As originally published in the IPC APEX EXPO Proceedings.

Case Study Comparing the Solderability of a Specific Pb Free No Clean Paste in Vapor Phase and Convection Reflow

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Abstract:
To help address the environmental requirements driven by the European Union RoHS Directive, consumer applications have changed the solder alloys for the manufacturing of printed circuit board assemblies (PCBAs) by removing Pb from solder. Based on the anticipated end to various exemptions and other market forces, high end server applications are now following suit. In addition, as the server/computer industry evolves, the requirements for speed and memory storage continue to increase, causing a need for higher levels of signal integrity along with greater density/mass of components and wiring within PCBA's. This change to more dense/higher thermal mass components on PCBA's and going to a Pb Free solder at higher melting temperature than SnPb Eutectic Solder will aggravate the temperature gradients that occur during reflow, causing major limitations when using standard IR/Convection reflow. Excessive temperature gradients can damage less massive components and less dense laminate areas of the PCBA's. Consequently, other techniques need to be investigated, and the leading alternative is Vapor Phase Reflow. Vapor Phase Reflow is a legacy soldering method that was popular before the 1990's. Vapor Phase Reflow has a processing advantage: its thermal blanket possesses a much greater heat density than convection or IR heating. This reduces the temperature gradients across the board assembly, preventing sensitive components from exceeding maximum temperature limitations. One of the many concerns for implementing Pb Free Vapor Phase Reflow is the effect on solderability. The objective of this publication is to compare the solder wetting between Vapor Phase Reflow and Convection Reflow using a specific Pb Free (SnAgCu) SAC solder paste. This study will compare the amount of area the solder wetted, solder heights, wetting angles, and voiding.

Introduction
In 2006, legislation known as the Restriction of Hazardous Substances (RoHS) Directive was enacted in Europe. This directive bans a number of substances including Pb solder in the manufacturing of Electronic Equipment (Johnson, 2004). Consumer applications migrated to new Pb free solder alloys to meet the 2006 implementation date of the European Union RoHS Directive. Since 2006, server computers have been exempt and can still use SnPb Solders, but this exemption will probably discontinue in 2014, or shortly thereafter. The electrical performance requirements and capabilities of server computers drive greater density/mass components and wiring within printed circuit board assemblies, resulting in significantly thicker printed circuit boards. An example of a higher mass component is the Ventura® (Registered trademark of Amphenol Corporation) SMT Connector System offered by Amphenol. In some IBM servers today, this connector system is used to connect the various I/O cards, processor cards, major backplanes, and other cards, like a nervous system within a human body. The largest connector design used is a 120 wafer connector offering 1,680 single ended signals on 5,040 SMT leads, which weighs over 3 lb. Even in SnPb soldering, due to the connector mass, Vapor Phase Reflow is required for certain applications of this connector system (George, 2007).

With the use of these more dense/higher thermal mass components on PCBA's, along with the transition to higher temperature Pb Free solder alloys the industry has reached a critical juncture. This juncture will aggravate the temperature gradients that occur during reflow, causing major limitations in using standard IR/Convection reflow. Excessive temperature gradients can damage less massive components and less dense laminate areas of the PCBA's. As a result, other techniques need to be investigated and implemented, and the leading alternative is Vapor Phase Reflow. Vapor phase was first used and patented in the 1970's. However, it became less popular in the late 1980's and early 1990's because the vapor fluid chemicals used at that time contained Freon (Suihkonen, 2007). Today, vapor phase fluids no longer use Freon and instead use perfluorinated heat transfer fluid. Vapor Phase Reflow has a processing advantage in that its thermal blanket possesses a much greater heat density than convection or IR heating, and this reduces the temperature gradients across the board assembly. The other great advantage to Vapor Phase Reflow is the absolute control on the maximum temperature that is applied across the printed circuit board assembly (PCBA). When a PCBA enters into a saturated vapor field/atmosphere, the fluid will condense onto the surfaces of the PCBA. This condensation transfers the total heat of evaporation to the PCBA causing the heat ramp. Once any portion of the PCBA has reached the condensation temperature of the vapor fluid, no further heat transfer occurs in this region, since vapor condensation is no longer possible. High mass regions of the board will continue to condense vapor until they also reach the condensation temperature. Thus, overheating of components higher than the condensation temperature is not possible, preventing sensitive components from going above maximum temperature limitations (Nowottnick, 2002). Another advantage associated with Vapor Phase Reflow is the minimal oxidation of the solder joints, since soldering is performed in an inert atmosphere. In addition, vapor phase fluid has a high thermal conductivity making it efficient in transferring heat, allowing use of a lower maximum heating temperature and shortens the soldering time. Disadvantages of Vapor Phase Reflow include expensive boiling media, the need for constant fluid level checks, and concerns for excessive heating ramp between pre-heat/soak and reflow. Such heating ramps can be stressful on certain electrical components (George, 2007). In addition, heat shielding techniques, often used in convection reflow, are much less effective in Vapor Phase Reflow.

One of many concerns for implementing Pb Free Vapor Phase Reflow is the effect on solder wetting. There are concerns that the liquid fluid media used for reflow will remove the solder paste or cause a liquid barrier preventing the solder/flux from spreading. Other studies/reports have presented data showing that vapor phase reflow has superior wettability than convection reflow (Samat, 2009; Sequeira, 2007). The objective of this publication is to provide a comparison of the solder wetting between Vapor Phase Reflow and Convection Reflow using a specific Pb Free SAC solder paste. This study will compare the amount of area the solder wetted, solder heights, wetting angles, and voiding.

Importance of Wetting Angle to Solderability

The wetting angle is one of the critical attributes in defining the solderability of metal liquid media soldering/wetting to a different metal surface. Other names for the wetting angle are contact angle or the dihedral angle. By definition solder wetting angle is the angle where the liquid-vapor (air) interface meets with the solid-liquid interface. Figure 1 shows an illustration of this wetting angle.

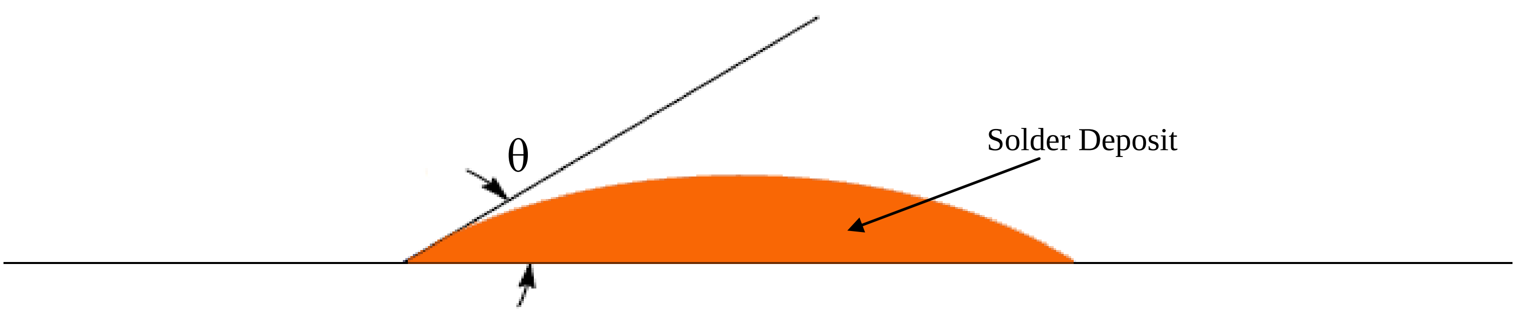


Figure 1: Example of Wetting Angle

Young's equation states that the vector surface force (surface energy/surface tension) that spreads the solder across the soldering surface is equal to the summation of the vector interface forces (interface tensions) between the solder and the metal being soldered to and the solder liquid to the air/vapor/liquid environment around the solder (Young, 1805). Note the vector surface force that spreads the solder across the soldering surface is in a parallel opposing direction to the vector interface force between the solder liquid to the metal soldering surface. Here is the mathematical relationship:

$$\gamma_{SV} = \gamma_{LS} + \gamma_{LV} \cos(\theta)$$

γ_{SV} =Vector Surface Force that spreads the solder across the soldering surface

γ_{LS} =Vector Interface Force between the Solder Liquid to the Metal Soldering Surface

γ_{LV} =Vector Interface Force between the Solder Liquid to the Air, Vapor/Gas, or Liquid that surrounds the solder.

