Manufacturing And Reliability Evaluation of a Lead-Free Electronics Network Card

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Abstract

Lead-free manufacturing is becoming an industry initiative for environmental and legislative reasons. Lead-Free processing is rather new to the industry and the development of a successful assembly process requires collaboration among the end user, the component and board suppliers, and the electronics manufacturer. This paper will document the Phase 1 development plans and results for converting a surface mount network card into a lead free product. Phase 1 involved changing the eutectic tin-lead solder paste used in manufacturing to a lead-free paste (Sn3.9Ag0.6Cu), use a lead-free surface finish PCB (Immersion Silver), and a lead free PBGA component. The higher process temperature of the lead-free solder paste poses greater risk to the component materials which were not made to withstand these higher temperatures. A statement of work and a development plan to certify the process according to the product and process qualification requirements were created. The development plan included the statistical design of experiments and process and product qualification requirements. The certification plan included four separate lead-free manufacturing builds, with functional and ICT contact resistance testing, followed by multiple reliability tests. The lead-free manufacturing builds revealed issues such as connector material blistering due to the higher processing temperatures and the insufficient solder joints on the LED soldered component. Root cause analysis was performed and defect reduction plans were implemented. The results demonstrated the capability to build a lead-free SMT network product. Reliability test data further confirmed that the lead-free product assembled met all the customer's product qualification requirements.

Introduction

A control set of tin-lead solder paste soldered boards was built following the standard process flow. These tin-lead boards were built to provide a one to one assembly data and product reliability comparison analysis against Sn3.9Ag0.6Cu solder paste assembled boards.

The evaluation was divided into different phases. Each phase used various factors best reflecting the changes that could occur in the actual manufacturing environment. Variable factors introduced during different phases of the Sn3.9Ag0.6Cu (SAC) lead-free builds were manufacturer of PCB, solder paste lots, manufacturing line and manufacturing operator/ shifts.

During the initial stage of the evaluation, concerns over the reliability of a few components that were temperature sensitive was brought up due to the increased reflow temperature with the use of the higher melting temperature SAC solder paste (217°C) compared with tin-lead paste (183°C). In order to verify the capability of the temperature sensitive components to withstand the elevated reflow temperature, different suppliers of these components were identified and requested to submit their components as part of the variables tested during the SAC sample builds. (See Figure 1.)

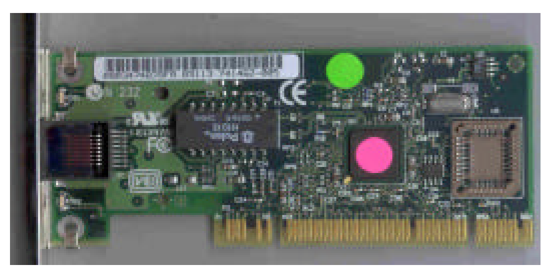

Figure 1 - Image of Fully Assembled SAC Board

Experimental – Phases of Assembly Builds

There were 5 Phases (1-5) of the board assembly builds.

Phase 1A: Control Sample Tin-lead (SnPb) Builds

- Use the existing printing and placement equipment and machine settings as used during mass production. Use the existing production tin-lead no-clean solder paste and tin-lead coated component and board coating material (tin-lead HASL).

- Use the same tin-lead reflow profile that is used during mass production. The lowest tin-lead solder joint temperature on the board is 214°C and highest solder joint temperature measured is 219°C. The lowest peak temperature measured at the component body is 217°C and the highest measured is 230°C. Time over 183°C is from 57sec to 73sec.
- Boards were assembled through the standard process flow.
- Perform visual inspection, ICT(In Circuit Testing) , FT(Functional Testing) and X-Ray inspection using standard processes.
- Randomly select 24 boards & remove the BGA, replace with new SnPb BGA to simulate the tin-lead BGA rework process. Paste flux used for the rework operation.

Phases 1B, 2, 3A, 3B, 4A, 4B and 5: Build various quantities of SAC soldered boards for each phase.

