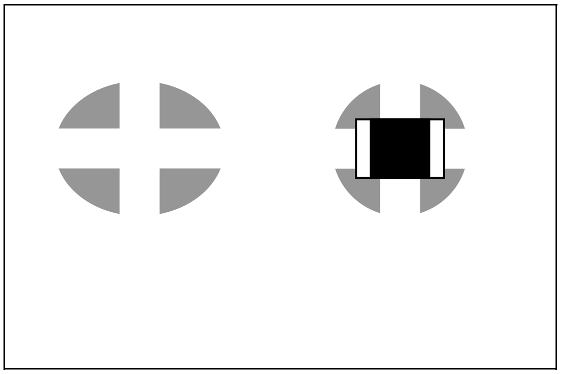


Figure 4: Chip component placement on reflowed solder paste.

A reflow simulator was used to observe the melting behavior in real time between the reflowed solder paste and the chip component. The reflow simulator equipment used is shown in Figure 5.

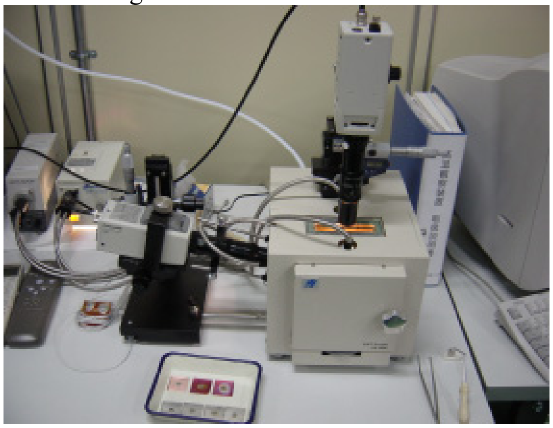


Figure 5: Reflow simulator used to observe real time melting behavior of the reflowed solder paste and the component.

The reflow conditions used in the reflow simulator had a ramp-up temperature of 1℃/sec, heating up to 215℃ peak temperature as shown in Figure 6. The atmosphere used during reflow was air.

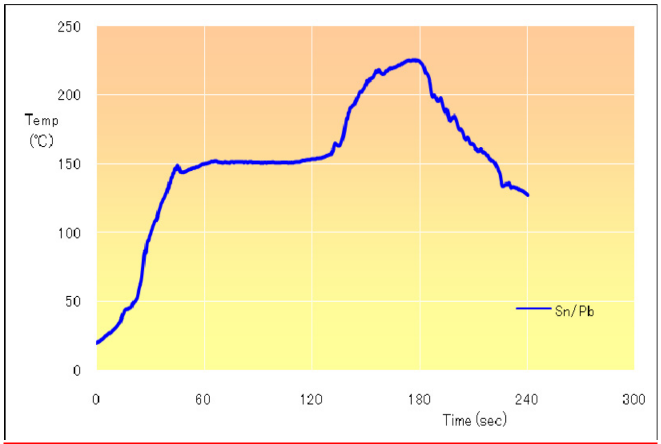


Figure 6: Reflow simulator tin-lead reflow profile used (Time above 183°C = 60 seconds)

SnAgCu Head in Pillow Paste Development

For lead-free solder paste development, chip components with reflowed solder paste could also have been used but at that stage of the development, BGA/CSP spheres were used as it more simulated the actual assembly test conditions.

Test Method on Ball Spheres

To show the effectiveness of a solder paste in preventing the head-in-pillow defect, a large amount of components and time would be required. To replicate the defect and accelerate the evaluation procedure, an evaluation was conducted to look at flux activation level retention at high temperature using solder ball spheres.

This involved printing solder paste onto the test board which was then placed on a static solder pot to melt the solder paste. Once the solder paste had melted, solder spheres were placed on top of the reflowed solder paste at various time intervals during reflow. If a solder ball melted and merged with the reflowed solder paste, it was judged as a good result and termed ‘O.K’. When no merger occurred, it was judged as a bad result and termed ‘NG’ as shown in Figure 7.