θ = Wetting Angle

From the previous relationship, total wetting is achieved when the wetting angle equals 0° and total nonwetting is achieved when the wetting angle equals 180°. Thus, the closer the wetting angle approaches 0° the greater the wetting / solderability (Manko, 2001). IPC-A-610, a common industry standard for solder joint workmanship criteria and one of the most commonly used standards for many IBM products, states that for a solder joint to be acceptable the wetting angle has to be less then 90°. If the angle is greater then 90°, then the solder joint is considered a dewet or non-wet. There are some exceptions that are acceptable: when the wetting angle exceeding 90° is created by the solder contour extending over the edge of the solderable termination area or over solder resist. Figure 2 is an illustration that covers the acceptable wetting angles for solder joints. Figure 3 shows a classic non-wet solder joint.

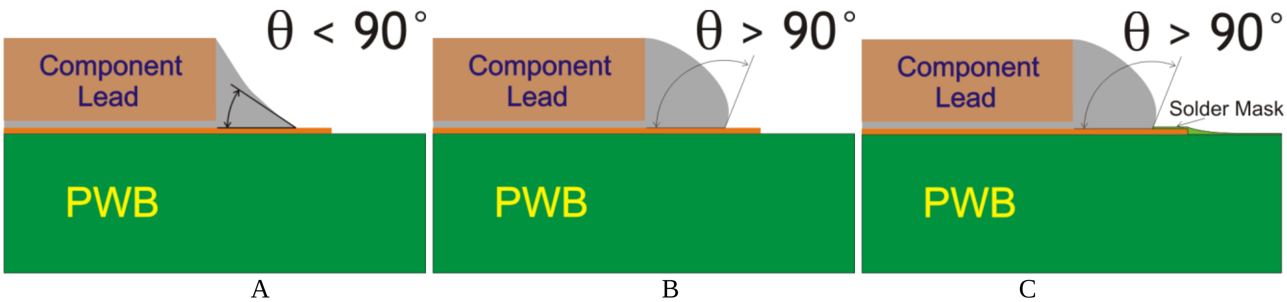


Figure 2: Acceptable wetting angles for solder joints are covered in IPC-A-610. Pictures A shows wetting angle less then 90°. Picture B shows a wetting angle greater then 90° formed over the edge of the solderable termination area. Picture C shows a wetting angle greater then 90° formed over solder resist (Bielick, 2010).

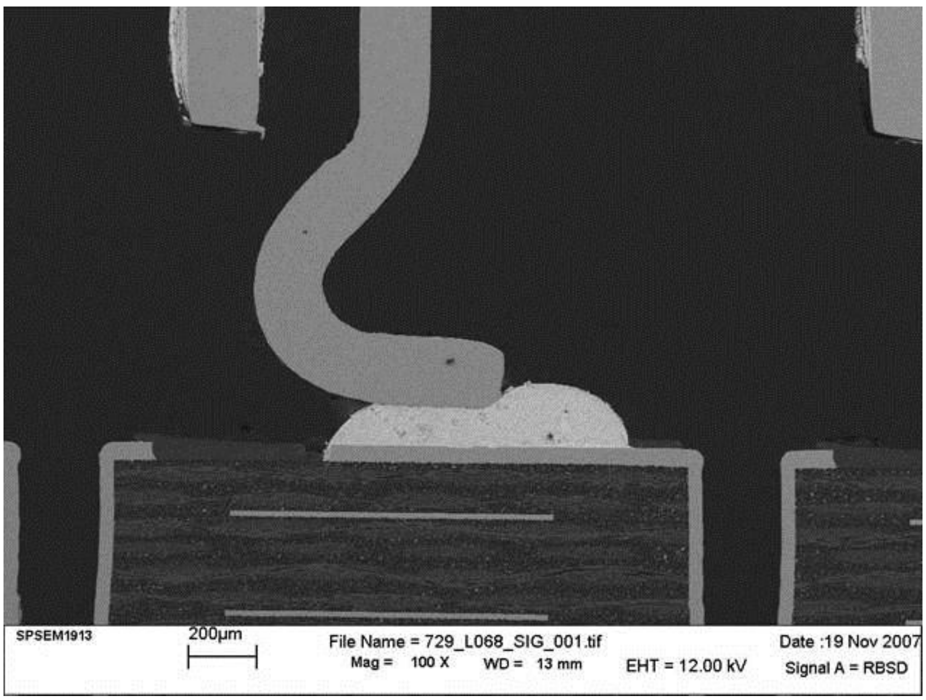


Figure 3: Example of non-wet Solder Joint.

During wetting, spreading has a greater speed then bulk material flow and thus, the amount of solder material present has little influence on the wetting angle. The greatest factors affecting the wetting angle are the following:

- Type of flux used
- How the flux is activated during reflow
- The solder metal alloy media
- Base metal material that is being soldered to
- Surface topography of the soldering surface
- Tarnish/oxidation layer thickness on the soldering surface
- Contaminants in the solder and solderable surface
- Rate of solidification of the solder on cooling (Manko, 2001).

Experiment Process

One of the major goals of this study was to control as much as possible the previous factors with the purpose of observing any difference in wetting behavior caused by the reflow technique. The samples used as the solderable metal surfaces were 10 Cu Blocks. Each Cu Block had the dimensions: 38 mm X 38 mm X 3.2 mm. Figure 4 shows an example of the Cu Block Sample.

Figure 4: Example of a Cu Block Sample after Cleaning and before Solder Paste Deposit and Reflow.

Five of the Cu Blocks went through Vapor Phase Reflow and five of the blocks went through Convection Reflow. A separate Cu Block had three thermocouples (TC'S) attached to it and was used to set up the recipes of the thermal reflow processes. The recipes developed were optimized for Pb Free SAC soldering parameters. All three TC's were attached to the topside surface and were adhered from one corner to the opposite corner. The Vapor Phase Reflow machine was manufactured by R&D Technical Services. The Vapor Phase machine was a batch unit that had a fully enclosed topside/bottomside convection heat pre-heat zone, and a reflow zone containing the vapor well. Both in the pre-heat and reflow zone Nitrogen (Inert) gas was supplied. The following was the recipe used:

- Boiling Fluid – 240 perfluorinated heat transfer fluid
- Pre-Heat - Oven at 290°C for 175 Seconds
- Reflow Dwell – 115 Seconds
- Vapor Flash Off Dwell – 25 Seconds
- Cool Dwell – 400 Seconds

Figure 5 shows the corresponding thermal profile on the Cu Block.

The Convection Reflow machine used was an inline unit from Heller Industries. The Convection Reflow oven had 12 Topside/Bottomside Zones and had Nitrogen (Inert) gas atmosphere. The Nitrogen source was same for both the Vapor Phase and Convection Reflow Machines. The following was the recipe used:

Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11	Zone 12
200	230	195	180	230	280	275	222	180	140	130	110

Belt Speed was 40 cm/min.

