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EVALUATION OF SOLDER PASTES FOR HIGH RELIABILITY APPLICATIONS

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ABSTRACT

Solder paste is the most important material in Surface Mount Technology (SMT) assembly, and contract manufacturers of high reliability electronics face the simultaneous challenges of multisite operations combined with mission critical customer applications. It is essential to select a solder paste that performs at a high level under optimum conditions and also gives stable performance under suboptimal conditions, such as common environmental and manufacturing time fluctuations. This study examined 63Sn/37Pb solder paste alloy with both 63Sn/37Pb and 96.5/3.0Ag/0.5Sn (SAC305) lead free components in mixed alloy reflow. Both water soluble and no-clean chemistries were evaluated. A design of experiments (DOE) approach was employed to examine solder balling and slump resistance. Additional experiments examined print quality utilizing automated Solder Paste Inspection (SPI) in terms of bridge resistance, CSP and 0201 insufficient resistance, and response to a 45 minute print pause. Assemblies were also built to check for defects, joint quality, and voiding. The result is a holistic approach to solder paste testing that includes weighting of numerous factors to assess solder paste performance and robustness to external variation such as humidity and exposure time.

Key Words: Solder paste, mixed alloy, multifactor evaluation

INTRODUCTION

Stencil printing has long been established as the most important process in all of surface mount technology (SMT) with up to 52-71% of defects attributed to this one process step. [1, 2] Similarly, solder paste is most important material selection in all of SMT assembly. [3] Solder paste powder size distribution and flux chemistry determine the following: 1) Acceptable range of reflow profiles; 2) Ability to print fine pitch apertures, 3) Ability to resist time and humidity dependent slump, 4) Ability to resist solder ball formation, 5) Small aperture release both at time zero and after a pause in printing, 6) Solder joint wetting and appearance, and 7) Void formation. In order for a solder paste to be a manufacturing relevant product, the performance must be adequate in each category with a high average performance, such that it is best overall. For example a solder paste that excels in most areas but is very sensitive to humidity induced solder balls, would not be practical. It is possible for the best overall solder paste not have the best performance in any test criteria. The result is that evaluation of solder paste is a complex multifactor problem.

High reliability electronics are experiencing a size and weight reduction in products ranging from soldier carried military accessories to biomedical implantable devices. This size and weight reduction has caused a surge in fine pitch Chip Scale Packages (CSP) such as 16 mil (0.4 mm) pitch as well as 0201 and 01005 discretes. In order to accommodate these small size challenges, the solder paste evaluation considered smaller Type 4 particle sizes in addition to traditional Type 3 particle sizes. The high reliability scenario provides a Reduction of Hazardous Substances (ROHS) legislation exemption and allows for 63Sn/37Pb solder paste to be used for enhanced reliability reasons. The combination of 63Sn/37Pb and Type 4 particle size is uncommon for the paste manufacturers as most Type 4 paste is used on fine pitch consumer products, which are lead free for ROHS compliance. Historically high reliability electronics have been larger pitches such that Type 3 solder paste particle size was viable. This issue gives rise to potential supply chain delays as the Type 4 particle size and 63Sn/37Pb solder paste is often blended upon ordering. Mitigation strategies were implemented to prevent a material shortage.

RESEARCH METHODOLOGY

The study consisted of a series of experiments that were conducted on six water soluble and seven no-clean solder pastes as shown in Table 1. Table 2 shows the experiment overview. The work reported herein will use the water soluble samples for explanation and any no-clean variations will be pointed out where they occur.