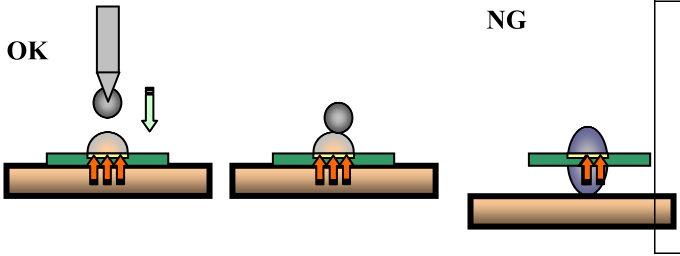


Figure 7: Diagram showing flux activation level evaluation for solder spheres with solder paste.

Test Method on Assembled Boards

To look at the joint formation on the BGA/CSP component, the board was reflowed after solder paste was printed on the test board. The BGA/CSP component was then placed on top of the reflowed solder on the board pads and reflowed again as shown in Figure 8. The melting behavior was observed in a reflow simulator with inspection of the soldered joints by peeling off the BGA/CSP component from the test board after reflow.

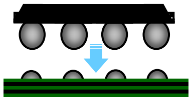


Figure 8: Joint formation evaluation using a BGA/CSP component on reflowed solder paste.

Test Vehicle Evaluation

Test boards were also used to assess head in pillow performance by intentionally oxidizing BGA/CSP components and then assembling onto paste printed test boards followed by reflow to see if the developed solder paste could help to improve head in pillow performance by analysis of soldering to the oxidized BGA/CSP sphere components.

RESULTS AND DISCUSSION

SnPb Head in Pillow Paste Development Results

Results on chip components

The wetting of the three different SnPb solder pastes with components with the reflow simulator are shown in Table 1.

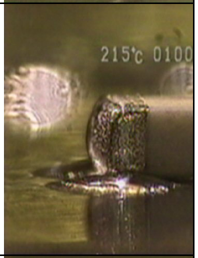
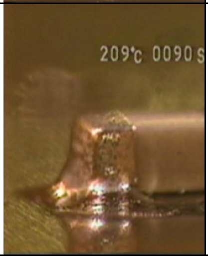
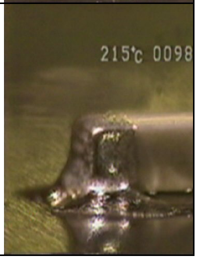
	210℃	215℃
Paste A		
Paste B		
Paste C		

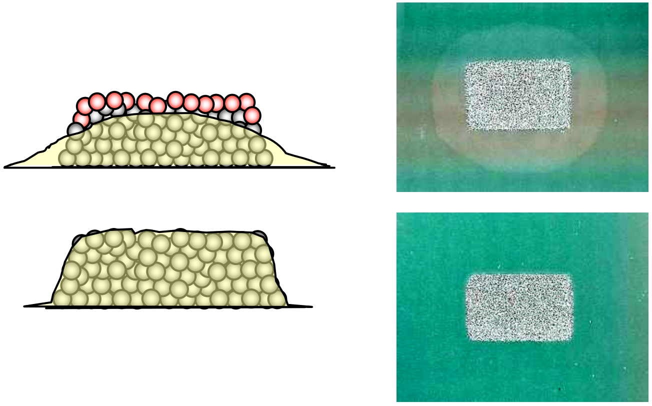
Table 1: Reflow simulator results for Control SnPb Paste A, Control SnPb Paste B and Head-in-Pillow SnPb Paste C.

From Table 1, for the control SnPb Paste A there was no real soldering connection between the reflowed paste and component after reflow. The Head-in-Pillow success rate was not very good because the flux in the solder paste was high in viscosity and it tended to stay underneath the component, and hindered a good connection/contact between the component terminal and the solder paste. The control SnPb Paste A had flux residue which was harder than the flux residue used in Head in Pillow SnPb Paste C. At the higher melting temperatures, the flux residue was less soft than the flux residue for Paste C which reduced the amount of contact of Paste A compared with Paste C with the component termination increasing the amount of head-in-pillow defects. The same principle would also apply to BGA/CSP components. The higher the flux viscosity, the more likely that there would not be good contact between the BGA/CSP component and the paste causing the head-in-pillow defect.