Figure 6 shows the corresponding thermal profile on the Cu Block. Table 1 compares thermal profile measurements between the two reflow processes.

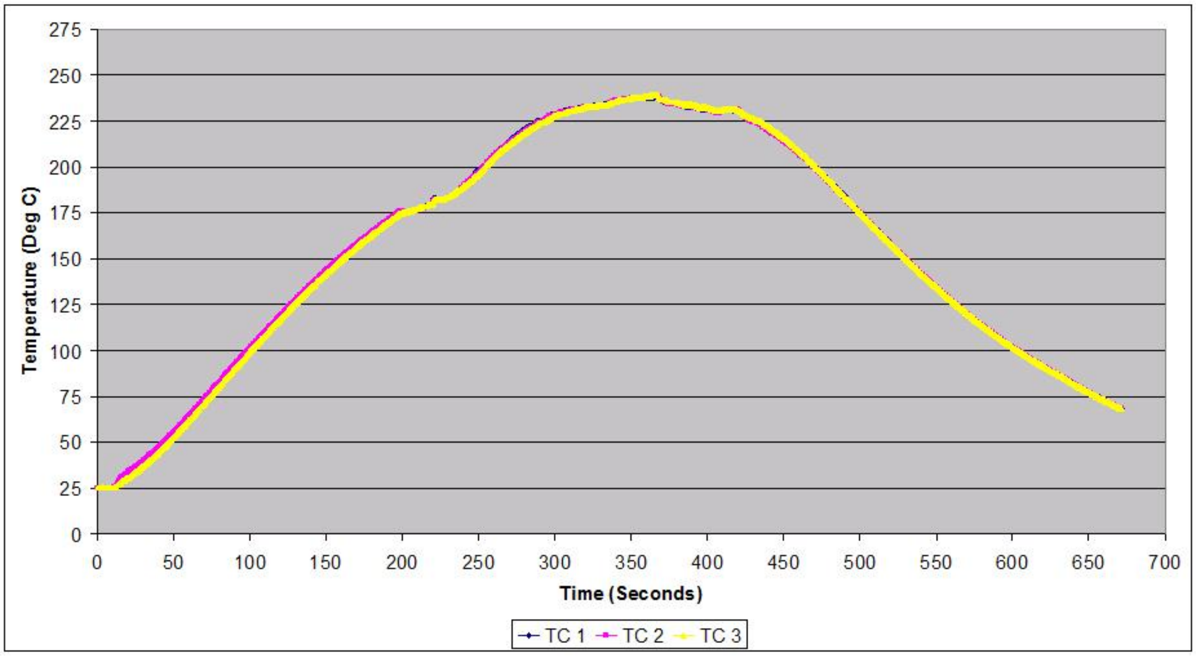


Figure 5: Pb Free Vapor Phase Thermal Profile used.

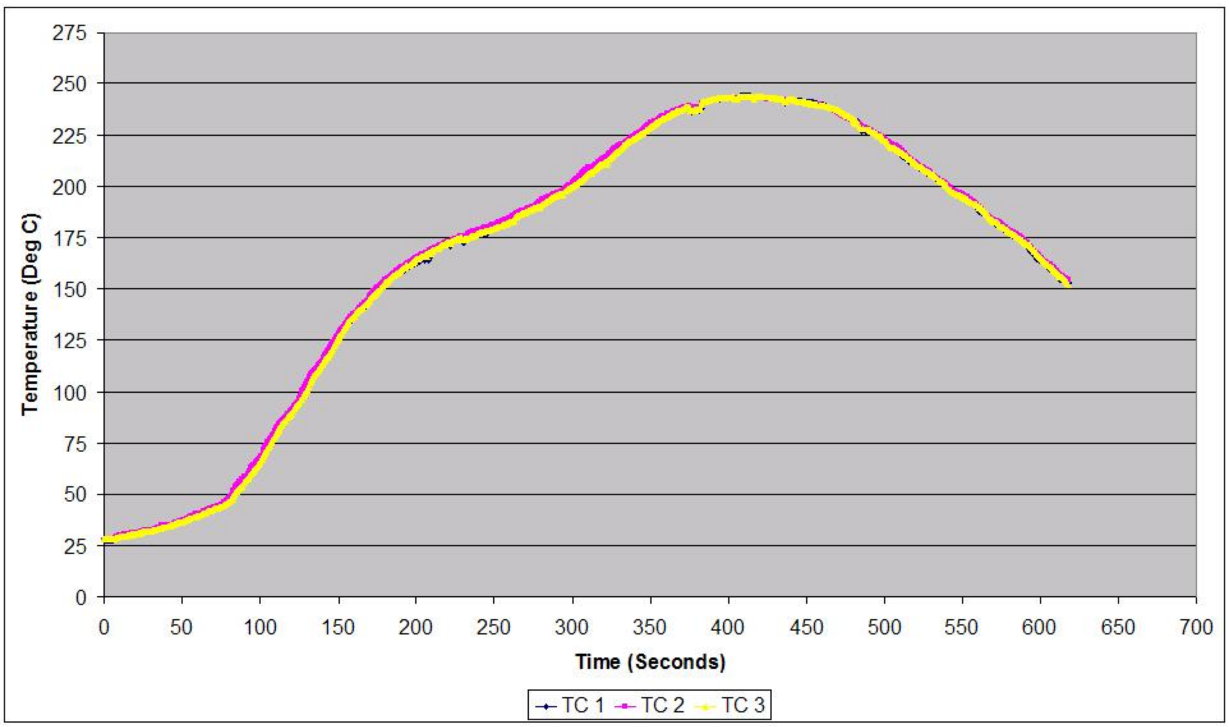


Figure 6: Pb Free Convection Reflow Thermal Profile used.

As shown in Table 1, the Convection Reflow profile peaked about 5 degrees hotter and stayed about 15 seconds longer above 217°C then the Vapor Phase Reflow profile. Note for the heating ramps and cooling ramps, both reflow processes were equivalent. For this experiment, the greater amount of heat and time above the liquidous was assumed to have minimal effect in reflowing the solder and solder solidification.

Table 1: Comparison of Thermal Profile Measurements Taken from the Same TCs used in Each Reflow Process

	Vapor Phase Reflow			**Convection Reflow**		
	TC1	TC2	TC3	TC1	TC2	TC3
Maximum Temperature (Deg C)	238.352	238.631	239.071	244.019	243.301	243.820
Time Above 217 Deg C (Seconds)	172.500	168.500	170.000	183.500	186.500	180.500
Ramp Rate from 0 to 180 Deg C (Deg C / Sec)	0.818	0.747	0.744	0.763	0.801	0.778
Ramp Rate from 180 Deg C to Max Temp (Deg C / Sec)	0.384	0.393	0.402	0.399	0.387	0.411
Cooling Rate from Max Reflow to 170 Deg C (Deg C / Sec)	-0.488	-0.495	-0.495	-0.413	-0.394	-0.408

For sample preparation, each Cu Block was cleaned using a Scotch Brite (Trademark of 3M Corporation) Pad, followed by Xylene and Isopropanol wipe, and allowed to dry. Figure 4 shows the Cu Block metal surface after cleaning. A SAC 305 Pb free solder paste was used for the solder deposition. Here are the data specifications for the solder paste (Indium, 2008):

- 96.5Sn/3.0Ag/0.5Cu (SAC305)
- Type 3 Mesh
- No clean Flux Chemistry – Flux Type R0L0
- Halide-Free
- Typical Solder Paste Viscosity (Malcom 10 RPM) – 1700 poise
- Typical Tackiness – 35 g

A manual mini-stencil was used to deposit the solder paste on each Cu Block. The 0.152 mm thick stencil had 0.508 mm diameter apertures on 1.27 mm pitch for a total of 624 apertures. Figure 7 shows an example of the solder paste deposition on a Cu Block Sample. After solder dispensing the Cu Samples were immediately run through the corresponding reflow process.