Table 1: Solder Pastes Tested

Paste Code	Water Soluble (WS) or No-Clean (NC)	Particle Size (Type)
A	WS	3
B	WS	3
C (Same product as B except for particle size)	WS	4
D	WS	3
E (Same product as C, except for particle size)	WS	4
F	WS	3
G	NC	3
H	NC	3
I (Same product as H, except for particle size)	NC	4
J	NC	3
K (Same product as J, except for particle size)	NC	4
L	NC	3
M	NC	3

Table 2: Experiment Overview

Characteristic	Method	Parameters	Measurement
Solder Ball	Modified IPC	DOE – 30%, 50%, 70%RH, 0, 2, 4 hr.	Number of solder balls
Slump	Modified IPC	DOE – 30%, 50%, 70%RH, 0, 2 hr.	Finest pitch unbridged
Printability	Koh Young		Bridges, Insufficients
Response to Print Pause	Koh Young Solder Paste Inspection (SPI)	45 min print pause	Number of insufficients on the 1^{st} print after print pause
Voiding	X-Ray		
Solder Joint Characteristics	IPC		
Wetting/Spread	Visual		
Visual Cleanability	Visual		
Ionic Cleanability	Solvent Extract Conductivity	NC cleaned after 1X and 3X reflow	
Flux Residue	Visual		

Time Zero Print and Slump Evaluation

Solder pastes were machine printed on blank Fire Retardant 4 (FR-4) laminate through a 4 mil laser cut stainless steel test stencil that had apertures repeated with progressively smaller gaps. Figure 1 shows a sample of the solder paste print specimens on FR-4 light green epoxy substrates. Print performance was assessed by noting the smallest gap that did not bridge on both the North and East deposits strips of the smaller standard IPC slump test pattern. Figure 2 and Figure 3 show the main and interaction effects on water soluble (WS) solder paste slump samples, respectively. The ANalysis of VAriance (ANOVA) results are in Table 2 and show the statistical analysis of each factor tested. At α=0.05, all main and interaction effects are statistically significant, indicating the data was reproducible among three replicates.

