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Size Matters - The Effects of Solder Powder Size on Solder Paste Performance

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ABSTRACT

Solder powder size is a popular topic in the electronics industry due to the continuing trend of miniaturization of electronics. The question commonly asked is "when we should switch from Type 3 to a smaller solder powder?" Solder powder size is usually chosen based on the printing requirements for the solder paste. It is common practice to use IPC Type 4 or 5 solder powders for stencil designs that include area ratios below the recommended IPC limit of 0.66. The effects of solder powder size on printability of solder paste have been well documented.

The size of the solder powder affects the performance of the solder paste in other ways. Shelf life, stencil life, reflow performance, voiding behavior, and reactivity / stability are all affected by solder powder size. Testing was conducted to measure each of these solders paste performance attributes for IPC Type 3, Type 4, Type 5 and Type 6 SAC305 solder powders in both water-soluble and no clean solder pastes. The performance data for each size of solder powder in each solder paste flux was quantified and summarized. Guidance for choosing the optimal size of solder powder is given based on the results of this study.

Key words: solder powder size, solder paste performance, solder paste printing, reflow, voiding, solder paste stability

INTRODUCTION

Size matters. That simple statement is true for many things in life. Small hands are better for speed texting. Large people are better at playing offensive or defensive line in the national football league. Antibodies are microscopically small, but they play a key role in our health and well-being. Who does not want a large cup of coffee (Figure 1)?

Figure 1 – Size Matters

Size also matters in the world of solder paste. The size of the solder powder used in a solder paste has an effect on solder paste performance. Solder powder sizes are classified by type in the IPC standard J-STD-005 Requirements for Soldering Pastes [1]. Table 3-2 details the solder powder size ranges for each type, and an excerpt from the table is shown below (Table 1).

Table 1 – Solder Powder Size. Adapted from Table 3-2 of IPC J-STD-005A

IPC Type	Less than 0.5% larger than (µm)	10% Max. between (µm)	80% Min. between (µm)	10% Max. less than (µm)
3	60	45 – 60	25 - 45	25
4	50	38 – 50	20 - 38	20
5	40	25 – 40	15 - 25	15
6	25	15 – 25	5 - 15	5

The main particle size range is normally associated with the type. For example, Type 3 solder powder mainly falls within the 25 - 45 µm size range, therefore Type 3 solder paste may be labeled as "Type 3 (25-45 µm)." Below are images of Type 3, 4, 5, and 6 sizes of solder powder (Figure 2).