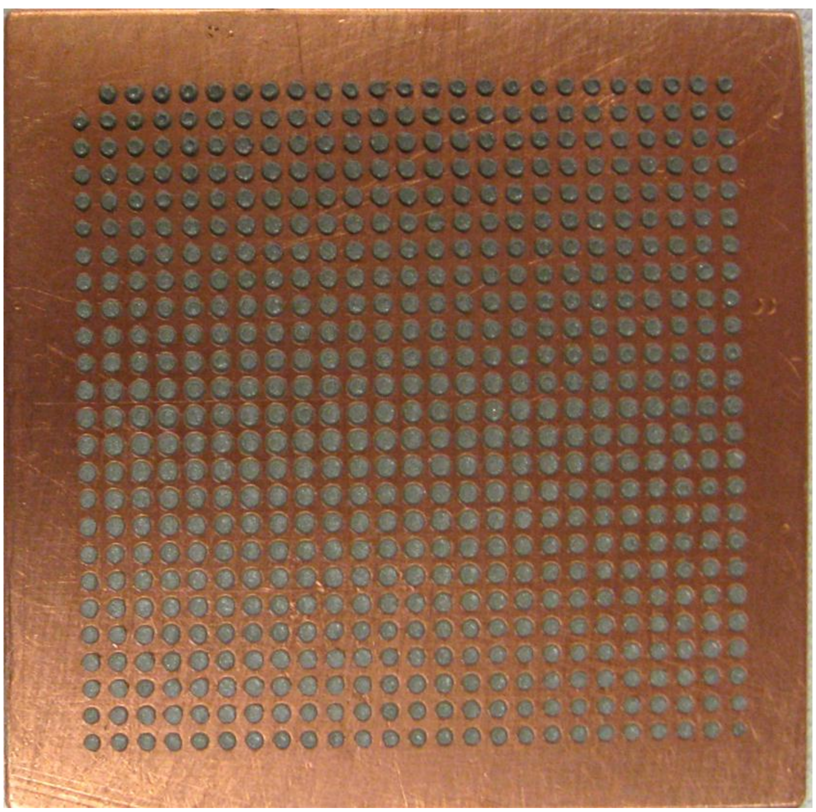
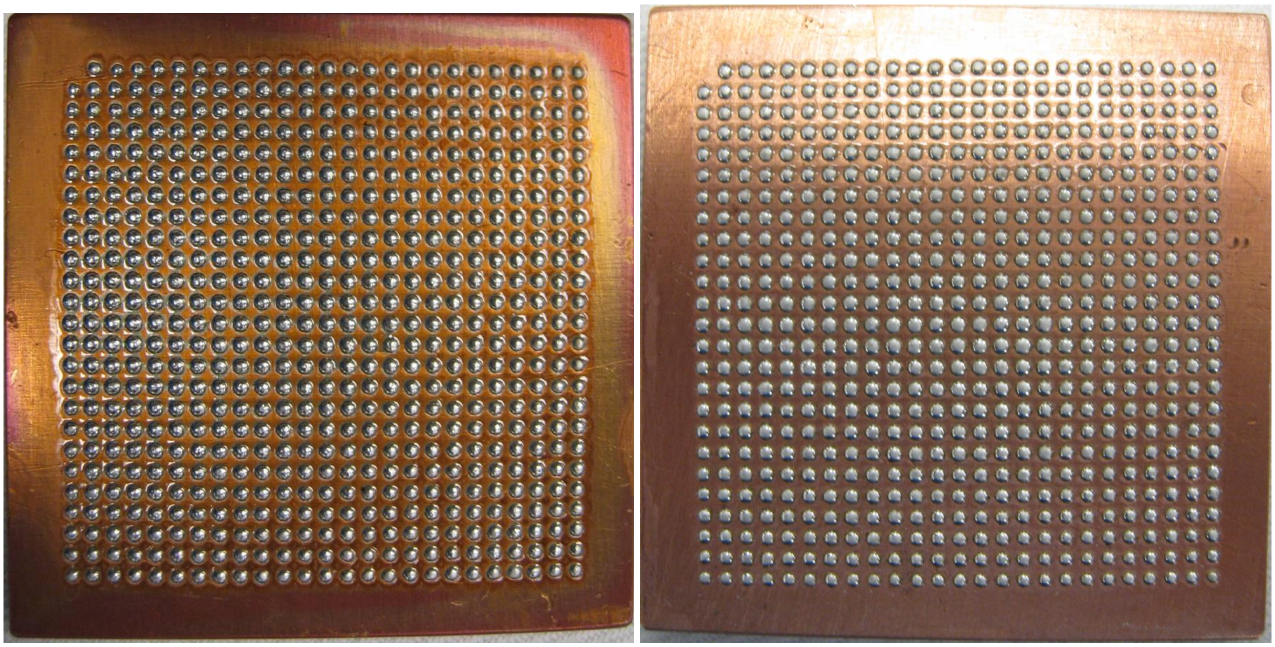


Figure 7: Example of the Solder Paste Deposition on Cu Block Sample.

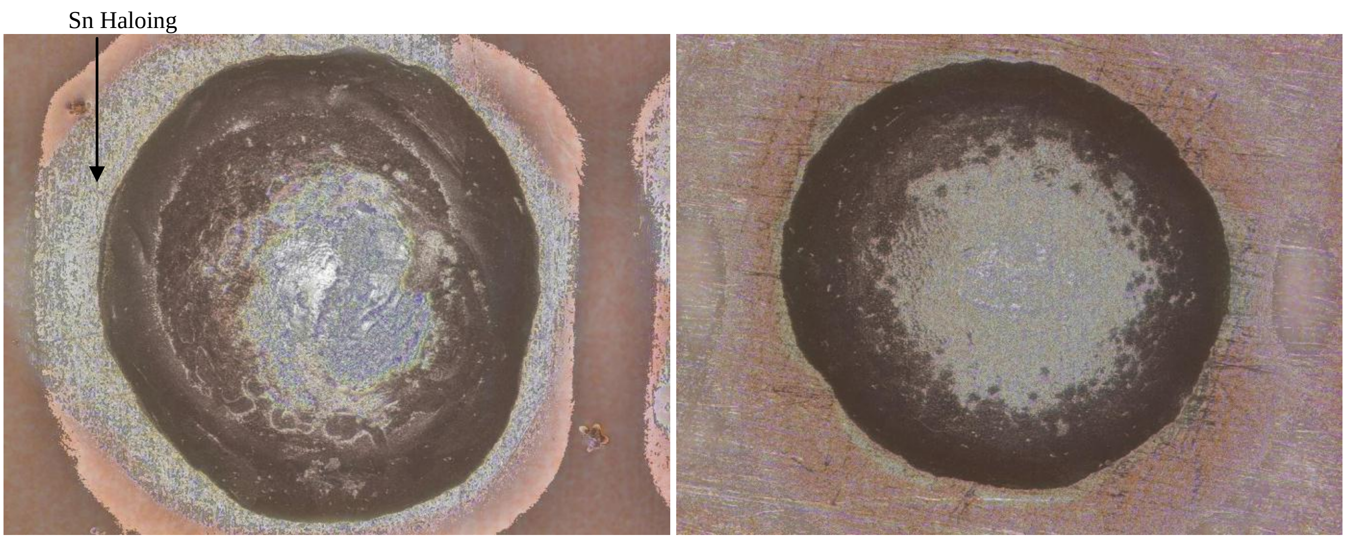
Optical Results of Solder Bumps Post Reflow

