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RE INTRODUCTION OF VAPOR PHASE SOLDERING TECHNOLOGY FOR LEAD FREE APPLICATION

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ABSTRACT
Vapor Phase soldering is a method of reflow technology developed by ATT Labs in NJ back in the 80s . Then, Vapor Phase soldering was the preferred reflow soldering technology because of its excellent heat transfer capability.. Heat transfer to the pcb is accomplished almost irrespective of the shape and thermal mass involved. The physically defined and unchangeable heat transfer of the condensing vapor ensures consistent repeatability and reproducibility. There were associated disadvantages like fast temperature rise, nearly no influence on the temperature profiles and high costs. As such the use of Vapor Phase Soldering was reduced to special applications with high mass or complex boards in low volume (e.g. for military or aerospace application). Over the last few years, a new Vapor Phase procedure and new machines were developed. Vapor Phase Soldering now offers new features for soldering, especially helpful when changing to Pb-free soldering. The main advantages of a state of the art Vapor Phase system are low process temperatures, freely adjustable temperature gradients and profiles, automatically controlled time above liquidus (TAL) and a perfect automatic inert gas atmosphere.

This paper will investigate the latest Vapor Phase soldering technology and compare its performance with convection reflow soldering technology. It will include a comprehensive process development with No-Clean Pb-free assembly carried out in Venture Corporation, Limited. The results were verified by employing different techniques, 5DX, SIR, Pull Test and Shear Test, micro-cross sectioning and SEM analysis. Effects of solder paste formulation, reflow profiles, time above liquidus and stencil aperture design on voids in vapor environment were determined. Minimum delta T repeatability and maximum vapor reflow cycles to delamination was characterized. Results from the evaluation on solder joint quality and joint strength, will be described in detail

INTRODUCTION
The work presented in this paper is a follow-up of an earlier Vapor Phase soldering process characterization studies done in Venture. The main objective of this project is to develop, optimize and qualify process parameters for Vapor Phase soldering with a readily available SAC305 Pb-free solder paste formulation. The optimized Vapor Phase soldering process parameters were used to qualify an identified complex mix technology RoHS pca.

A three stage qualification plan was designed to determine the material, assembly and soldering process to give the best solder joint condition

1. Solder paste selection
2. Process parameters optimization
3. Process qualification using optimized parameters.

VAPOR PHASE SOLDER PASTE SELECTION
Current solder paste flux systems used for Pb-free assembly was originally developed for convection reflow process. Initial investigation of Vapor Phase soldering process indicated that due to the blanket nature of the Galden vapor, additional flux will be present after the soldering process when the current selected solder paste was used. This additional flux may lead to increased presence of voids in BGA solder fillets. Four Pb-Free SAC305 solder pastes were identified for evaluation. They were named solder paste A, B, C and D. as per the Table 1.

Item	Paste B	Paste A	Paste C	Paste D
Appearance	Creamy Grey Paste	Grey Paste	Grey Paste	Grey Paste
Alloy	96.5Sn3.0Ag0.5Cu	96.5Sn3.0Ag0.5Cu	Sn96.5Ag3Cu0.5	Sn96.5Ag3Cu0.5
Flux Type	No-clean	No Clean	No Clean	No-Clean
Melting Point (degC)	217 - 220	217 - 220	217 ~ 220	217-221degC
Particle Size (µm)	25 - 45 / Type 3	25 - 45 um Type 3	25 - 45 um Type 3	25-45um Type 3
Powder Shape	Spherical	Sphetical	Spheres	Spherical
Flux Content (% by weight)	11.50%	12%	11%	12%
Halide Content (%)	Halide-free. Passes Ag Chromate Test	Halide-free by titrtion & IC	0%	None Detected
Viscosity (Pa.s)	1500 poise	1600 poise	1600 poise	1500 poise (typical)
Flux Type Classification	ROL0	ROL0	ROL0	ROL0
Flux Residue Tackness	Not available	Approximately 5% by weight	34 grams	non sticky

Table 1: Solder Pastes Properties

Pb-Free solder paste C and D are currently used in the convection reflow soldering production of RoHS pcas. Solder paste A and C were selected from two different vendors based on their specially developed formulation to achieve low voiding and high SIR test readings. The final selection of the solder pastes to be used in the optimization and qualification process was based on IPC-TM-650 criterion for printability and SIR test.