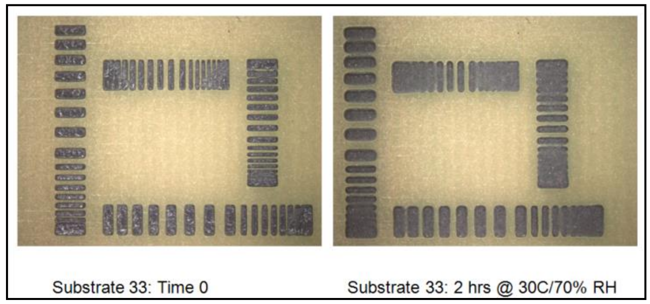

Figure 1: Solder Paste Slump Test Samples

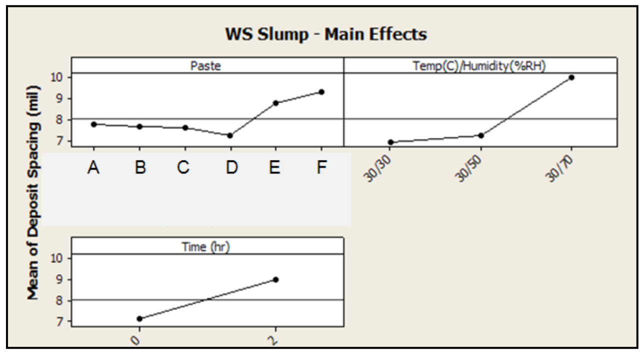

Figure 2: Slump/Unbridged Deposit Spacing - Main Effects

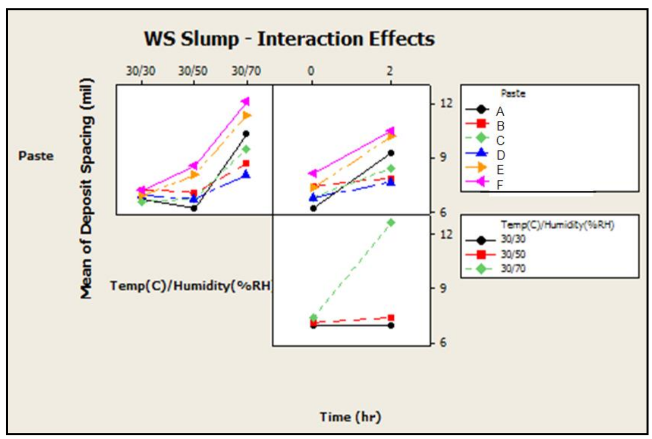

Figure 3: Slump/Unbridged Deposit Spacing Interaction Effects

Table 3: WS Slump ANOVA

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Paste	5	57.2	57.2	11.4	18.0	**0.000**
Temp(C)/Humidity (%RH)	2	206.7	206.7	103.4	162.3	**0.000**
Time (hr)	1	94.3	94.3	94.3	148.0	**0.000**
Paste*Temp(C)/Humidity (%RH)	10	41.6	41.6	4.2	6.5	**0.000**
Paste*Time (hr)	5	25.7	25.7	5.1	8.1	**0.000**
Temp(C)/Humidity (%RH)*Time (hr)	2	162.7	162.7	81.4	127.7	**0.000**
Paste*Temp(C)/ Humidity(%RH)* Time (hr)	10	57.2	57.2	5.7	9.0	**0.000**
Error	72	45.9	45.9	0.6		
Total	107	691.3				

Solder Ball Evaluation

A modified IPC solder ball test was conducted by printing solder pastes through an 8 mil (0.20 mm) stencil onto alumina substrates. The pastes were exposed to times for 0 and 2 hrs, and humidity levels of 30, 50 and 70% relative humidity, with 4 replicates of each combination. Figure 4shows sample of various degrees of solder paste coalescence on alumina substrate samples. Figure 5 and Figure 6 show the main and interaction effects on solder ball formation. Figure 7 shows the ANOVA for all factors tested. At α=0.05, all main and interaction effects are statistically significant, indicating the data was reproducible among four replicates. Paste F was dropped from the evaluation after slump and solder ball analysis and paste E had to be reworked for slump robustness. The rework was initiated because the type 3 counterpart, paste D, had performed well.