Figures 8 and 9 show the typical solder bump results on each Cu Block sample post reflow. Each figure includes an (a) and (b) picture, where the (a) picture was from the Vapor Phase Reflow, and the (b) picture was from the Convection Reflow. From an optical / qualitative perspective, the Vapor Phase deposits appear to have larger area coverage than the corresponding Convection Reflow samples. Also with the Vapor Phase Reflow Solder deposits a larger halo of silver/gray material formed around the bump, which is shown in Figure 9. This halo was confirmed by EDX as Sn and is shown in Figure 10. One hypothesis is that at some point during the vapor phase reflow process the solder liquid had spread further in area but during solidification the solder perimeter pulled back leaving Sn metallization on the Cu Surface. Another hypothesis is that Vapor Phase Reflow caused a greater slumping/spreading of the solder paste, then the coalescence of solder paste occurred followed by a pull back of the molten solder boundary to a state of stable equilibrium (Bielick, 2010). This Sn haloing was not observed as much on the Convection Reflow solder deposits. Also observed with the Vapor Phase samples was a greater amount of transparent residues and the Cu Blocks appeared to be more tarnished from Vapor Phase than Convection Reflow. One last visual observation about all the samples was that there was variability in the amount of solder, specifically that the solder bumps were smaller near the corner and edges than the solder bumps in the middle of the array.



a. Vapor Phase Reflow **b. Convection Reflow**

Figure 8: Example of Overall View of both Vapor Phase Reflow and Convection Reflow Samples.



a. Vapor Phase Reflow **b. Convection Reflow**

Figure 9: Average/Typical Solder Bump Result from Vapor Phase Reflow and Convection Reflow.

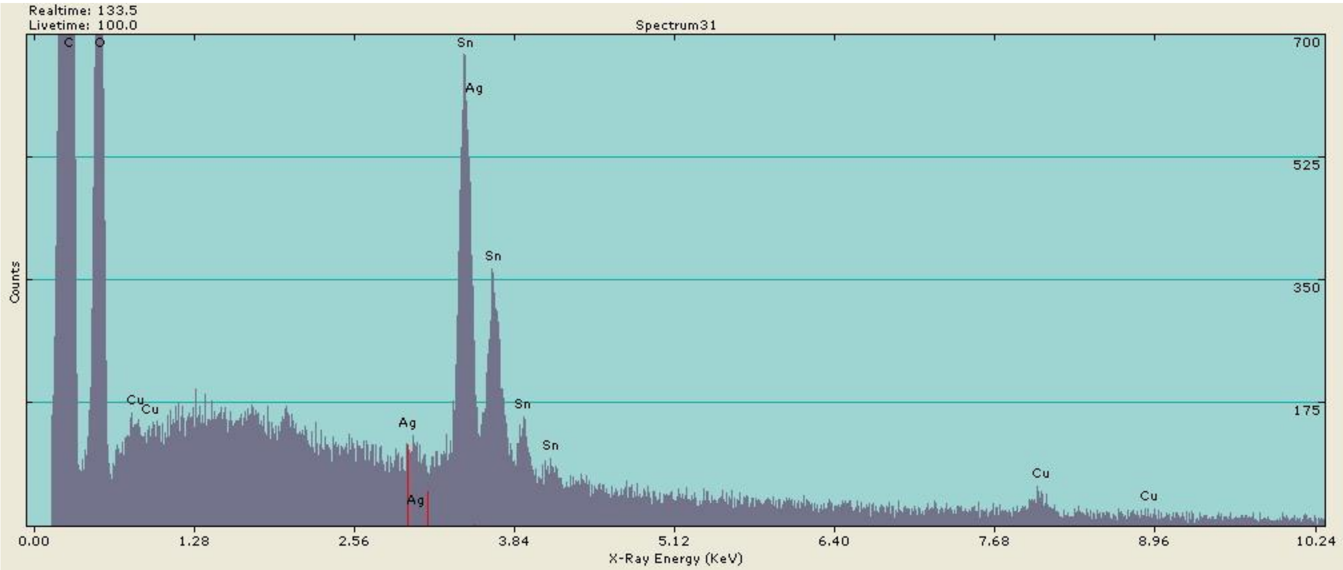


Figure 10: EDX Scan of Surface Metal Haloing Around the Solder Deposit.

Mechanical Measurements / Analysis of Solder Bumps Post Reflow

On each Cu Sample, seven solder deposits were examined, where the wetted area, solder height, wetting angles and diameters of the bump were measured on each deposit. These measurements were done using a high magnification Laser/Optical Keyence Scope. Figure 11 shows the specific seven deposits measured on each Cu Block and Figure 12 shows how the different mechanical measurements were taken.