Printability Test
All four Pb-free solder pastes were tested as IPC-TM-650 for solder balls, solder spread, hot & cold slump and printability aperture test.

Solder Spread Test
Solder Paste B has better Spread %

Hot and Cold Slump Test

All four solder pastes showed good slump resistance both hot & cold slump tests to a minimum spacing of ≥ 0.125mm. Solder Paste A showed the best slump resistance with minimum spacing of ≥ 0.075mm without bridging.

Printability Aperture Test

All four of the pastes were able to achieve good printing results for aperture Aspect Ratios >1.30. All four solder pastes showed irregular printing release failures at Area Ratio ≤ 0.58.

SIR Test

Four selected solder pastes were printed on IPC B24 test coupons. Half the test coupons were reflowed in convection and the other half were reflowed in Vapor Phase. The reflowed test coupons were subjected to SIR test as per IPC IPC-TM-650 2.6.3.7. Six readings were taken at 0hr, 2hrs, 24hrs, 48hrs, 168hrs and Recovery interval with a 10V bias voltage applied. The results of the SIR test were tabulated in Table 2 and log graph plotted as per Figure 1. All process assemblies in the evaluation passed the SIR testing test of 10^8Ω. Solder paste D displayed the lowest value. As expected, the results showed a lower SIR value of test coupons run through Vapor Phase soldering.

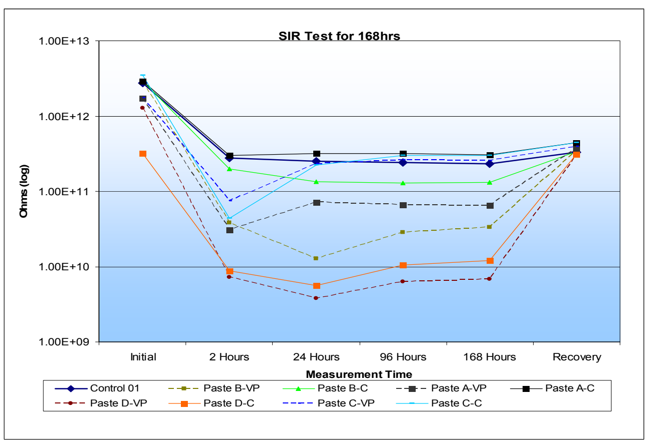


Figure 1: Log Plot of SIR Results

	0hr	2hr	24hr	48hr	96hr	168hr
Contro 0l	2.72E+12	2.75E+11	2.51E+11	2.40E+11	2.34E+11	3.31E+11
Paste B-VP	2.85E+12	3.82E+10	1.29E+10	2.87E+10	3.31E+10	3.41E+11
Paste B-C	2.88E+12	1.97E+11	1.35E+11	1.29E+11	1.32E+11	3.39E+11
Paste A-VP	1.72E+12	3.07E+10	7.12E+10	6.61E+10	6.53E+10	3.74E+11
Paste A-C	2.92E+12	2.99E+11	3.16E+11	3.16E+11	3.04E+11	4.42E+11
Paste D-VP	1.28E+12	7.29E+09	3.78E+09	6.27E+09	6.88E+09	2.97E+11
Paste D-C	3.16E+11	8.86E+09	5.66E+09	1.05E+10	1.21E+10	3.14E+11
Paste C-VP	1.76E+12	7.50E+10	2.30E+11	2.62E+11	2.56E+11	3.96E+11
Paste C-C	3.45E+12	4.37E+10	2.21E+11	3.02E+11	2.99E+11	4.42E+11

Table 2: SIR Test Results

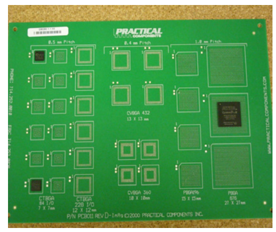
Solder Paste Selection Result and Recommendation

The printability study on all four Pb-free selected solder paste showed acceptable printing quality. Due to the stringent product requirements, solder paste D with the lowest SIR reading was eliminated from the selection. Solder paste A, B and C were recommended for further testing

VAPOR PHASE SOLDERING PROCESS OPTIMIZATION

Test Vehicles

A standard test vehicle from practical component was used.