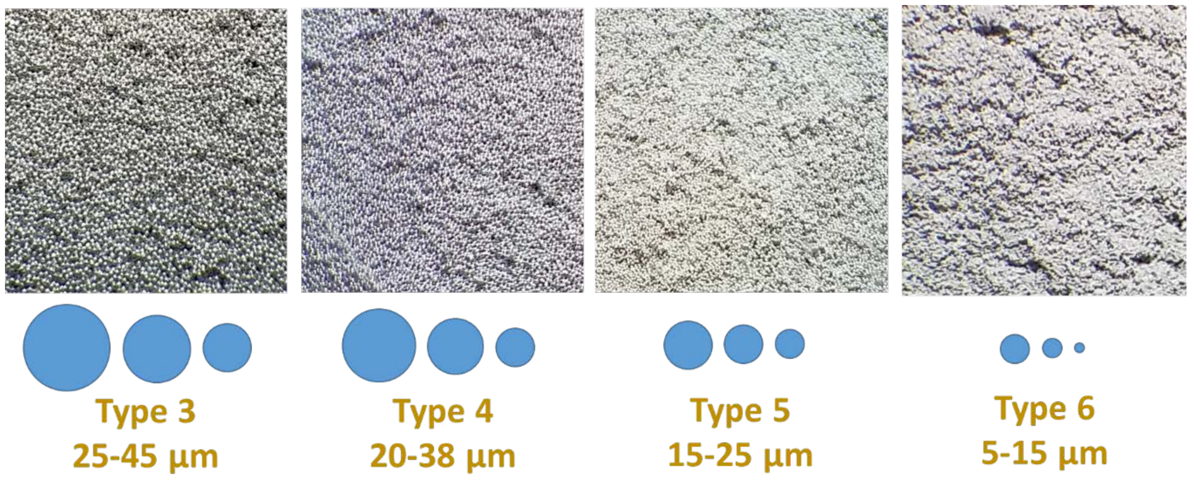


Figure 2 – IPC Type 3, 4, 5 and 6 Solder Powders

Why use Type 4, 5 or 6 solder powder rather than Type 3? The main reason to use smaller solder powders in solder paste is to improve printability for miniature components. As solder powder size decreases, the solder pastes can be printed through smaller stencil apertures. If the "5-ball" rule is followed from the IPC-7525 stencil design guidelines standard [2], then the minimum aperture size through which printing can occur can be calculated for each solder powder size [3]. These calculations for minimum aperture size were performed using five times the maximum solder powder size of the main size range (Table 2).

Table 2 – Solder Powder Size and Minimum Stencil Aperture Size for Printing Using the 5-Ball Rule

IPC Type	Size Range (µm)	Size Range (mil)	Minimum Aperture Size (mil)
T3	25 - 45	1.0 - 1.8	**9**
T4	20 - 38	0.8 - 1.5	**7.5**
T5	15 - 25	0.6 - 1.0	**5**
T6	5 - 15	0.2 - 0.6	**3**

Generally speaking, Type 3 solder paste can be used for components ranging in size down to the 0402 imperial package size. Most solder paste users prefer Type 4 solder paste for 0201 imperial, micro-BGAs and similar components. Type 5 solder paste is used for even smaller soldering applications like 01005 imperial components [4], or when Type 4 solder paste does not print adequately. Type 5 and Type 6 solder pastes are used for dispensing applications like jet printing. Type 6 solder paste is also used for other ultra-fine feature applications [5, 6].

Aside from the printing capabilities given by smaller solder powders [7], there are other performance changes that occur when smaller solder powders are used. Stencil life and shelf life of the solder pastes may be shortened when using smaller solder powders. Smaller solder powders have a higher potential for random solder balling and graping. Voiding behavior can also be affected with a change in solder powder size. The goal of this study is to quantify the performance for IPC Type 3, 4, 5 and 6 SAC305 (Sn / Ag 3.0% / Cu 0.5%) solder powders in both water-soluble and no clean solder pastes. Experimental data for each solder paste is compared and contrasted, and recommendations for the optimal use of each solder paste are given.

METHODOLOGY

Surface Area of Solder Powder and Reactivity

As the solder powder size decreases, the surface area of solder powder increases for a given mass [8] (Table 3). These surface areas were calculated using middle value in the main particle size range.

Table 3 – Solder Powder Size and Surface Area for a 1Kg Mass

IPC Type	Middle Surface Area of 1Kg (m^2)	Normalized Area	Amount of Surface Area Over T3 (%)
T3	22.9	1.00	-
T4	27.7	1.21	21
T5	40.2	1.75	75
T6	80.3	3.50	350

The surface area of the solder powder is important because it plays a role in the reactivity of the solder powder. As the surface area increases, the rate of reaction increases. Imagine trying to dissolve a cube of sugar in a cup of water. It takes time and a lot of stirring for the sugar to dissolve completely. If the same mass of granular sugar is mixed into a cup of water, it dissolves much more quickly (Figure 3).

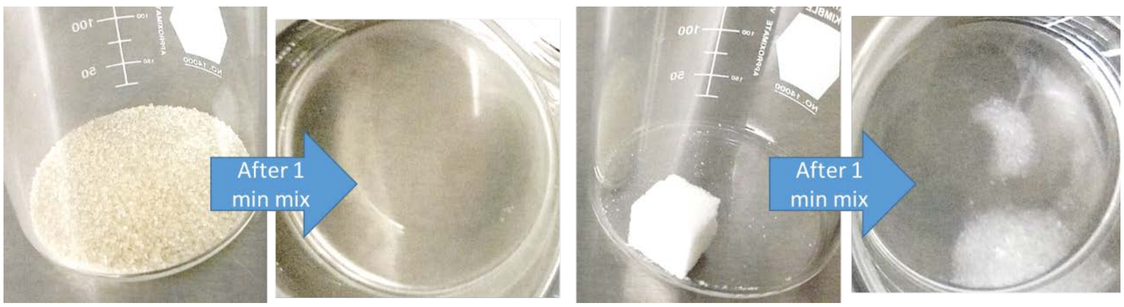


Figure 3 – Granular Sugar (Left) Versus Cubed Sugar (Right) Dissolved in Water with a 1 Minute Mix Time

After 1 minute of mixing the granulated sugar dissolved completely while the cube of sugar was partially dissolved. The granulated sugar has a higher surface area than the cube of sugar which enables the granulated sugar to dissolve more quickly.