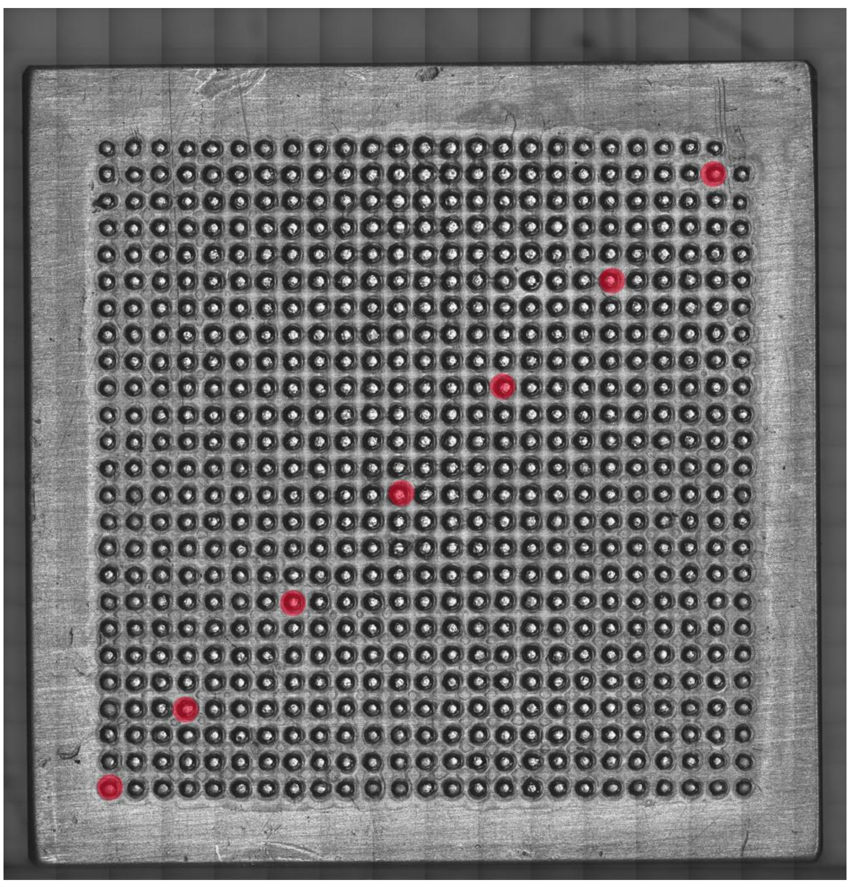
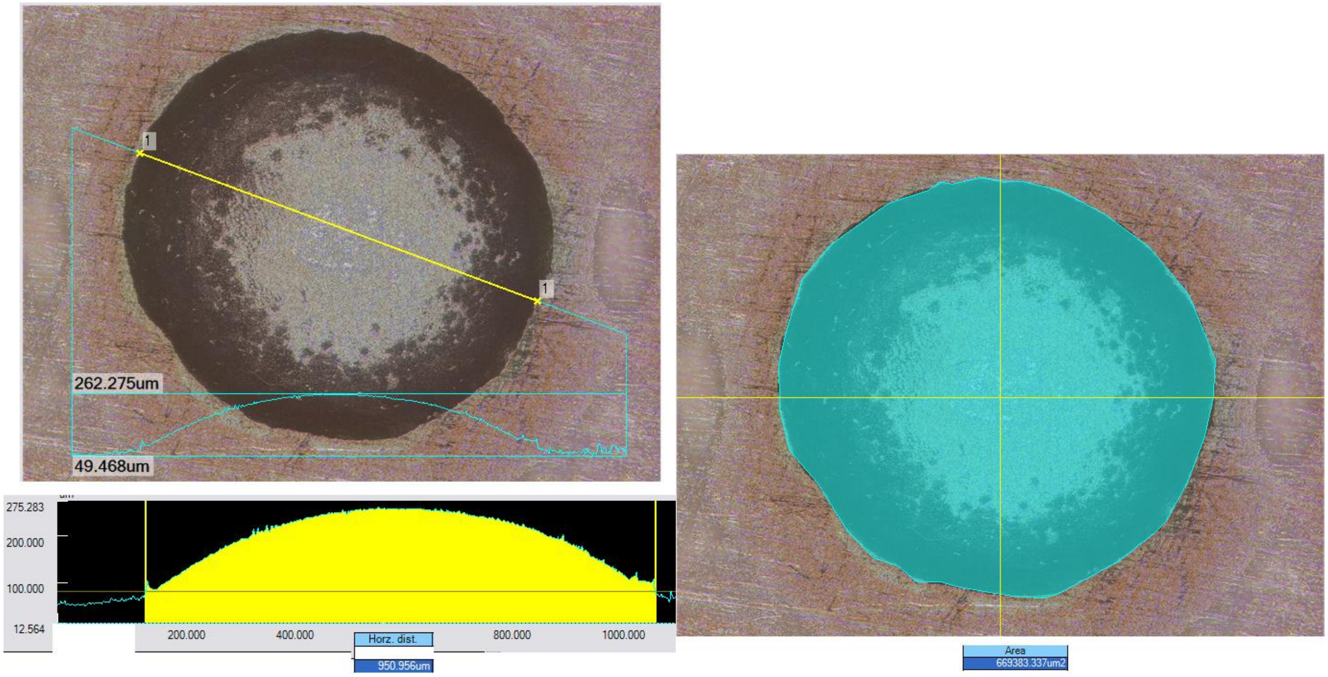
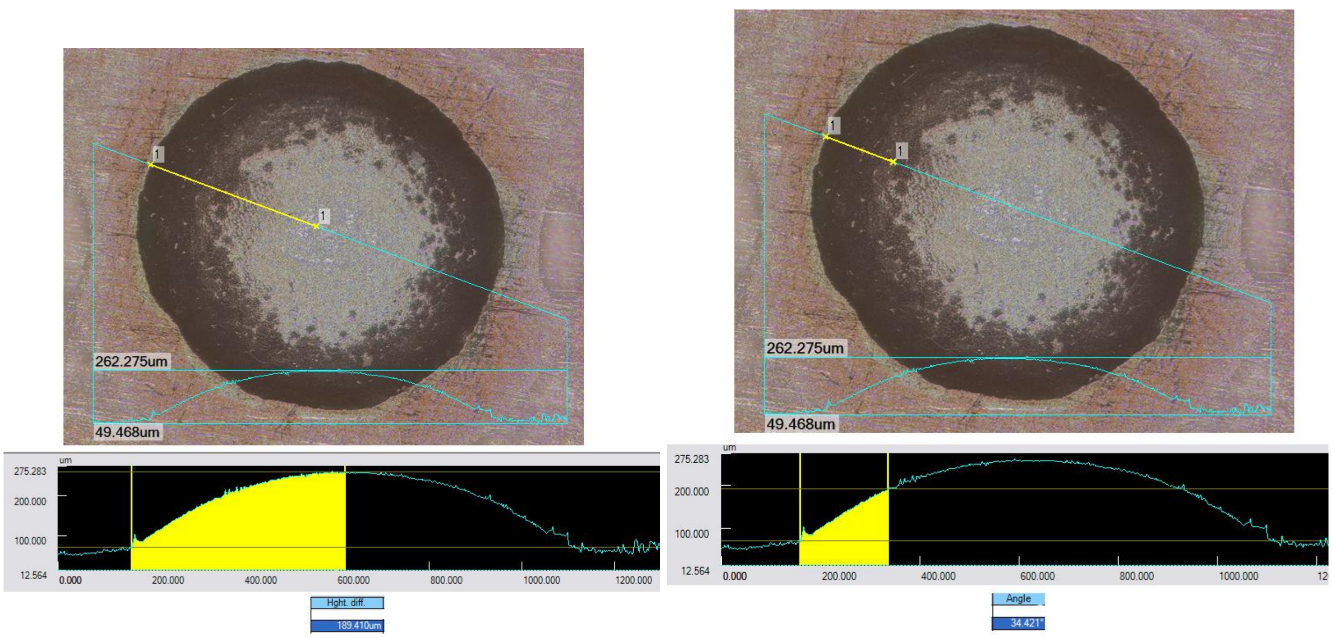


Figure 11: The 7 Solder Deposits Examined on Each Cu Block Sample. Red Dots show measurement locations.



a. Diameter = 950.956 um **b. Area = 669383.337 um^2**



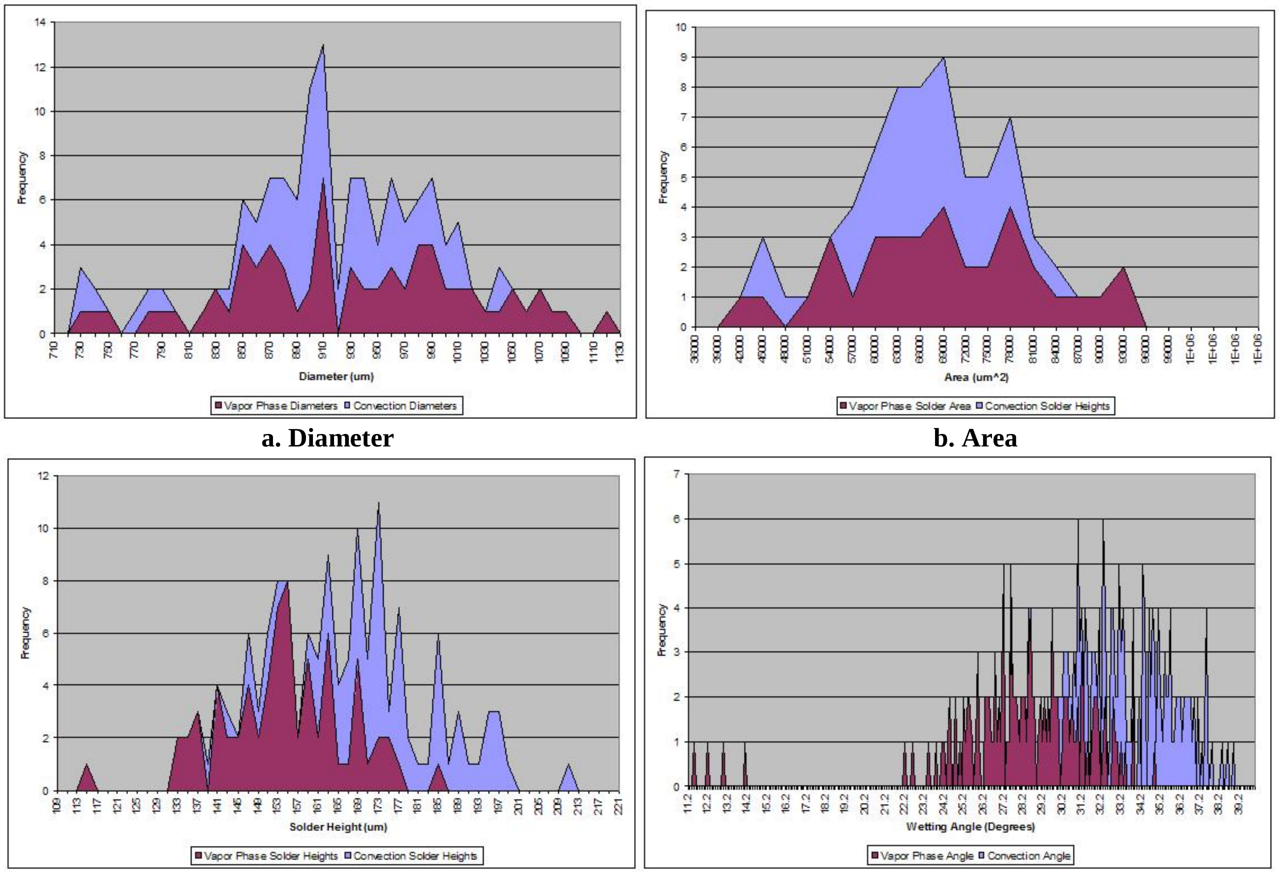
c. Solder Height = 189.410 um **d. Wetting Angle = 34.421°**