PCB Material: FR4,Tg180ºC
Number of layers: 2
Size : 8.0”x5.5”x0.062”
Surface Finish: Imm Silver
Components :
PBGA 0.5mm pitch 84 I/C
PBGA 1.0mm Pitch 225 I/O

Figure 2: Test Coupons for Process Optimization

Design of Experiment

Solder paste A, B and C were selected based on the SIR test result. All other factors were selected based on initial study done by Venture.

Factor	Level 1	Level 2	Level 3
Solder Paste	C	B	A
Reflow Profile (deg/sec)	Linear 1.02	Step 0.48, 1.5	
TAL (sec)	30	60	
Stencil Aperture (5 mils thickness)	100%	85%	

Table 3: DOE Factors for Process Optimization

Process Optimization Process Flow

Twenty four test vehicles were ran based on the permutations of the DOE. The test vehicles were printed with solder paste A, B and C and sent through an AOI solder paste inspection to ensure good and consistent solder paste was achieved for all assemblies. Test vehicle assembled with three BGAs on one side of the board were sent through Vapor Phase reflow soldering. Galden HL240 was used in vapor soldering as it was believed that it provides thermodynamically good soldering condition. All soldered assemblies were 5DX inspected for voids.

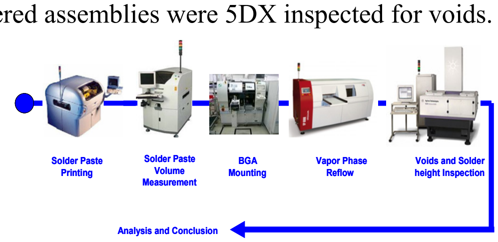


Figure 3: Process Optimization Flow

Optimization Results

The main effects for voids suggest:

1. Solder pastes have the largest effect. Solder Paste A and C produced smaller voids.
2. Time-above-liquidus (TAL) and reflow profile have large effects. 1.02ºC/sec (Ramp) and 30 sec (TAL), produced smaller voids.
3. Stencil has less effect.

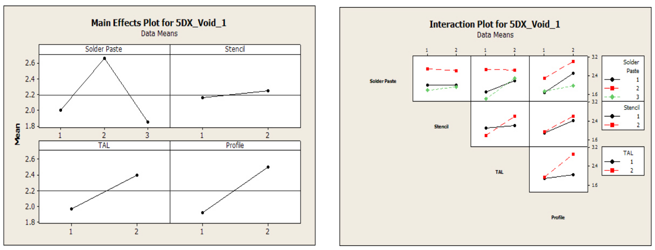


Figure 4: Plot of DOE Main Effect and Iteration Analysis

The interactions for voids suggest:

1. Stencil aperture has very little effect on solder paste used.
2. Solder paste B and C were affected more by reflow profile than TAL, while Solder paste A was affected more by TAL than reflow profile.
3. TAL has more effect on larger stencil openings, where reflow profile has same effect on stencil openings.
4. Profile has more effect on longer TAL.

ERSA SCOPE Inspection and 5DX image.

All assemblies showed good BGA fillet wetting when inspected under ERSA scope

Optimization Process Parameters Recommendation for minimum voids.

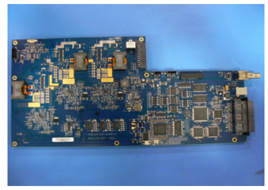
Solder Paste : A and C
Reflow Profile : Linear 1.02 ºC/sec
TAL : 30 sec (TAL)

VAPOR PHASE SOLDERING PROCESS QUALIFICATION

Process qualification was run using optimized parameters. Both solder paste A and C were used to verify the earlier findings from the process optimization. Solder joint quality i.e. voids, intermetallic layer thickness were determined using Agilent Series III 5DX and HITACHI SEM (Scanning Electron Microscope) respectively. Solder joint strength was verified through pull and shear tests as per EIAJ ED 4702 Test method 002 and method 3 strength tests for solder joints respectively.