For the control SnPb Paste B, the flux in the solder paste had a lower viscosity than the control SnPb Paste A which gave good contact between the component termination and the solder paste, which would help to reduce the head-in-pillow defect. However, as the amount of flux remaining around the reflowed solder paste in contact with the component was relatively small, wetting to the component was not very high which increased the potential for head in pillow defects.

For Head in Pillow SnPb Paste C, with the flux viscosity being lower, the paste made good contact between the component termination and the solder paste. The reduced flux flow compared to control SnPb Paste B helped to leave the required amount of flux around the solder paste in contact with the component which helped to remove the oxidized component film. In addition the flux in Paste C retained its flux activity during the tin-lead reflow profile better than Paste A or B which allowed for better wetting at a lower soldering peak temperature (210°C).

One of the developments for SnPb Paste C was a solder paste with a certain flux fluidity, so that the solder particles were protected more during the preheat and reflow operation which helped to improve head-in-pillow performance as shown in Figure 9.



Protection of the solder by flux

Figure 9: Flux flow comparison between two types of flux showing different solder particle coverage

For Figure 9 for the top pictures, the flux flows out during preheat with the top of the solder deposit exposed, leaving it more vulnerable to failures such as the head-in-pillow soldering defect. For the bottom pictures the flux covers up to the top of the solder deposit as the fluidity of the flux is low. This helps to prevent oxidization of the solder during heating which improves head-in-pillow performance.

SnAgCu Head in Pillow Paste Development

Results on ball spheres

The testing results for lead-free SnAgCu spheres with the developed lead-free head-in-pillow solder paste and a control paste are shown in Table 2.

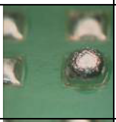
After 30sec	After 50sec	After 70sec
		
		

Table 2: Retention of flux activation level for Lead-free Head-in-Pillow SnAgCu Paste D (Top Row) versus Control Lead-free SnAgCu Paste E (Bottom Row)

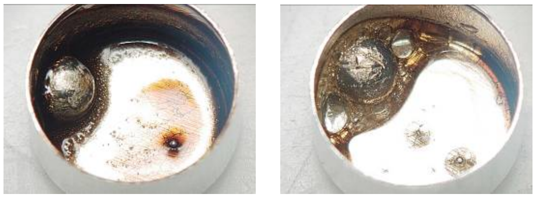
The lead-free SnAgCu head in pillow paste D showed better performance in the solder paste to ball merging test even after longer reflow times versus the control SnAgCu Paste E. This was because the flux used in Paste D was more resistant to heat, and capable of removing the oxidized film from solder ball even after the prolonged melting time.

As already indicated, the development of the lead-free head-in-pillow paste included improving the coverage of the solder particles after melting to reduce oxidation and improving the flux heat resistivity. By covering the solder surface with flux after melting, the solder was protected from oxidization at peak soldering temperatures, thereby enhancing resistivity to the head-in-pillow defect as shown in Figure 10 compared with a conventional lead-free solder paste.

Upon melting 20sec after melting Conventional paste

Figure 10: Lead-free paste melting behavior comparing the Head-in-Pillow paste with the conventional paste

For improved flux heat resistivity tests were done on the flux by heating at 300°C to determine flux rosin color change. Good results were indicated by only a light color change after heating (Fig. 11).



Conventional flux Improved flux version

Figure 11: Comparison of flux rosin color after heating at 300ºC for lead-free SnAgCu paste showing conventional versus head-in-pillow solder paste performance

As shown in Figure 12, it takes a longer time for the Head in Pillow SnAgCu Paste D to deteriorate in the bonding performance test between the solder paste and the solder ball (60 sec) in comparison with the Control SnAgCu Paste E and other SnAgCu paste materials (Pastes F to I) assessed (20 to 50 seconds).