Figure 12: Shows the Different Type of Measurements Taken on Each Solder Bump

Table 2 presents the overall averages and standard deviations for all the measurements taken on Vapor Phase and Convection Samples. Also, Table 2 presents the averages and standard deviations for each individual Cu Sample Block. Figure 13 shows the histograms for all Vapor Phase Samples and Convection Samples for each of the measurements. From examining the data in Table 2 and the histograms in Figure 13, the measurements demonstrating the greatest differences between the two reflow techniques were the solder heights and the wetting angles. Convection Reflow Solder bumps had taller solder heights and greater wetting angles. The data does show that the Vapor Phase Solder bumps had slightly greater soldering areas and diameters, but the data also shows the Vapor Phase Solder bumps had a greater amount of variability in all the measurements. All the histograms appear to follow normal (Gaussian) distributions.

Table 2: Averages and Standard Deviations for Various Measurements Done on Cu Sample

Data Set	Average Diameter (um)	Standard Deviation for Diameter (um)	Average Wetting Angle (Deg)	Standard Deviation for Wetting Angle (Deg)	Average Solder Height (um)	Standard Deviation for Solder Height (um)	Average Solder Area (um^2)	Standard Deviation for Solder Area (um^2)
Overall Vapor Phase Samples	924.26	88.24	28.10	3.70	153.55	12.51	676590.54	128735.45
Overall Convection Samples	908.44	67.26	33.92	2.25	172.79	14.66	650101.54	93649.19
Cu- Block 1 - Vapor Phase	1016.11	74.62	24.84	5.53	153.67	18.41	811733.23	112593.84
Cu- Block 2 - Vapor Phase	931.64	69.82	29.47	2.71	158.76	11.08	668262.86	106494.57
Cu- Block 3 - Vapor Phase	887.63	64.31	28.30	2.36	149.31	11.68	623611.92	95471.69
Cu- Block 4 - Vapor Phase	902.44	85.08	29.77	2.59	157.67	7.91	652069.38	136183.56
Cu- Block 5 - Vapor Phase	883.47	81.33	28.12	2.07	148.32	8.57	627275.30	118455.16
Cu- Block 6 - Convection	894.12	28.42	33.57	2.88	166.93	5.37	634643.77	46972.41
Cu- Block 7 - Convection	906.50	38.95	35.45	1.61	177.28	13.34	641717.18	62764.48
Cu- Block 8 - Convection	921.59	46.62	34.59	1.39	183.61	11.77	670049.47	67278.96
Cu- Block 9 - Convection	918.89	91.91	33.70	2.33	170.89	16.37	663493.68	127194.38
Cu- Block 10 - Convection	901.10	102.36	32.31	1.47	165.23	16.64	640603.58	147334.53



a. Diameter **b. Area**

c. Solder Height **d. Wetting Angle**

Figure 13: Histograms of Various Measurements Taken from the Different Solder Bumps.

Thus, from the previous wetting angle data, during the Convection Reflow process, the solder bumps did not spread as much and had greater cohesion than the solder bumps that went through the Vapor Phase Reflow, or in other words, the Vapor Phase Reflow solder bumps had greater wetting on the Cu Block Surface. For further analysis, a One Factor ANOVA was conducted on the wetting angle measurements between the two reflow techniques. Table 3 shows ANOVA results and Figure 14 shows the Factor plot. The ANOVA showed that the type of reflow process has a major affect on the wetting angles of the solder bumps. The Factor plot shows, as did the data in Table 2 and the wetting angle histogram of Figure 13, that the Convection Reflow process will cause larger wetting angles then the Vapor Phase Reflow Process.

Table 3: ANOVA Table

	Sum of		**Mean**	**F**		
Source	**Squares**	**DF**	**Square**	**Value**	**Prob > F**	
Model	1134.84	1	1134.84	124.647	< 0.0001	significant
A	1134.84	1	1134.84	124.647	< 0.0001	
Pure Error	1256.40	138	9.10438			
Cor Total	2391.24	139				
The Model F-value of 124.65 implies the model is significant. There is only						
a 0.01% chance that a "Model F-Value" this large could occur due to noise.						