The same principal is true with solder powder. The higher surface area of smaller solder powder types causes the rate of reaction to be higher than the larger solder powder types. Therefore, the smaller solder powder types are more susceptible to oxidation when exposed to air [9]. The chemical reactions for oxidation of tin (Sn) are shown below.

$$Sn_{(s)} + \tfrac{1}{2} O_{2\,(g)} = SnO_{(s)}$$
$$Sn_{(s)} + O_{2\,(g)} = SnO_{2\,(s)}$$

As oxygen reacts with the solder powder metal oxides are created. The primary oxide that forms on SAC305 alloy is Sn0 [10]. The solder paste flux removes the metal oxides and helps to slow further oxidation [8]. Oxidation of the solder powder can continue, albeit slowly, as long as the solder paste is exposed to air. Mixing and increased temperature accelerate this process. This reaction process of solder powder oxidation and oxide removal by the flux tends to thicken the solder paste. Over time, this can lead to clogged stencil apertures and cause the solder paste to stick to the squeegee blades. The usable stencil life of the solder paste may be shortened by the smaller solder powders. The good news is that solder paste fluxes are made with ingredients to protect the solder powder which significantly slows this oxidation process.

Oxidation of the solder powder also occurs during reflow. The solder paste flux reacts with and removes the oxides from the solder powder during reflow. As the solder powder size decreases, more flux is required to deal with these oxides. When reflowing solder pastes made with smaller solder powder sizes the flux may run out of activity, then oxides are left on the solder powder which interferes with proper coalescence of the solder. Solder pastes made with smaller solder powders are susceptible to potential issues like random solder balling and graping (Figure 4).

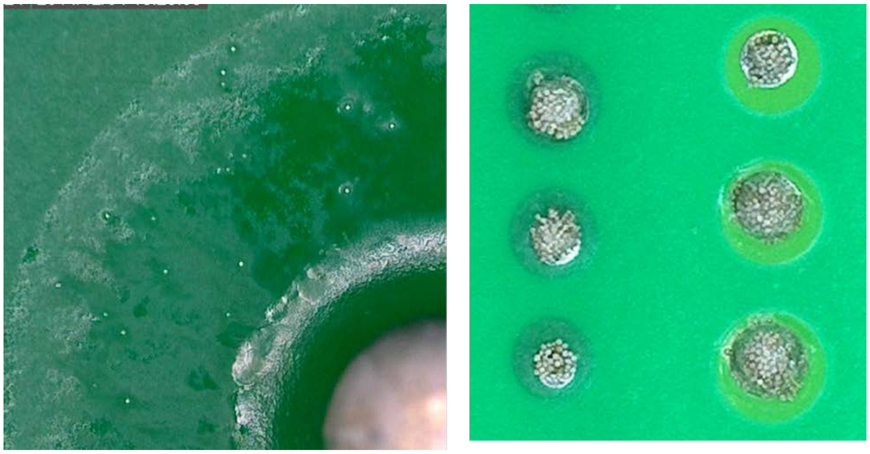


Figure 4 – Random Solder Balling (Left) and Graping (Right)

The shelf life for solder pastes made with smaller solder powders may also be shorter than solder pastes made with larger solder powders. During storage, the flux can react with the solder metal creating metal salts. The flux activity is depleted through this reaction over time and this reaction is faster for smaller solder powder sizes. As more reactive solder pastes age the solder paste may thicken and a change from a smooth and creamy appearance to more of a dull grainy appearance (Figure 5).