- Generate new SAC reflow profile and use this profile throughout the SAC build phases.
- The lowest solder joint temperature on board was 237°C and highest solder joint temperature was 245°C (total time above 217°C was 57 to 64 second). The lowest component body temperature measured is 238°C whereas the highest component body temperature measured is 245°C (total time over 217°C for the component bodies were 51 to 56seconds).
- Use Immersion Silver PCB surface finish, SAC alloy solder paste, Sn3.5Ag rework solder wire, SAC PBGA, SnPb finishes for all other components.
- Use the existing machine configuration, tools and parameters for printing and placement. Adjust reflow profile settings accordingly.
- Boards were assembled through the standard process flow.
- Perform visual inspection, ICT, FT & X-Ray inspection using standard processes.
- Randomly select different quantities of boards & remove the lead-free SAC BGA, replace with new SAC BGA to simulate the rework process. Paste flux used for the rework operations.

Manufacturing Line

Two manufacturing lines assembling the existing SnPb boards were selected to build SAC boards of the same model. The manufacturing lines are denoted as line 3.1X and 3.2X.

Reflow Ovens

The standard production reflow oven used for SnPb mass production assembly is capable of achieving the higher reflow temperatures needed by SAC solder paste and maintain a similar temperature variation across the board as the SnPb soldered board.

Two reflow ovens were used since the different phases of the SAC builds took place on two different manufacturing lines. These two reflow ovens are the same model from the same manufacturer. They have similar capability and performance, hence no adjustment to the reflow profile settings was required.

SnPb and SAC sample boards were reflowed in nitrogen environment. The nitrogen level was monitored throughout the sample builds and maintained below 100ppm O_2.

Rework Machine

The production rework machine used for SnPb BGA rework is capable of achieving the higher reflow temperatures desired to rework the lead-free SAC BGA component.

The rework profile for the lead-free BGA used a solder joint temperature of 240°C with time over 217°C of 48 seconds (Figure 2a). The temperature measured at the top of the BGA component was 255°C with time over 217°C of 54 seconds (Figure 2b). Lead-free paste flux was used for the lead-free BGA rework operation.

The standard SnPb BGA rework profile was achieved with solder joint peak temperature of 208°C with time over 183°C of 62 seconds (Figure 3). The peak temperature measured at the top of the BGA component was 219°C.