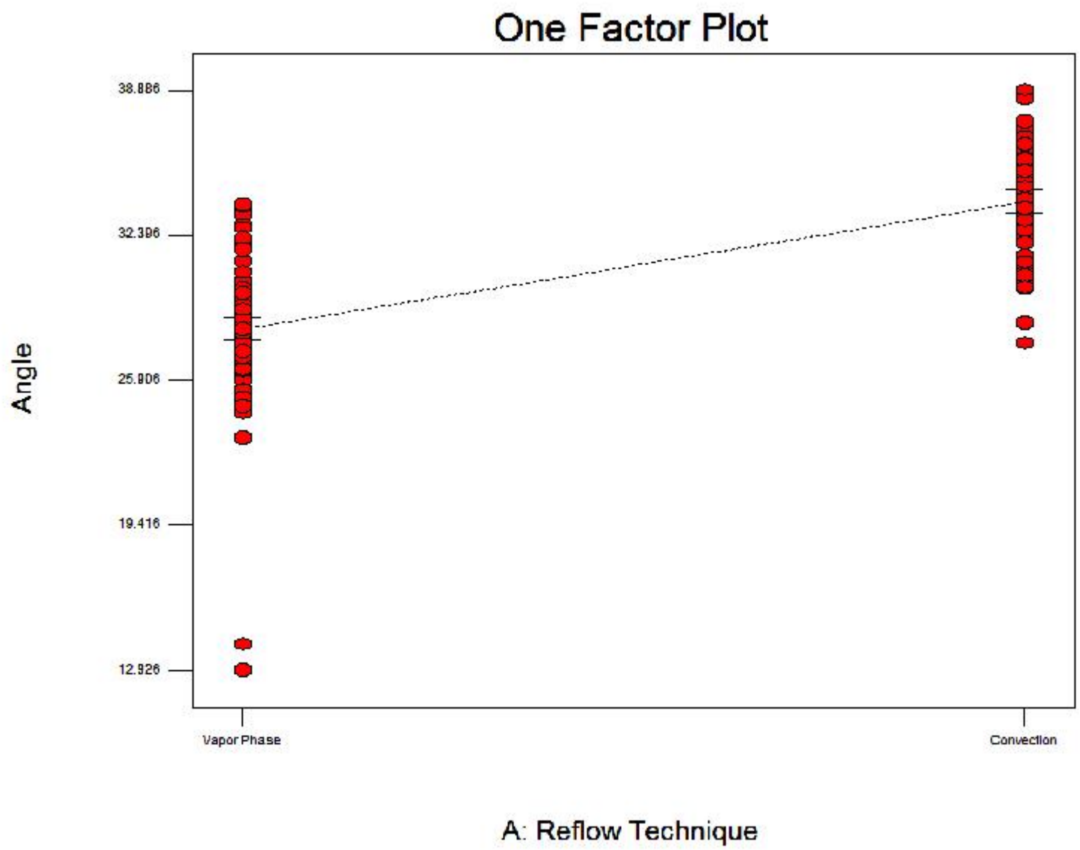
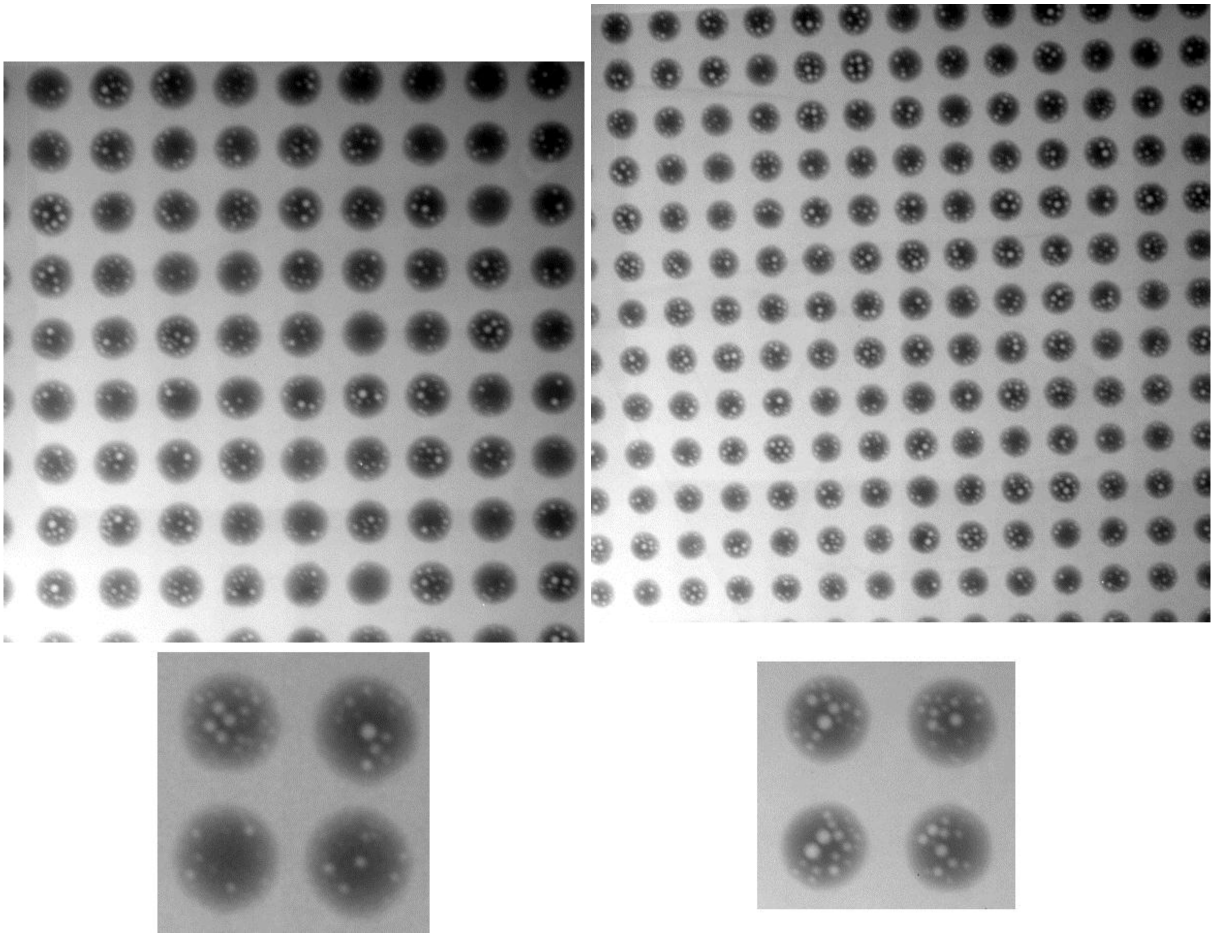


Figure 14: ANOVA One Factor Plot of Wetting Angles Between Vapor Phase and Convection Reflow.

Examination of Solder Voiding

All the Cu Block Samples were examined through X-ray inspection, and it appeared that all the samples had a similar amount of solder voiding. There appears to be little difference in the size or the frequency of voiding. Figure 15 shows the solder voiding comparison that was typical for both Vapor Phase and Convection samples. Thus, in this situation, the type of reflow did not have much of an effect on the voiding.



a. Vapor Phase **b. Convection Reflow**

Figure 15: Comparison of X-ray Inspection of Solder Bumps between Vapor Phase and Convection.

Study Conclusion

In this study, the goal was to control as many factors that affect solder paste solderability so that the effect of the reflow process itself could be observed. The factors that were controlled were:

1. Solderable Cu Block surface was the same and recently cleaned for each reflow process.
2. The reflow processes had Nitrogen (Inert) atmospheres.
3. The same Pb Free (SAC305) Solder Paste was used.
4. The solder paste deposition procedure was the same for each Cu Block. The amount of material was equivalent within the process capability of the screening process.
5. The actual thermal profile, maximum temperatures, heating rates, cooling rates, and time above liquidous were similar, but not exactly the same for each reflow process.

With these controlled factors, it was discovered that Vapor Phase Reflow caused the solder to have greater wetting of the Cu metal surface than Convection Reflow. This conclusion was reached through the examination of the wetting angles of the solder rather than the amount of wetting area observed. The solder bumps from the Vapor Phase samples had a wetting angle average of 28° versus the Convection sample with a wetting angle average of 34°. As the wetting angle approaches 0° or total wetting, the greater the solderability. The Sn haloing around the solder bumps on the Vapor Phase samples showed that melted solder during Vapor Phase Reflow covered a greater area and then was pulled back during solidification. Also the type of reflow did not affect the amount of voiding observed within the solder bumps. The Vapor Phase Reflow did appear to cause a greater amount of tarnishing on the Cu Block and left a greater amount of no clean residues.

The demonstration of good wetting in a Vapor Phase reflow process as shown in this study should address one of the concerns related to implementing Vapor Phase reflow for the Pb free soldering of high thermal mass PCBAs. From a wetting perspective, Vapor Phase reflow has been shown to be a viable candidate for Pb free soldering as compared to Convection reflow. The results of this study correlate well with past studies where Vapor Phase Reflow had been investigated as an option for Pb Free Soldering for printed circuit board assembly. This study's contribution was investigating further into specific wetting effects caused by the type of reflow.

Most of the past studies showed improvements in the actual application of Pb Free soldering between SMT components to PCB's (Samat, 2009; Sequeira, 2007). These past studies provided a broader comparison between Vapor Phase Reflow and Convection Reflow with respect Pb Free Soldering, while the current study analyzed the wetting phenomenon in depth.

Acknowledgements

- Special Thanks to Jim Bielick and Marie Cole from IBM, and Dr. Janice Lewis Ph.D. for Technical/Engineering Content Editing and Providing Technical Writing Input
- Special Thanks to Kevin Splittstoesser of IBM Conducting SEM/EDX Analysis.

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