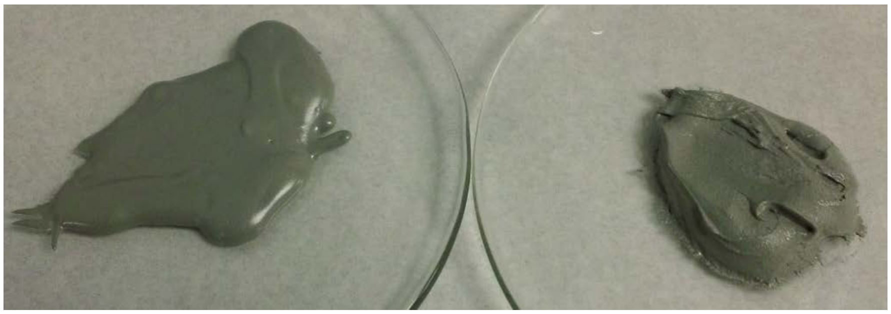


Figure 5 – Fresh Solder Paste (Left). Aged Solder Paste (Right)

Print and reflow characteristics may degrade over time if the solder paste is too reactive. Solder pastes are formulated to prevent or slow this process. Storing the solder paste in a refrigerator also helps to slow this process and preserve the intended performance characteristics. Proper storage is especially important to prolong the shelf life of solder pastes made with smaller solder powder sizes.

<u>Materials and Test Methods</u>

The circuit board used for this experimentation is shown below (Figure 1). This circuit board is made of FR4 0.062 inches thick, with etched copper pads and electroless nickel immersion gold (ENIG) surface finish.

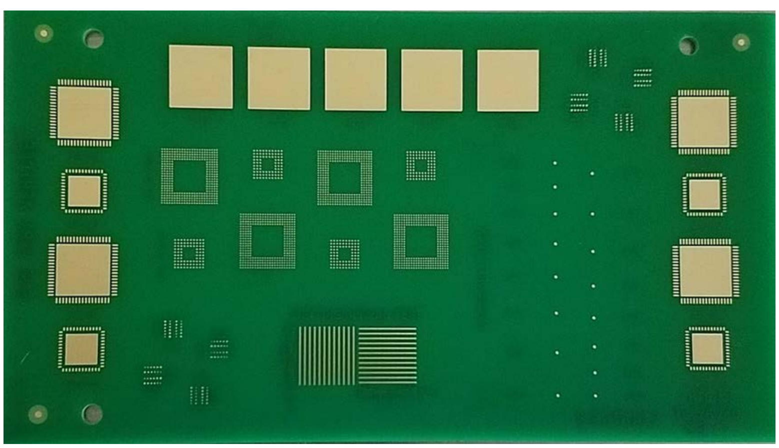


Figure 6 – Print and Reflow Test Circuit Board

This print and reflow test board has patterns that are used to quantify printed solder paste volume, wetting or spread, random solder balling, graping and voiding (Figure 7).