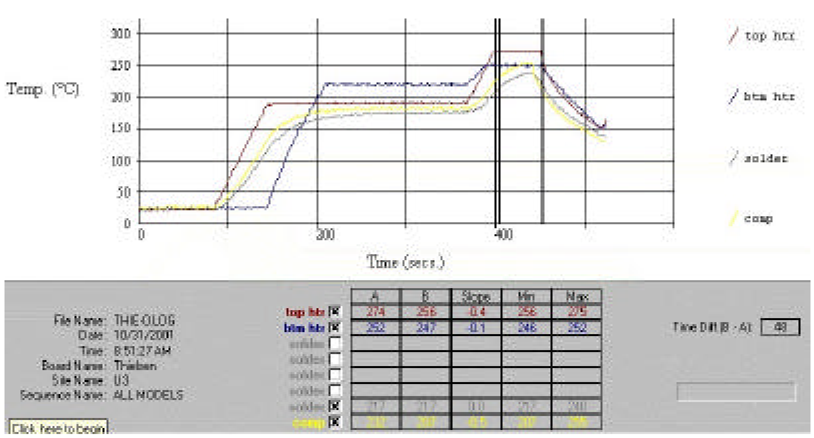

Figure 2a- SAC Rework Profile– Solder Joint

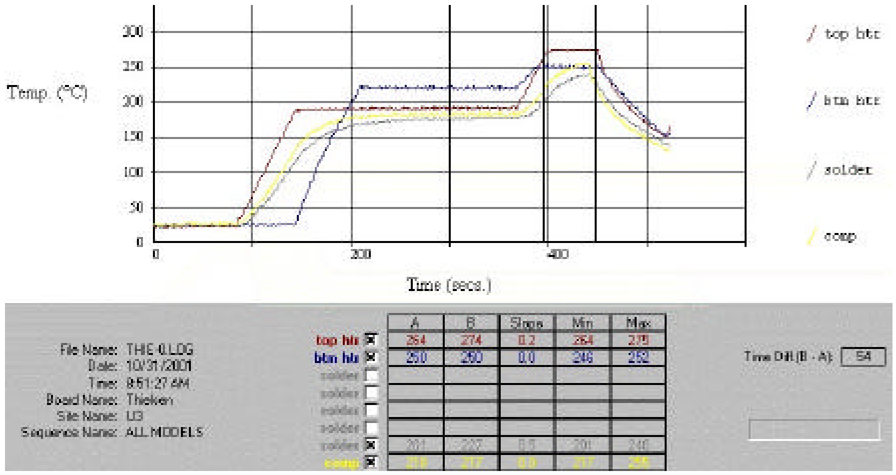

Figure 2b - SAC Rework Profile – Component Body

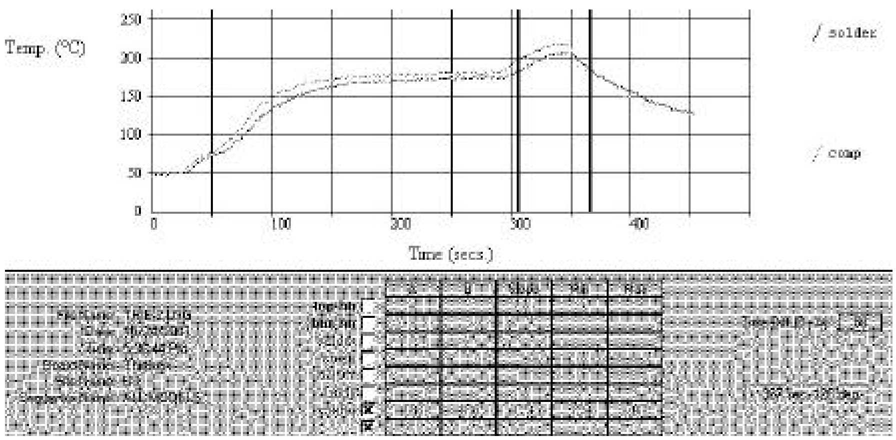

Figure 3 - SnPb Rework Profile

Solder Paste

The SnPb no-clean Type 3 solder paste used was the same material used in mass production. The contract electronics manufacturer recommended the supplier of SAC (Sn3.9Ag0.6Cu) solder paste to use based on their in-house lead-free solder paste evaluation results. The solder paste supplier was instructed to supply five different batches of solder paste to support the five different phases of the evaluation builds. The intention was to measure the consistency of the SAC solder paste manufacturing process over various lead-free solder paste lots.

Component

Five temperature sensitive components were identified upfront (XFMR; CRYSTAL; SOT-VREG; SOT-FET; SOIC-EEPROM) from the list of components used on this product. Each type of temperature sensitive component had more than one supplier. Different suppliers were used to support different phases of the evaluation builds.

Printed Circuit Board

Lead-free immersion silver PCB finish was selected for the lead-free builds. Two existing PCB suppliers fabricating the production board supplied the lead free PCBs to simulate the actual production conditions.

Process Control

Component

The lead-free SAC PBGA component carries a different part number than the standard SnPb PBGA component. In addition to that, this component has different body marking to clearly differentiate them from SnPb PBGA even after it is assembled into the final product.

Printed Circuit Board

Immersion Ag boards have a more even surface finish than tin-lead HASL boards. However, the identification of the lead free board might be confusing. In order to prevent confusion over the type of PCB board finish, the Ag board carries different part numbers than the tin-lead HASL boards.

Assembled Board

Immersion Ag boards, that were assembled with SAC solder paste was identified by attaching additional labels summarizing the specific phases of the build at the back of the boards and color sticker at the front side of the boards immediately after the post reflow inspection station. This provided a clear identification and control over the SAC assembled boards.

Process

Tin-Lead Control Build – Phase 1A

Boards supplied by supplier B were used during this control build. 186 boards were built at line 3.2X using SnPb solder paste and 24 boards were randomly selected to go through the BGA rework process. SnPb rework profile and paste flux were used during the process of BGAs removal and the new SnPb BGA replacement process.

Lead Free Build - Phase 1B (part 1)

A total of 120 boards from PCB supplier A were built on line 3.2X using lot 1 SnAgCu solder paste in Phase 1B.

The first 30 boards were built to assess the process readiness (Phase 1B - Part 1) prior to building the remainder of the 90 boards (Phase 1B- Part 2). The first 30 boards went through standard inspection gate processes including In Circuit Test (ICT) and Functional Test (FT). Investigation of possible root cause for problems and solutions were implemented before proceeding to build Phase 1B (part 2).

Phase 1B (part 2)

In addition to the study on standard lead-free assembly processes, lead free rework capability and reliability were also considered and included in the evaluation. 18 boards were randomly selected from the Phase 1 build and the BGAs were removed using standard rework process, except the rework profile was adjusted to meet higher temperature SAC alloy rework requirements. New SAC BGA components were placed utilized the SAC rework profile and paste flux.