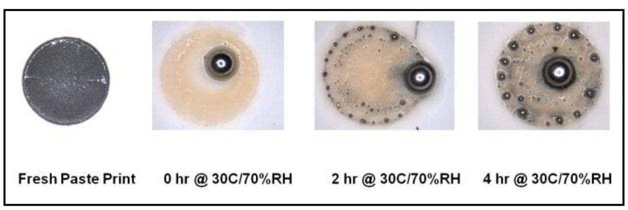

Figure 4: Reflowed Solder Ball Samples on Alumina Substrates

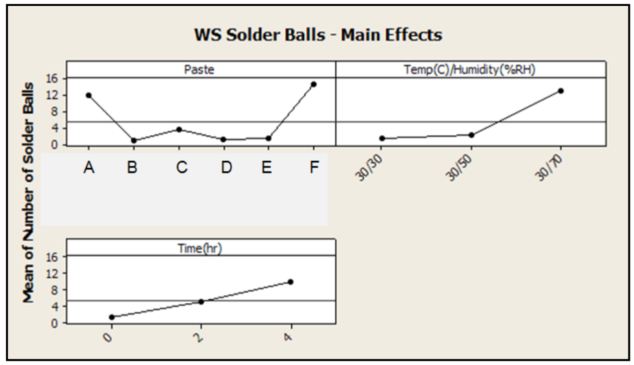

Figure 5: Water Soluble Solder Balls - Main Effects

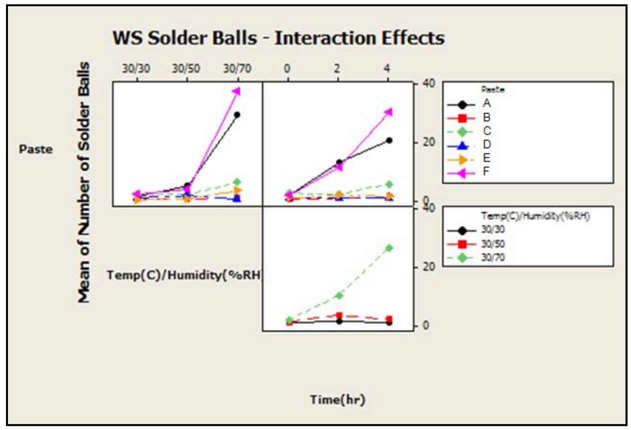

Figure 6: Water Soluble Solder Balls – Interaction Effects

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Paste	5	6692.6	6692.6	1338.5	38.3	**0.000**
Temp(C)/Humidity(%RH)	2	6113.0	6113.0	3056.5	87.4	**0.000**
Time(hr)	2	2680.9	2680.9	1340.4	38.3	**0.000**
Paste* Temp(C)/Humidity(%RH)	10	9251.1	9251.1	925.1	26.5	**0.000**
Paste*Time(hr)	10	4537.8	4537.8	453.8	13.0	**0.000**
Temp(C)/Humidity(%RH)*Time(hr)	4	4994.3	4994.3	1248.6	35.7	**0.000**
Paste* Temp(C)/Humidity(%RH)*Time(hr)	20	9611.6	9611.6	480.6	13.7	**0.000**
Error	162	5666.8	5666.8	35.0		
Total	215	49548.0				

Figure 7: WS Solder Ball ANOVA

Printability and Response to Print Pause

Printing was done on an automated stencil printer on FR-4 substrates without pads to avoid any unintended stencil to pad gasketing differences cause by board variations. The following components were assessed using solder paste inspection (SPI) equipment:

1) Quad Flat Packs (QFP) with 10 mil (0.25 mm) pad widths and 6 mil (0.15 mm) spaces);

2) Chip Scale Packages (CSP) with 11 mil (0.28 mm) diameter with 9 mil (0.23mm) spaces; and
3) 0201s with 11 mil (0.28mm) X 15 mil (0.38mm) apertures.

The QFP pad was deliberately extra difficult to print to enable use as a strong indicator because no defects occurred on a typical QFP with 8 mil (0.20 mm) width pads and spaces.

Five printed wiring boards (PWB) were printed back to back (less than one minute delay) followed by a 45 minute print pause and then boards 6 through 10 were printed back to back. The purpose of the 45 minute pause was to simulate a line delay similar to a lunch and production meeting. While stencils are washed after breaks, measurement of response to print pause was used to assess production robustness. Figure 8 shows the print defects on PWBS 1-5. Again note the QFP bridges are extra high due to the aggressive 10 mil (0.25 mm) pads on 6 mil (0.15 mm) spaces. On typical 8 mil (0.20 mm) pads and spaces no bridges occurred so the 10 mil (0.25 mm) pad and 6 mil (0.15 mm) space was used as a strong indicator of print performance. Comparing Figure 8 and Figure 9 shows the change in print performance after a 45 minute print pause and pastes B and C show marked increase in CSP aperture clogging.