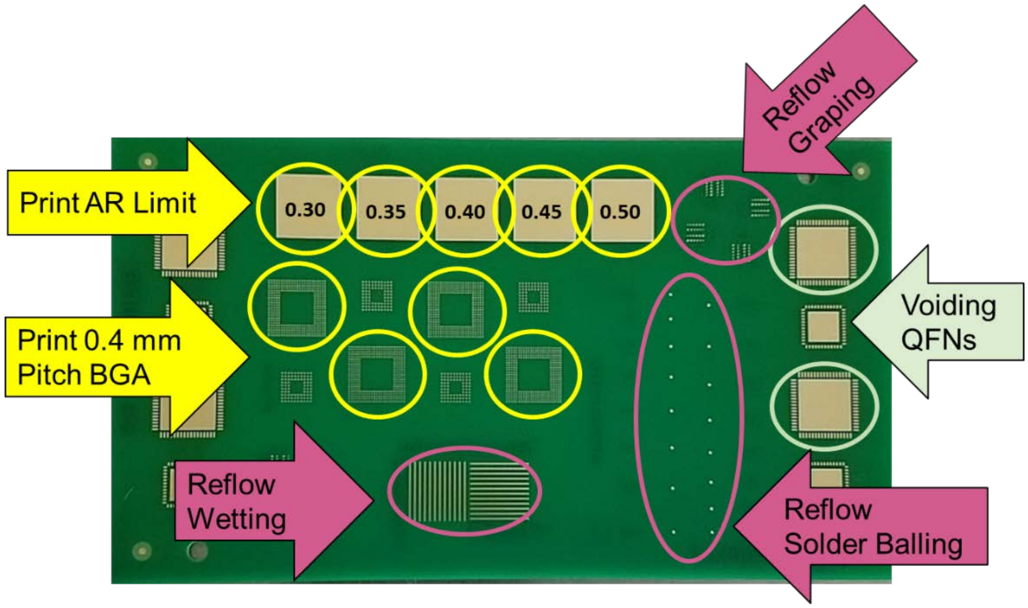


Figure 7 – PR Test Board Patterns for Quantifying Print, Reflow, and Voiding Performance

<u>Solder Pastes</u>
Eight solder pastes were made for this study including four water-soluble solder pastes, and four no-clean solder pastes. The no clean flux has an IPC J-STD-004 classification of ROL0, and the water-soluble flux is classified as ORH1. The solder alloy chosen was SAC305 (Sn / Ag 3.0% / Cu 0.5%). The solder paste metal concentrations were varied based on solder powder size and are shown below (Table 4).

Table 4 – Solder Paste Metal Concentrations

IPC Type	No Clean Metal Content (% wt)	Water-soluble Metal Content (% wt)
T3	88.5	88.5
T4	88.3	88.3
T5	88.0	88.0
T6	87.5	87.5

<u>Print Performance</u>
Print performance was measured using the area ratio limit patterns which have stencil aperture area ratios ranging from 0.30 up to 0.50 in 0.05 AR steps. The stencil is made of 5 mils thick (127 microns) fine grain (2-5 µm) stainless steel without nano-coatings. The aperture sizes range from 6 mils to 10 mils in the area ratio limit patterns. These small area ratios show the printing limit of the solder paste (Figure 8).

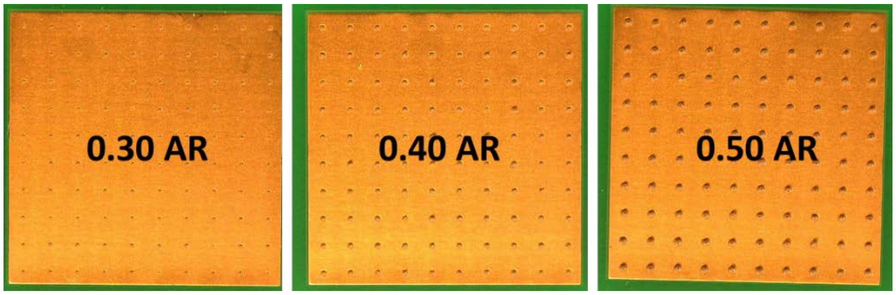


Figure 8 – Printed Solder Paste in the Area Ratio Limit Patterns

Print performance was also measured using the 0.4 mm pitch ball grid arrays (BGA) which have a stencil aperture area ratio of 0.50. The apertures are 10 mils square with 2 mil radiused corners ("squircles"). Solder paste volumes were measured in the area ratio limit and the 0.4 mm BGA patterns using a solder paste inspection system (SPI) and statistical analysis performed to compare solder paste performance. Lower limits of area ratios are suggested for each solder paste.

<u>Stencil Life and Response to Pause</u>

A print and pause test was conducted on each solder paste to measure stencil life and response to pause. The process used is shown below (Figure 9).