Phase 2

On successful completion of Phase 1, 252 boards from PCB supplier A were built at line 3.2X using SnAgCu solder paste lot 2 in Phase 2. Other variables were kept constant apart from the solder paste lot in order to assess the performance of the solder paste.
Another 18 boards were randomly selected from this build and followed through the same BGA rework procedure as in phase 1B.

Phase 3A

252 boards from PCB supplier B were built at line 3.1X using SnAgCu solder paste lot 3. A new stencil design was used based on the phase 2 build findings.
Additionally, 5 boards were randomly selected from this build and went through the same BGA rework procedure as in Phases 1B.

Phase 3B

252 boards from PCB supplier A were built at line 3.1X using SnAgCu solder paste lot 3.
Similarly, 5 boards were randomly selected from this build and went through the same BGA rework procedure as in phase 1B.

Phase 4A

228 boards from PCB supplier A were built at line 3.1X using SnAgCu solder paste lot 4.

Phase 4B

360 boards from PCB supplier B were built at line 3.2X using SnAgCu solder paste lot 4. 5 boards from each of Phase 4A and 4B were randomly selected and went through the same BGA rework procedure as described in phase 1B.

Phase 5

90 boards were built using SnAgCu paste solder paste lot 4 with the usual 5 mil thick stencil used in Phase 4. 420 boards were built using SnAgCu solder paste lot 4 with a 6 mil thick stencil.

Results / Discussion

Phase 1B Part 1

During Phase 1B (part 1) build, at the visual inspection SMT station, a few anomalies were observed. There was discoloration on the PCB silk-screen, non-wetting at the LED component on the center lead (Figure 4) and 'blistering' defects found on a connector component (Figure 5).

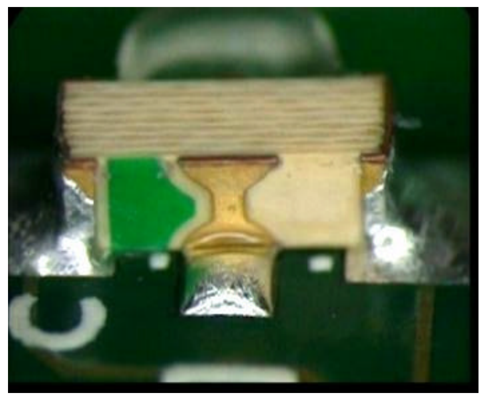

Figure 4 - Image of Non-Wetting SAC Soldered LED

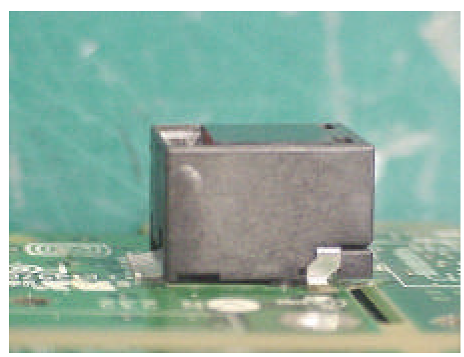

Figure 5 - Image of Blistering Connector

An assessment was done to investigate the cause of these anomalies.

The level of PCB silkscreen discoloration was verified against the current specification. It was determined that the discoloration was within the threshold of the specification.

Moisture was identified as the most probable culprit of the blistering connector defect. Therefore, a sample of the components from the same lot were baked at high temperature (120^{0}C for 24 hours) before passing it through the reflow oven set at the lead free reflow profile. These components were removed from their original tape and reel packaging before baking due to the packaging material not being able to withstand the high baking temperatures. Simultaneously, another control sample without prior baking was passed through the oven for comparison purposes.

It was evident that the components baked prior to heating has no popcorning defect at all whereas the fresh component without baking, exhibited the same blistering defect.

Later, the component connector supplier conducted an evaluation in their facility to address this issue. The conclusion made was that in future the component manufacturer would redefine the shipment/packaging requirements in order to reduce the moisture absorption rate and hence, eliminate popcorn defects during higher temperature lead free reflow production.

Since the connectors' tape and reel packaging cannot withstand high baking temperatures and there was enough time prior to the next build to bake the connectors in their reels at lower baking temperatures and for a longer time, the connectors were not removed from their original packaging with minimal handling and baked at 80 ^{o}C for 48 hours prior to further use.