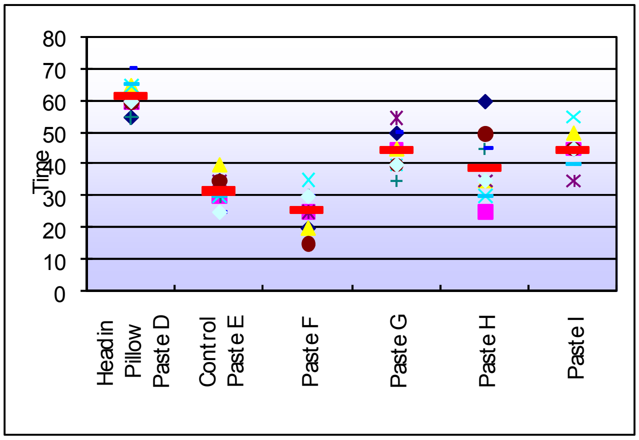


Figure 12: Comparison of the retention of the paste bonding performance for Lead-free Head-in-Pillow SnAgCu Paste D versus the other SnAgCu paste materials

Results on assembled boards

Test boards were used to confirm the ability of the lead-free Head-in-Pillow developed paste to have good heat resistivity and fluxing ability in the solder paste to remove oxidized film under more severe test conditions in a reflow simulator as shown in Figure 13.

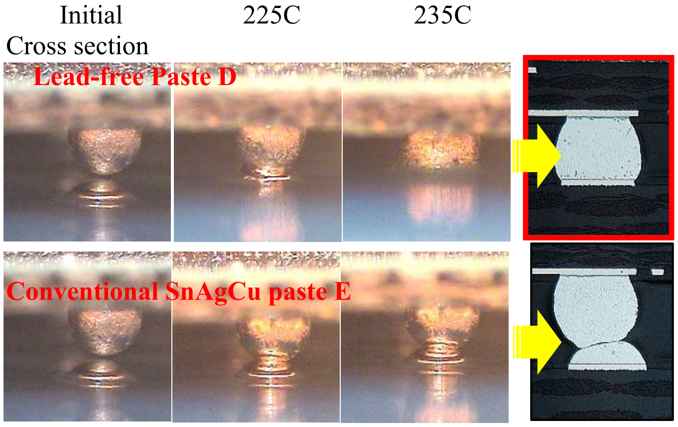


Figure 13: Observations in a reflow simulator for oxidized BGA/CSP sphere components with Lead-free Head-in-Pillow SnAgCu Paste D versus the conventional SnAgCu Paste E.

The newly developed Head-in-Pillow SnAgCu paste D started to form a solder joint between the paste and the solder ball at 225°C and achieved complete merger with the solder ball at 235°C. For the control SnAgCu paste E, the merging of the solder paste and ball was incomplete as both the solder and flux were oxidized in the first reflow and the flux remaining was unable to remove the oxidized film on the solder ball during a subsequent reflow. Example visual appearance pictures of the solder joint after peel-off of the component from the board are shown in Figure 14. The lead-free SnAgCu head in pillow paste D showed better performance in joint formation compared with the control SnAgCu paste E.