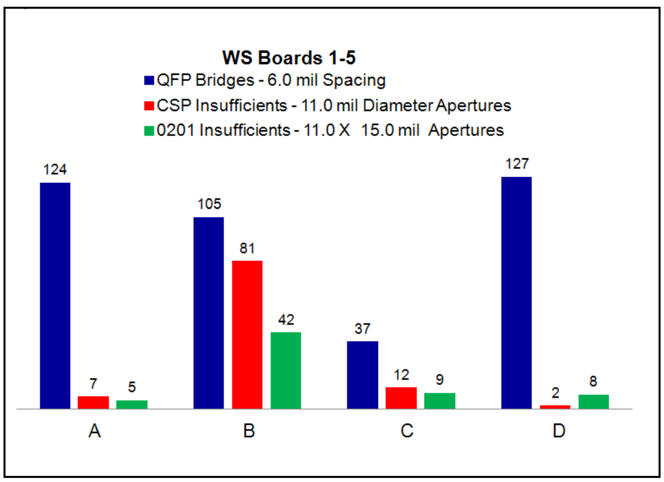

Figure 8: Prints 1-5 for Each Paste – No Pause

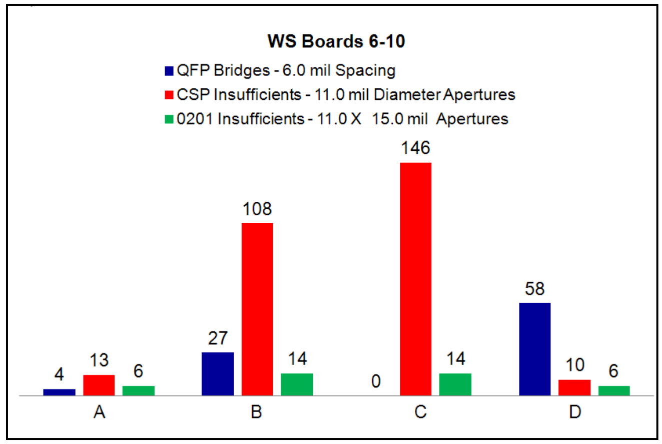

Figure 9: Prints 6-10 for Each Paste – 45 Minute Pause Between Prints 5 and 6

Joint Visual Characteristics

Test boards were built with components and joints as described in Table 3. Visual inspection was done on the test boards to IPC-610A, class 3 standards. Figure 9 shows QFP 208 joints with good wetting and joint shape on each sample. Figure 9 shows 0201 solder joints and reveals a mottled appearance on pastes A, B, and C which is also shown in the close up image of A. The spots are a surface phenomenon on the solder joint and are not uncoalesced solder paste spheres, but could be the oxide residue from individual solder spheres. This could possibly indicate the flux activity of the 63Sn/37Pb solder paste was being consumed on small deposits (0201) at elevated mixed alloy reflow temperatures. Each PWB built also had a D-PAK window pane stencil design and the spread of the solder on the ground plane was used to assess wetting of each paste as shown in Figure 10. Pastes B and C were formulated by the same vendor and had improved solder spreading over the other pastes. All pastes had adequate wetting as shown on the solder joint images in Figure 8 and Figure 9.

Table 4: Test Board Components Placed

Component Type	Qty Placed	Number of Solder Joints
CABGA208 (SAC305 Balls)	1	208
QFP208	1	208
0201	30	60
0402	34	68
0603	31	62
0805	21	42
1210	14	28
SOT-23	24	72
MLF100	1	100
PLCC68	1	68
QFP100	1	100
	Total	**1016**