Phase 1B Part 2

The data collected during this phase showed there was no blistering defect at the connectors that had been baked. However, the LED non-wetting defect on the center lead was still evident. Since only one defect was found and the board build sample size was too small to make a definitive conclusion, it was decided that we should proceed to the next phase of evaluation without any modification to the process.

For the lead-free rework process, the lead-free BGA components were inspected under X-ray after rework and no defects found. The similar rework process was applied to other BGA reworked boards randomly selected from phase 2, 3A, 3B, 4A and finally 4B. These reworked boards were clearly labeled and identified. The boards with reworked BGAs underwent the same set of reliability tests as the non-reworked assembled boards.

ICT Resistance Repeatability (Phase 1B Part 2)

An additional study on ICT resistance repeatability was conducted during the evaluation to ascertain the impact the lead free process had on ICT test resistance with relation to the tin-lead assembly process for the same product board. The result showed that the test resistance Cpk is more than 1.33. The deduction made from the ICT study is that there was no impact to the current ICT test rate with the lead-free SnAgCu process compared with the SnPb process.

Phase 2

Non-wetting on the center lead of the LED component was the only solder joint defect found during this 252 SnAgCu board build. Since the same type of defect occurred consistently at the LED location, solder paste volume increment at the LED location was suggested to be the remedy to improve solder wetting. A new stencil was built to use in Phase 3A with an enlarged center lead LED stencil aperture opening designed.

There was one defective transformer found during Functional Testing after assembly in Phase 2. This transformer was sent back to the component supplier for root cause analysis. The component supplier confirmed later that the failure was purely component related and was not induced by the higher lead free temperature assembly process.

Phase 3A

With the enlarged LED center lead stencil aperture opening and hence increased solder paste volume deposited, the solder wetting quality improved for the LED component during this 252 SnAgCu board build.

The improvement in the wetting quality resulted from a higher lead-free solder fillet formed. There was no soldering defect encountered at the LED location(Figure 6). Since the new stencil showed promising results, the same stencil was used in the next evaluation build (Phase 3B) to confirm these findings.

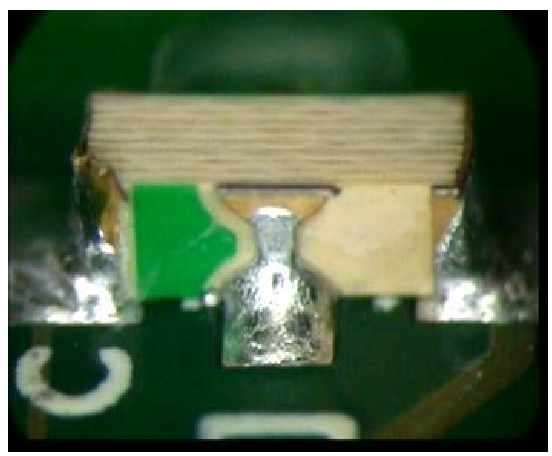

Figure 6 - Image of Good Wetting for SAC Soldered LED

Phase 3B

A different PCB supplier compared with Phase 3A with a different SnAgCu paste lot was used for the 252 SnAgCu board builds. The different PCB supplier used had no impact to the assembly.

The LED solder joint fillet height during phase 3B build is similar to phase 3A boards but randomly, the LED non-wetting defect surfaced again. It was decided that more boards would be built with the same stencil having the enlarged stencil LED center lead aperture opening in the next phase in order to have a better picture on the defect rate with a larger total sample size.

Phase 4A and Phase 4B

A different SnAgCu paste lot was used for the SnAgCu board builds in Phase 4A and 4B with no impact to the assembly associated with the change was observed from Phase 3B.

The only issue arose during phase 4A and 4B builds was again the LED non-wetting defect. The SnAgCu board assembly defect per million (dpm) rate observed is similar to that of phase 3B. The new enlarged stencil did not seem to resolve the LED non-wetting defect consistently.

Phase 5

A special build was conducted to evaluate another new thicker stencil (6 mil thick) with the thought that by increasing the paste volume and also the solder paste height deposited on the board, it may help to improve the solder wetting. The stencil thickness was increased from 5 mils to 6 mils and the aperture size was maintained to the exact dimension of the LED center board pad.