Test Vehicles

An actual production pca was selected as a test vehicle to simulate an actual production process. Test vehicles were populated with actual components 0402, 0603, QFN, BGA, LPGA, Transformer.



PCB Material: ISOLA 370HR, Tg:180º C
Number of layers: 8
Size : 13.8"x 6.7"x 0.09"
Surface Finish: Imm Gold

Figure 5: Test Vehicle for Process Qualification

Qualification Process Flow

Eighteen test vehicles ran included Pb-free solder paste A and C using two factor-two level DOE permutations. All parameters were derived for earlier process optimization result. A linear 1.48ºC/sec profile was substituted for the step profile.

Factor	Level 1	Level 2	Control
Solder Paste	A	C	
Reflow Profile (ºC/sec)	Linear 1.02	Linear 1.48	Convection
TAL (sec)	30	60	

Table 4: DOE Factors for Process Qualification

The test vehicles were printed with Pb-free solder pastes A and C. They were inspected through an AOI solder paste inspection to ensure good and consistent solder paste was achieved for all assemblies. All test vehicles assembled with passives and active components on both sides of the board were reflowed in Vapor Phase. Two control test vehicles were reflowed in convection oven. All soldered assemblies were 5DX inspected. Samples of each run were sent for Pull Test, Shear Test and SEM Analysis.

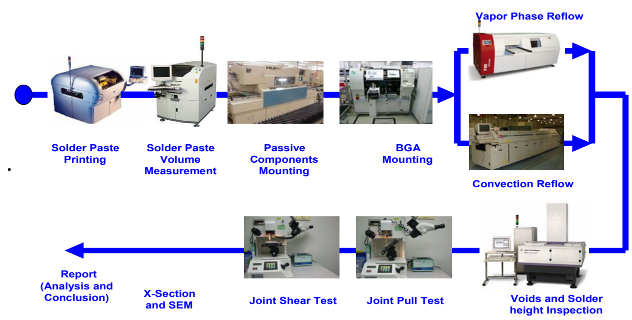


Figure 6: Process Qualification Flow

Qualification Results

Visual Inspection

Visual inspection for solder balls, tombstones, bridging, de-wetting indicated no apparent difference between the two solder joints produced by the two solder pastes. No tombstones were experienced on the production test boards. Visual inspection indicated that while convection reflow process produced good solder wetting, Vapor Phase soldering process produces excellent solder wetting and a much shiner solder joint.

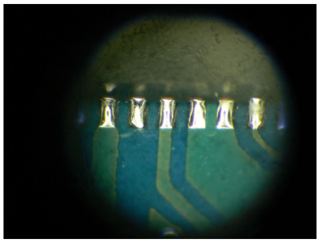


Figure 7:
Excellent Wetting of QFN in Vapor Phase Reflow

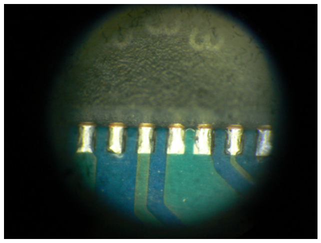


Figure 8:
Good Wetting on QFN in Convection Reflow

Large thermal load transformer soldered on the pca in Vapor Phase environment produced good wetting and shinny solder joints. The same component was not able to be soldered under convection reflow process.

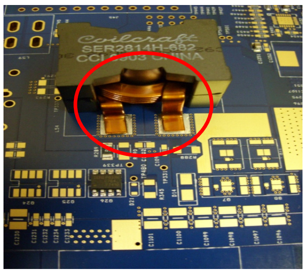


Figure 9:
Good Solder Fillet Form In Vapor Phase Soldering

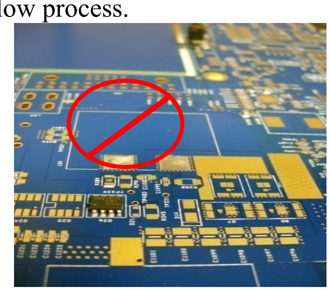


Figure 10:
Transformer unable to be Soldered in Convection

Inspection under ERSA scope showed good wetting of BGA balls for all process conditions.