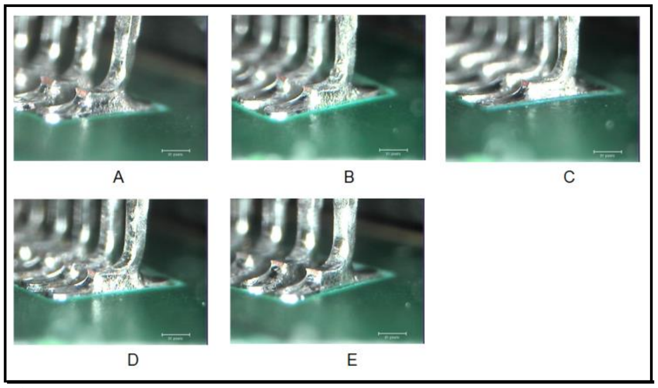

Figure 10: 208 QFP Joints

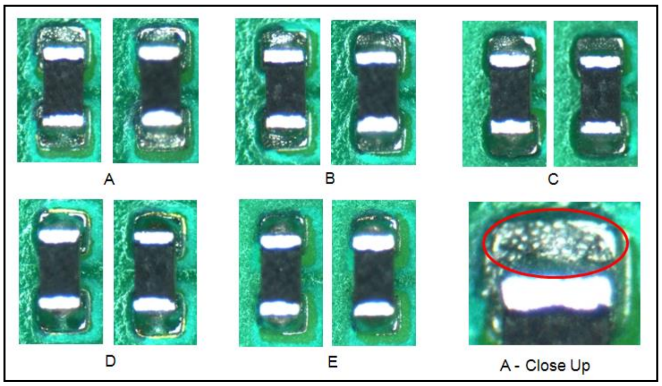

Figure 11: 0201 Joints – A, B, C Mottled Solder Appearance

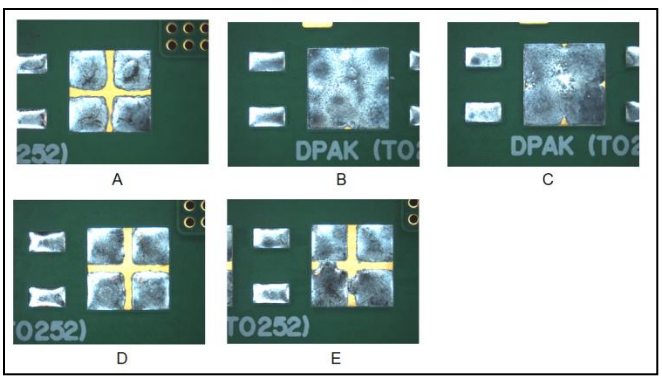

Figure 12: D-PAK Window Pane Wetting Observation

Joint Cross Sectioning

High reliability manufacturing often involves 63Sn/37Pb solder paste and supply chain limitations result in components with only SAC305 solder balls being available, such that mixed alloy reflow is necessitated. Cross sectioning was done on ball grid array (BGA) components to ensure proper alloy mixing and homogeneous microstructure as shown in Figure 12. Correct QFP solder joint fillets were formed as shown in Figure 13.

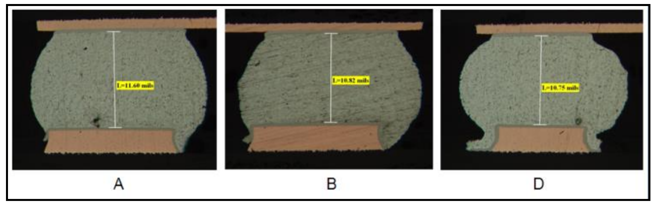

Figure 13: Mixed Alloy BGA Cross-Sections (63Sn/37Pb Paste and 96.5Sn/3.0Ag'0.5Cu Component Balls) – Homogenous Microstructure

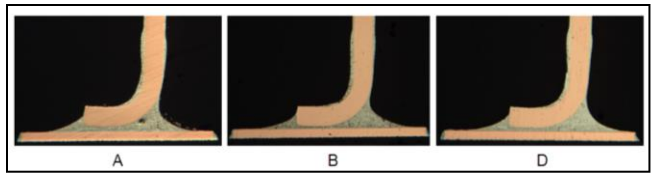

Figure 14: QFP Fillet Cross Sections

Voiding

The mixed alloy BGA joints were X-RAY inspected for void content as shown in Figure 15. While paste A had the most voids, all pastes past IPC criteria. The ball size and shape were consistent and there was evidence of wetting to the pads. The QFN void inspection showed large variation in void content with more voids on pastes D and E, which are the same chemistry in types 3 and 4, respectively. There is no IPC criterion on QFN voids and the worst sample was adequate in both form and function in that it was adequately electrically and thermally grounded.