A control build of 90 SnAgCu boards were built with the stencil used during phases 3-4 prior to running the evaluation with the 6mil thick stencil. This was to ensure that the process conditions had not changed and no other variables would affect the evaluation data other than the new stencil fabricated.

After seeing similar non-wetting defect rates in the 90 SnAgCu control builds , the 5mils stencil was replaced by 6mils stencil and 420 SnAgCu boards were built. The result showed approximately the same solder dpm for both stencils with no improvement.

Cross-section/ SEM analysis was undertaken to observe the solder joint and component/ board metallurgy of the soldered SnAgCu LED component. This was to understand why the solder did not wet onto the LED center lead despite the increased solder volume paste volume deposited.

Cross sectioning was performed along the Y-axis of the center lead of the SAC soldered boards produced using the 5mils and 6 mil thick metal stencils. For each stencil thickness, a LED center lead joint with a good solder joint and one with a non-wetted solder joint was compared. Cross-sectional analysis was also done with SnPb paste soldered LED components that had good solder joints to provide an additional picture of the differences between SnPb and SAC soldered joints.

It was noticed that for the non-wetted SnAgCu soldered LED components, where the pad meets the lead, there is a metal burr(whisker) protruding up from the component lead cutting at an angle of around 45 to 60° from the board (Figure 7 and 8). This phenomenon is consistent on both non-wetted SnAgCu soldered samples produced with either the 5 mil stencil or 6mil thick stencils.

On the other hand, the SAC soldered LED having good solder joints produced from both 5 mil and 6 mil stencils, had the metal burr(whisker) protruding down or horizontally from the component lead cutting or parellel to the component terminal(Figure 9 and 10). The cross-sectional image of the good SnPb soldered LED using the 5 mil thick stencil shows that the metal burr/ whisker also present on the LED cutting lead but it is sticking up vertically parallel to the component terminal (Figure 11).

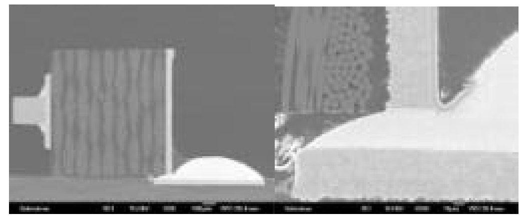

Figure 7 - SEM Image of SAC Soldered LED – Non-Wetting Solder Joint (5mils Stencil)

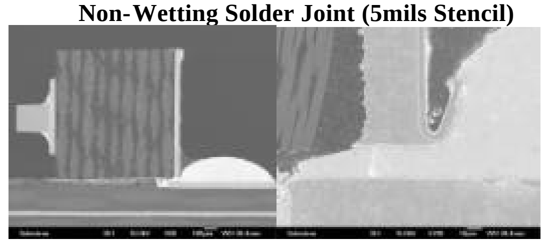

Figure 8 - SEM Image of SAC Soldered LED – Non-Wetting Solder Joint (6mils Stencil)

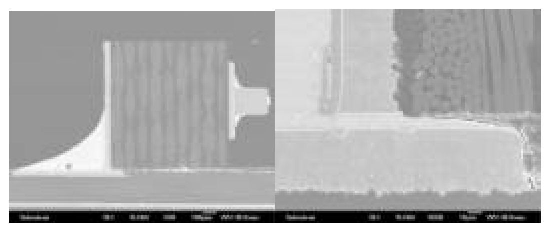

Figure 9 - SEM Image of SAC Soldered LED – Good Solder Joint (5mils Stencil)

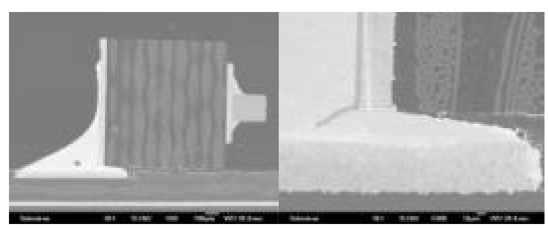

Figure 10 - SEM Image of SAC Soldered LED - Good Solder Joint (6mils Stencil)

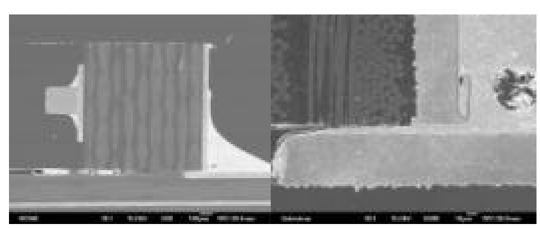

Figure 11 - SEM Image of SnPb Soldered LED – Good Solder Joint (5mils Stencil)