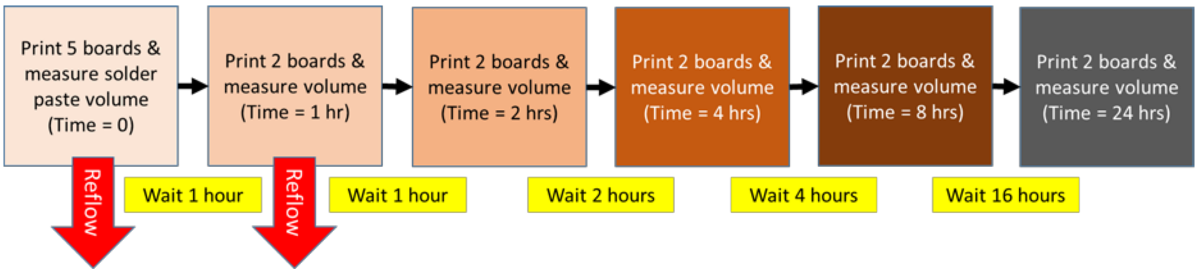


Figure 9 – Print and Pause Test Method

The solder paste volume data for the area ratio limit patterns and the 0.4 mm BGA patterns was compared for each time. During this test, significant drops in solder paste volume indicate that thickening or drying of the solder paste has occurred. This data is used to give a suggested stencil life for each solder paste.

The first 5 circuit boards from the print and pause test were used for reflow performance and voiding measurement. The next 2 circuit boards from the print and pause test were placed on a counter and left open to the air overnight. They were reflowed the following day (after 24 hours) and reflow performance was measured.

<u>Reflow Profile and Performance</u>

Reflow was done in a 10-zone convection reflow oven. A linear ramp-to-spike (RTS) type profile was used (Figure 7).

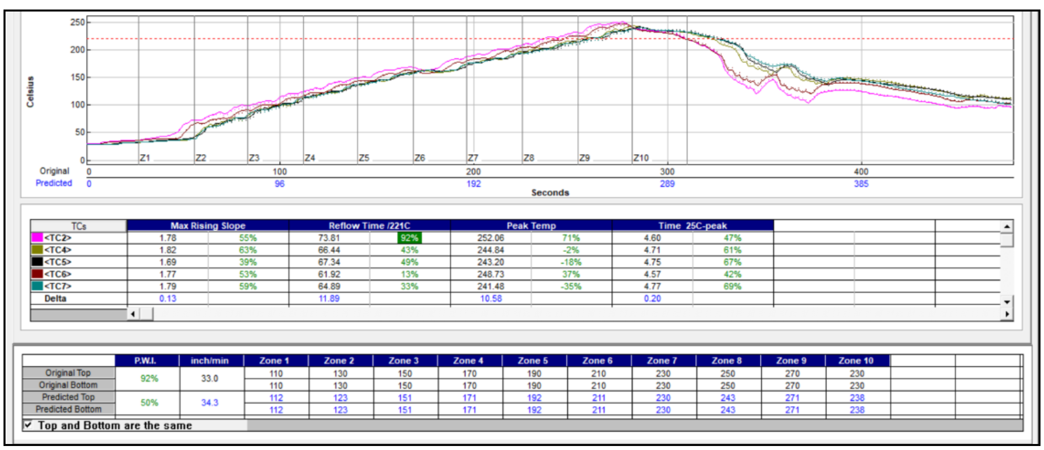


Figure 7 – Linear Ramp to Spike (RTS) Reflow Profile

The parameters for the profile are summarized below (Table 4).

Table 4 – Reflow Profile Parameters

Setting	RTS Profile
Ramp rate	1.7 – 1.8 °C/sec
Reflow Time (>220 °C)	61 – 67 sec
Peak temperature	241 to 248 °C
Profile length (25 °C to peak)	4.70 minutes

Wetting, solder balling, and graping were measured for each solder paste. This was done with freshly printed solder paste, and again with circuit boards that sat open to the air for 24 hours. The wetting pattern on the PR test board is shown below (Figure 10).

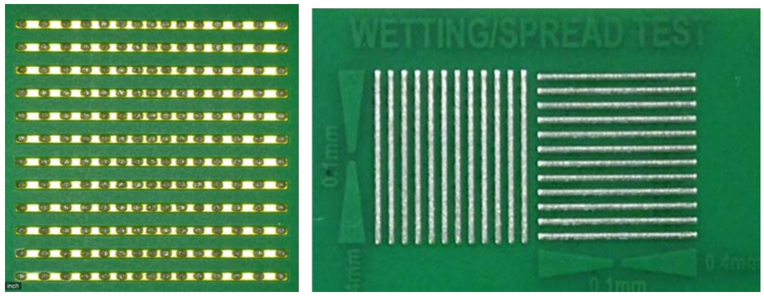


Figure 10 – PR Test Board Wetting Pattern Before (Left) and After Reflow (Right)

This pattern includes 12 vertical and 12 horizontal parallel lines with 15 solder paste bricks printed down each line. The solder paste bricks are 0.4 mm wide (15.7 mils) and spacing ranges from 0.1 mm to 0.4 mm (3.9 mils to 15.7 mils). During reflow the solder paste bricks spread together down each line. A wetting or spread percentage is calculated by counting the number of solder paste bricks that bridged together and dividing by the total possible number of bricks. Ideal solder paste performance is 100% wetting.