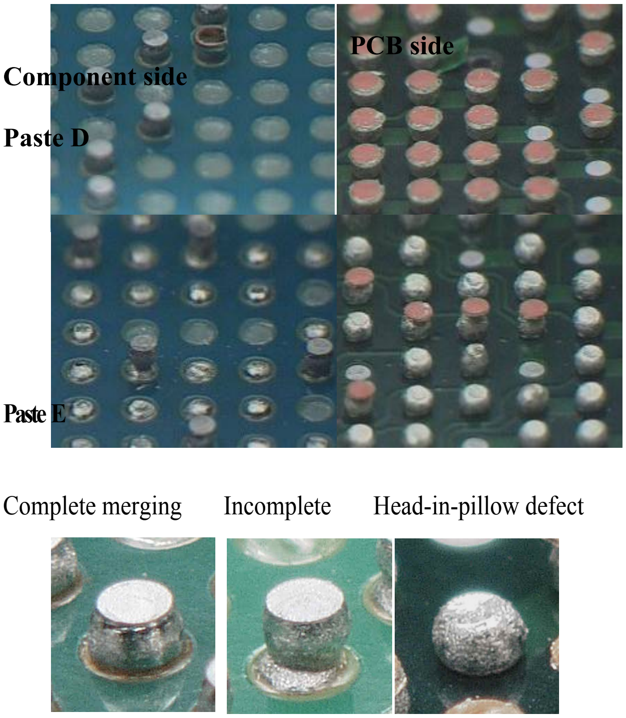


Figure 14: BGA Joint formation results for Lead-free Head-in-Pillow Paste D versus conventional SnAgCu paste E.

The results of the evaluation for the different lead-free SnAgCu pastes are shown in Figure 15.

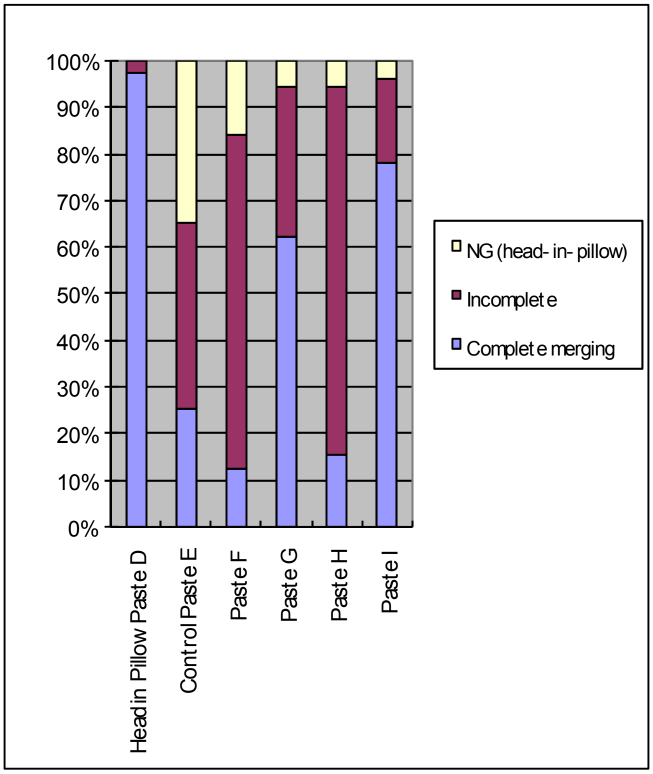


Figure 15: Solder joint formation of the different lead-free SnAgCu pastes tested

From Figure 15, the head in pillow paste D showed no occurrence of the head-in-pillow defect compared with control SnAgCu Paste E and the other SnAgCu solder paste materials tested.

Lead-free SnAgCu solder paste Nitrogen versus Air atmosphere reflow test results

In a study comparing nitrogen versus air reflow it was found that head in pillow performance improved with the use of Nitrogen atmosphere (1,000 ppm O_2) presumably because the nitrogen helped to retain and improve flux activity during the reflow profile for the lead-free SnAgCu solder paste as shown in Figure 16.

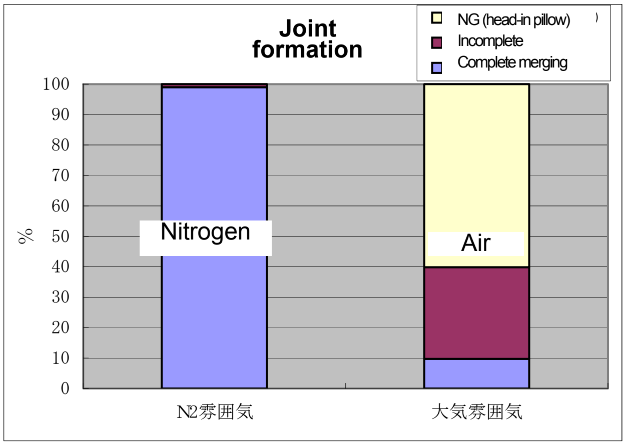


Figure 16: Occurrence of head-in-pillow soldering defect in Air versus Nitrogen atmosphere during lead-free SnAgCu soldering

As already indicated because of concerns for Nitrogen cost in reflow soldering the main development work concentrated on improvements of the lead-free SnAgCu paste with improved flux formulations developed using reflow profiles in air atmosphere as already described.