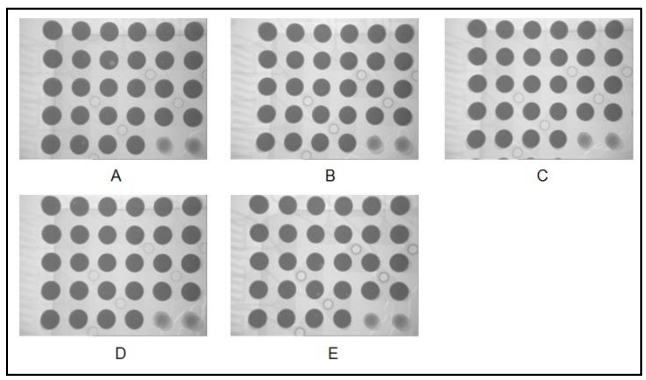

Figure 15: Mixed Alloy BGA Transmission X-RAY,

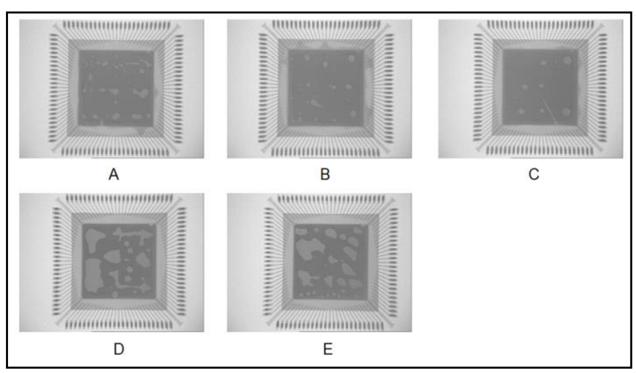

Figure 16: Quad Flat No-Lead Transmission X-RAY

Cleaning and Flux Residue

Cleanliness was assessed both visually and using solvent extract conductivity (SEC) testing to assess equivalent μg $NaCl/in^2$. Table 3 shows the water soluble ionic cleanliness results after in-line washing. The no-clean pastes were also cleanliness tested after process of record batch washing. While fluxes are washed off after each reflow, select no-clean samples were reflowed three times prior to washing to check for possible reduced cleanability due to thermally induced flux polymerization. No-clean flux residue appearance pre-wash was assessed by looking at both solder ball samples and actual reflowed joints to assess quantity and color of flux residue.

Table 5: Water Soluble Ionic Cleanliness Results

Paste	Board Number	Cleanliness Reading (μg $NaCl/in^2$)
A	1	2.7
B	3	2.4
D	7	3.0
E	9	2.3

Table 6: No-Clean Ionic Cleanliness Test Results – Including Multiple Reflows

Paste	Board Number	Cleanliness Reading (μg NaCl/in2)
G	12	1.8
G (3X Reflow)	13	1.5
I	15	1.9
I (3X Reflow)	16	1.6
J	18	1.9
J (3X Reflow)	19	1.7

MULTIFACTOR ANALYSIS AND SELECTION

Given all of the data on the different criteria for each paste, it was initially overwhelming to determine an optimum solder paste to use. In order to weight the multiple criteria at one time a modified failure mode effects analysis (FMEA) was used, wherein, a rating factor of importance to customer factor (1-10) was assigned to each criteria and a performance score (1-10) was assessed for each criterion and solder paste combination. Then the products of importance factor and performance score were summed for each paste. Table 6 and Table 7 show the water soluble and no-clean paste results, receptively. A performance score of 7 is the minimum for a solder paste to perform well enough to be manufacturing viable. The solder paste with the maximum total score and all individual criteria above 7 is the preferred solder paste. This approach allowed for sensitivity analysis to be performed where uncertainty in the performance score could be reanalyzed by varying the score and seeing if the overall best paste changed. This allowed the certainty of the outcome to be evaluated repeatedly. Given this approach, the solder and the number scales between water soluble and no-clean pastes were independent due to the significantly better performance of the no-clean solder pastes in nearly every performance criteria.

CONCLUSIONS

Evaluation of solder pastes is a complex multivariable problem. It is not sufficient for a solder paste to excel in many areas but be inadequate in one or more critical areas. Rather, an assessment of best overall must be made to determine a most effective solder paste. It is quite possible that the best solder paste overall not be the best in any one test criteria.

The variation of humidity and exposure time over each paste allowed for selection of a robust product that will run in a quantified range of operating environments. The use of the modified FMEA with weighting factors, allowed numerous criteria to be analyzed at one time. This combined with ANOVA in designed experiments and simpler low sample size experiments, provides a practical and balanced approach to selecting an optimum paste when multiple performance criteria are at play.