The hypothesis deducted from the above observations for SnAgCu soldered joints with reduced wetting was that there was an increased solder damming action formed by the burr with the higher surface tension of the SnAgCu solder (compared to the low surface tension of tin-lead). This caused the surface tension force of the SnAgCu solder to remain centered on the board pad instead of wetting up the lead. The wetting of SAC solder paste is also slower than tin-lead solder paste.

The possible explanation as to the intermittent nature of this visual defect is that the varying length and angle of the burr inherited from the component terminal production process, which the maximum component specification for burr length is 0.1mm and the burr cannot be wholly eliminated.

In addition, another observation from the SEM images show the LED center lead to pad geometry has the lead barely sitting on the pad. This observation had led the team to look into the PCB pad pattern design on this product and compare with the design recommended by the component supplier. The findings have revealed that the component supplier recommends a center lead pad pattern 0.4mm larger than the design used on this product. The non-centered lead to pad geometry issue combined with a component termination burr with varying length and angle causes the conditions for potential marginal wetting with lead free SnAgCu solder paste.

The defect level range for the assembled SnAgCu boards which included boards with LED visual defects were within the low defect level range accepted for the existing tin-lead assembled boards in production. In addition, the solder joint quality is within the acceptable limits based on IPC-610 visual inspection industry standard for SnPb solder paste and also based on the customer's product visual inspection standard.

Further investigations could also be conducted on the LED components to reduce the defect level further.

Reliability Testing

Boards built in Phases 1, 2, 3 and 4 were reliability tested.

The type of reliability testing conducted included:

1. Temperature and Humidity testing in Non-operating conditions. 148 lead-free SAC boards were tested at 85°C and 85%RH for 500 hours. Samples were inspected for corrosion and contamination failures.
2. Temperature and Voltage Testing under operating conditions. 3 lead-free SAC boards were tested at –5°C, 25°C, 60°C at 4.7V, 5V and 5.3V power cycles every hour. Components were inspected for thermal or parameter drift problems or manufacturing process issues.
3. Accelerated Temperature Cycling. 160 lead-free SAC boards were tested from –40°C to 85°C for 1000 cycles. Solder joints, connectors and other components on the boards were inspected for failure.
4. Unpackaged shock. 10 lead-free SAC boards were tested. Three drops in each of the six directions. Components were inspected for displaced or dislodging and cracking of the components or intermittent operation.
5. Unpackaged vibration. Lead-free SAC boards were tested with a random profile from 5 to 500 Hz with 10minutes per axis. Components were inspected for displaced or dislodging and cracking of the components or intermittent operation.

The lead-free SAC boards passed all five of the reliability tests conducted above. (See Figure 12.)

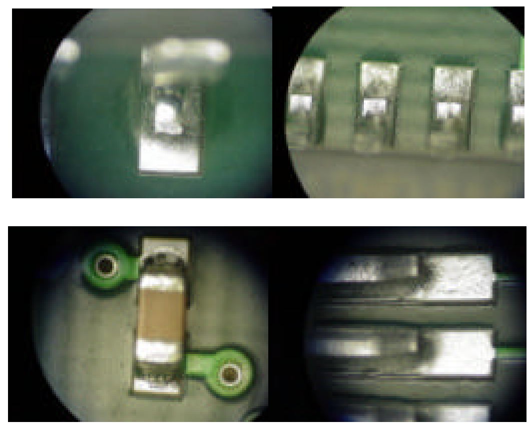

Figure 12 - Images of good SAC Solder Joints Observed

Conclusions

The lead-free builds conducted from Phase 1 to Phase 4 has shown the feasibility of building SnAgCu soldered lead-free product successfully over different paste lots, from different PCB and component suppliers over different manufacturing lines and operating shifts.

Some issues were highly with the use of lead-free SnAgCu such as the lower wetting at the LED component and blistering defects at the connector but these issues can be worked through.

The lead-free product defect per million is within the range acceptable for tin-lead production. The reliability testing of the lead-free product showed no issues. The assembly is capable to be made with lead-free SnAgCu solder paste.

Acknowledgements

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