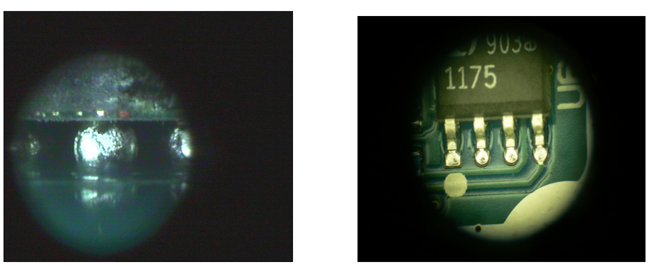


Figure 11: Good BGA ball and PLCC leads wetting in Vapor Phase soldering.

5DX Inspection

5DX inspection for voids showed all voids were well below IPC 610-D requirement of 25%. The increase in the percentage of voids content produced by Vapor Phase soldering as compared to convection reflow was an expected result as initial investigation of Vapor Phase soldering process indicated that due to the blanket nature of the Galden vapor, additional flux was present after the soldering process since. This additional flux was a concern for voiding in BGA solder fillets. The data from qualification run concurred and confirmed the findings obtained in the earlier optimization process. Solder paste A and profile one produced the least amount of voids

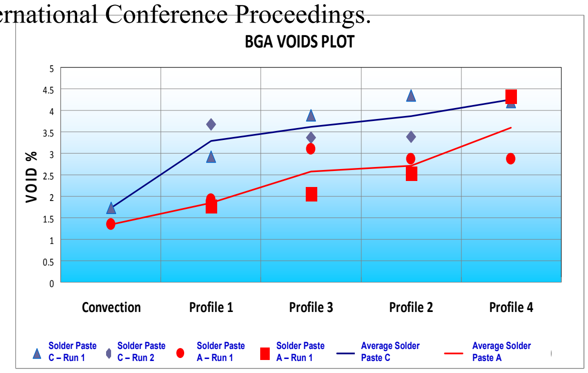


Figure 12: Voids vs. Solder Paste/Profile

Pull and Shear Test

The pull and shear test results indicated the average strength is comparable for all assemblies. Furthermore the average strength is greater that 1.0 lbf. These values are typical for high quality solder joint. The pad-pull-out failure mode observed for the majority of samples indicate that the solder joints were mechanically sound. Solder paste A and C produced good solder strength in both soldering processes. Pb-free solder joints created using Vapor Phase soldering have equivalent performance to those created using convection soldering.

	Pull Test (lbf)	Shear Test (lbf)
Paste C Convection 01B	2716	1472.75
Paste C VP01B	2674	1273.5
Paste C VP02B	3106	1356.25
Paste C VP03B	2022.5	1259.5
Paste C VP04B	2402.5	1355.75
Paste A Convection A	3167	1403.75
Paste A VP01B	3121	1199.5
Paste A VP02B	2995.5	1256
Paste A VP03B	3464.5	1285
Paste A VP04B	2420	1324.75

Table 5 : Pull and Shear Test Results

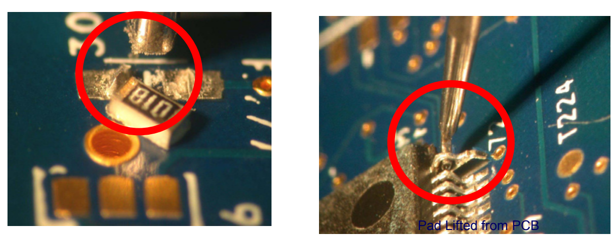


Figure 13: Pull Test and Shear Test Failure Mode is Lifted Pad

Intermetallic Thickness Measurements

Intermetallic thickness was measured diagonally across the BGA. Readings were taken on eight BGA balls along the diagonal. Low intermetallic thickness was observed in all BGA balls. This is probably due to the direct connection of the BGA balls onto the nickel layer of the immersion gold coated surface. The thickness measured was well within the acceptable range of one micron to eight micron.