As a group the seven no-clean solder pastes greatly outperformed the six water soluble solder pastes in every category, but especially in slump, solder balling and printing. Discussion with the solder pasted vendors confirmed that most new flux effort goes into lead free chemistries with no-clean first, followed by water soluble. Then remaining effort goes into 63Sn/37Pb chemistries with most effort in no-cleans and then water soluble chemistries. Some vendors disclosed that any 63Sn/37Pb flux development is simply a testing of lead free chemistries in 63Sn/37Pb alloys.

It became evident that major solder paste vendors have limited experience blending 63Sn/37Pb water soluble solder paste in type 4 particle size. In order to prevent any supply chain delays, a safety stock of one standard shipment was always held in reserve at the paste manufacturer such that when a shipment is ordered and a batch does not pass stringent quality controls, the safety stock batch can still be shipped. The paste vendor's limited development effort 63Sn/37Pb water soluble sold pastes and limited experience in blending type 4 powders in this metallurgical and chemistry combination, necessitate detailed quantitative paste evaluation and acceptance criteria.. This is an result of 63Sn/37Pb water soluble type 4 being the unique domain of high reliability manufactures that produce mission critical electronics where weight limitations result in smaller components and finer paste particle sizes. High reliability electronics manufacturers find themselves in the domain of mission critical products that are built with 63Sn/37 Pb for maximum reliability, and yet these same solder pastes are not the research or product focus of major

Table 7: Water Soluble - Multifactor Analysis with Weighting Factors Multiplied by the Performance Score for Each Criterion

Criteria	**Solder Balling Characteristics**	**Slump Characteristics**	**Printability**	**Printability (Response-to-Pause)**	**Voiding**	**Solder Joint Characteristics**	**Wetting (Spread)**	**Visual Cleanability**	**Low Ionics Cleanability**	**Total**
Rating of Importance to Customer/Weighting Factor	8	10	10	8	5	10	8	8	10	
A (Type 3)	3	5	6	10	7	7	6	10	9	**537**
B (Type 3)	10	7	3	3	9	7	9	10	9	**561**
C (Same as B, but in Type 4)	7	8	8	2	9	7	8	10	9	**581**
D (Type 3)	9	9	6	9	6	9	6	10	9	**632**
E (Same as D, but in Type 4)	9	8	7	9	6	9	7	10	9	**640**
F (Type 3)	1	1	DQ	DQ	DQ	DQ	DQ	DQ	DQ	**DQ**
Maximum	10	10	10	10	10	10	10	10	10	**770**

Table 8: No-Clean - Multifactor Analysis with Weighting Factors Multiplied by the Assessment for Each Criterion

Criteria	**Solder Balling Characteristics**	**Slump Characteristics**	**Printability**	**Printability (Response-to-Pause)**	**Voiding**	**Solder Joint Characteristics**	**Wetting (Spread)**	**Uncleaned Flux Appearance**	**Visual Cleanability**	**Low Ionics Cleaning**	**Total**
Rating of Importance to Customer/ Weighting Factor	8	10	10	8	5	10	8	8	8	10	
G (Type 3)	3	7	9	1	8	7	6	7	3	9	**520**
H (Type 3)	5	8	7	10	8	10	8	9	9	9	**708**
I (Same as H, but in Type 4)	8	10	10	8	8	10	8	9	9	9	**766**
J (Type 3)	9	6	9	10	9	8	9	6	10	9	**717**
K (Same as J, but in Type 4)	7	9	9	10	9	8	10	6	10	9	**739**
L (Type 3)	10	6	2	10	DQ	DQ	DQ	DQ	DQ	DQ	**DQ**
M (Type 3)	6	7	1	9	DQ	DQ	DQ	DQ	DQ	DQ	**DQ**
Maximum	10	10	10	10	10	10	10	10	10	10	**850**

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solder paste manufactures. There seems to be a vacant niche for a solder paste manufacturer to differentiate themselves with a focus on 63Sn/37Pb water soluble solder pastes in type 4 for the high reliability market sector.

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