Discussion of Board and Component Warpage Standards and Other Factors Influencing the Head-in-Pillow Soldering Defect

As already mentioned, one of the primary factors causing the head in pillow issue is warpage of the component and/or board. For the component, the JEDEC JEP-95 standard[6] refers to measurements of component coplanarity/flatness at room temperature. The maximum package warpage at room temperature is 3 to 8 mils (0.075 to 0.2 mm), dependent on the ball pitch from 0.4mm to 1.27mm [7]. However, component coplanarity and flatness at room temperature could be different than at the SMT reflow temperatures at which HIP defects occur. JEITA and JEDEC standards are being developed to provide guidelines on the component coplanarity and flatness specifications during SMT reflow [8, 9]. Some of the suggested changes include having a maximum package warpage during reflow of 3 to 6 mils (0.075 to 0.15mm) dependent on the ball pitch in the range of 0.4mm to 1.27mm [7].

For the board, current IPC standards refer to a maximum board flatness of 7.5mils/inch [7]. For a large I/O BGA component this would allow the maximum coplanarity/warpage along the board pad diagonal to be too high. The current board standards do not scale correctly with package size and I/O count and need to be adjusted accordingly. Currently, there is work underway by iNEMI to measure board land coplanarity at room and reflow temperatures [7]. Based on this work, recommended acceptance criteria will be proposed to the relevant IPC standard groups. In addition, the results of the INEMI work will be provided and input into the board and component coplanarity requirements for JEITA and JEDEC so common standards can be developed.

Some other areas to consider when a head-in-pillow issue has occurred are to check for insufficient solder paste deposit by understanding stencil aperture and stencil area/ aspect ratios as well as non-wetting of the component or board due to potential contamination or excessive oxidation of the coating. In production, the solder paste screen printer could also cause Head-in-Pillow joints if it does not deposit sufficient solder paste or if there is inaccurate print registration on the board. The BGA/CSP component placer could also be the cause of Head-in-Pillow defects if there is inaccurate x-y component placement or if there is insufficient downward pressure pushing the component spheres into the solder paste deposit. Some of the remedies have been to modify stencil thickness and stencil apertures to increase paste deposition to compensate for the component package and board warpage causing the defects [10]. In addition to solder paste inspection to ensure good paste deposits, the placement pressure in the pick and place machine could be adjusted to ensure the BGA balls were correctly seated in the printed solder paste.

Optimization of the reflow profile also may be needed as well as the already mentioned development of flux formulations with higher heat resistance throughout the reflow profile which could help to reduce the Head-in-Pillow defects on tin-lead and lead-free assemblies.

In summary, the head-in-pillow defect has many potential causes, including component and board warpage, ball coplanarity and ball oxidation, paste volume and type, component placement and reflow profile used. Some of these, such as warpage, oxidation and coplanarity, may be increased by the higher temperatures associated with lead-free soldering. The typical solution would require a systematic approach to identify the specific cause leading to the issue which would then focus efforts on removing/ reducing the defect rates.

CONCLUSIONS

Newly developed tin-lead and lead-free solder pastes have been shown to help to reduce the occurrence of the head-in-pillow defect by controlling flux fluidity and improved heat resistance of the flux used in the solder paste.
However this would only be a partial solution as there also needs to be progress in reducing warpage of components and boards during reflow by updating/developing the industry standards related to this area.

FUTURE WORK

As already indicated more work is needed on development of standards for the component and board to reduce warpage during reflow. Also new developments are starting to occur with Halogen-free lead-free head in pillow solder pastes to develop new halogen-free flux formulations with improved heat resistance and fluxing ability.

ACKNOWLEDGEMENTS

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