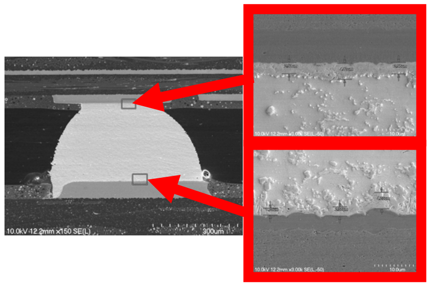


Figure 14: SEM of BGA Showing Good IMC layer

The reliability of these lead-free systems can be pursued with more extensive tests, such as accelerated thermal cycling

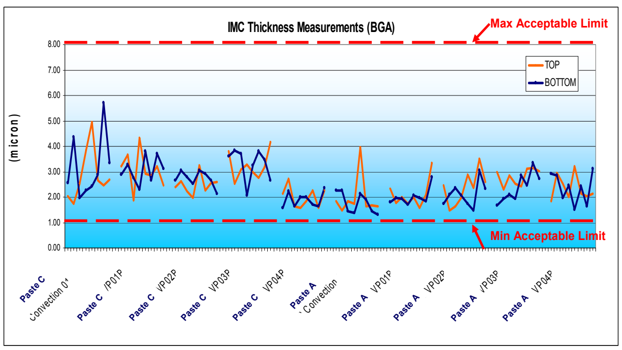


Figure 15: Intermetallic Plot Diagonally Across BGA

PROCESS CHARACTERIZATION

Repeatable Minimum Delta T

A variability study, using Gauge R&R range, of VP6000 Vapor Phase machine to produce repeatable delta T was conducted with one 1590IO CBGA, 13.98g and one 0.005g 0603 passive, 0.005g mounted on a test vehicle, FR4, 12"x11"x 0.2",556g. Ten profiles of the optimized settings were plotted at 30mins interval. The result showed a delta T<5ºC/sec at peak temperatures between two adjacent component was achieved consistently.

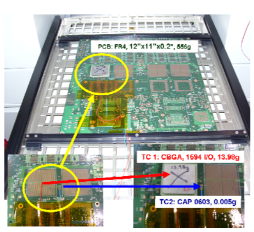


Figure 15: Test Vehicle Set-Up for DeltaT Measurement

Maximum Reflow Excursion to Delamination

The same test vehicle use in repeatability study was used to determine the maximum Vapor Phase reflow cycles to cause delamination on the pcb. Ten profiles of the optimized settings were plotted at 30mins interval. The pcb was inspected to IPC 610D for delamination after each Vapor Phase reflow cycles. . The result showed no delamination of the pcb after 10 reflow cycles.

CONCLUSIONS

Vapor Phase soldering qualification was run using optimized parameters. The data from solder joint quality of voids, intermetallic thickness and older joint strength verified through pull and shear test indicates Pb-free solder paste A produced the best solder joint quality and strength in Vapor Phase soldering environment. Time-above-liquidus (TAL) and reflow profile have large effects. 1.02ºC/sec(Ramp), 30 sec (TAL), produced smaller voids. Vapor Phase soldering process produces excellent wetting and shinier solder joints as compared to convection reflow process. Vapor Phase soldering allows high thermal mass components to be reflowed with small delta T between adjacent smaller components. The pcb can withstand more than 10 Vapor Phase reflow cycles without delamination.

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REFERENCES

[1] *"Impact of Metallic Growth on the Mechanical Strength of Lead Free BGA Assemblies"*, Patrick Roubaud, Ph.D., Grace Ng, Greg, Ronald Bulwith, Robert Herber. Swaminath Prasad, Flynn Carson, Sundar Kamath, Alexander Garcia IPC SMEMA Council APEX, 2001.

[2] "*Formation, distribution and failure effects of voids in Vapor Phase soldered small solder*", Villain, J: Beschorner, M; Hacke, H.J ; Brabetz, B; Zapf, J. Proceedings of Advanced Packaging Material: Processes, Properties and Interfaces, 2000.

[3] "Vapor Phase Vs Convection Reflow In RoHS Compliant Assembly", Chris Munroe, EPIC Technologies, Norwalk, OH USA.

[4] *"Vapor Phase Soldering Technology: Secure Lead Free Process"*, ASSCON Systemtechnik-Elektrononik GmBH.

[5] *"Lead Free: Using Vapor Phase Reflow in Lead Free Processing"*, Steve Fraser, Chris Munroe. SMT Article.