Solder balling is measured using solder balling / pullback patterns. The solder paste is over-printed onto the solder mask. When the solder paste reflows, it pulls back into a central sphere of solder. Random solder balls are left behind in the flux pools (Figure 11).

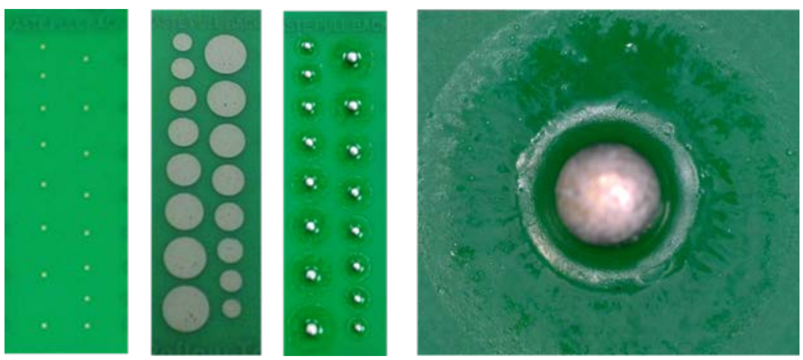


Figure 11 – PR Test Board Solder Balling / Pullback Patterns

The overprint percentages range from 500% to 1250% over the pad size. Solder balling is evaluated by the largest overprint percentage that has: 0 solder balls, less than 5 solder balls, and less than 10 solder balls. Ideal solder paste performance is 1250% overprint in each category.

Graping is measured using graping patterns. These patterns include square and circular, solder mask defined and non-solder mask defined pads. The pad sizes range from 0.18 mm (7 mils) to 0.30 mm (12 mils) and the corresponding stencil aperture area ratios range from 0.35 to 0.60 respectively (Figure 12).

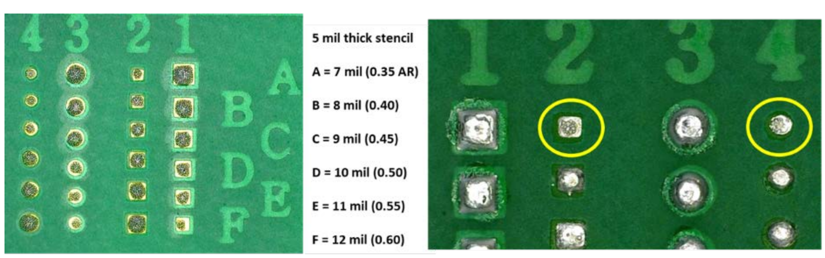


Figure 12 – PR Test Board Graping Patterns

After reflow the solder deposits are evaluated for graping. Graping typically occurs at the smaller solder paste deposits (Figure 12). A graping percentage is calculated by dividing the total number of solder deposits with graping by the total possible. Ideal solder paste performance is 0% graping.

Voiding

The larger quad flat no lead (QFN) thermal pads were used for void measurements. The QFN components have 68 perimeter leads on a 0.5 mm pitch, a 10 mm body size, and a matte tin finish (Figure 13).

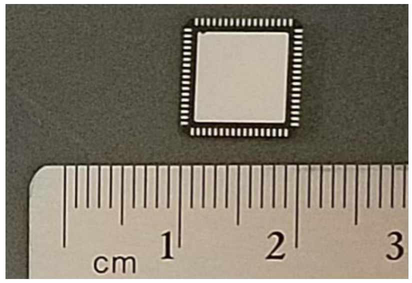


Figure 13 – QFN (MLF68) Dummy Component

The stencil design was identical for each QFN location (Figure 14). In each case the solder paste coverage was approximately 65% of the thermal pad area.

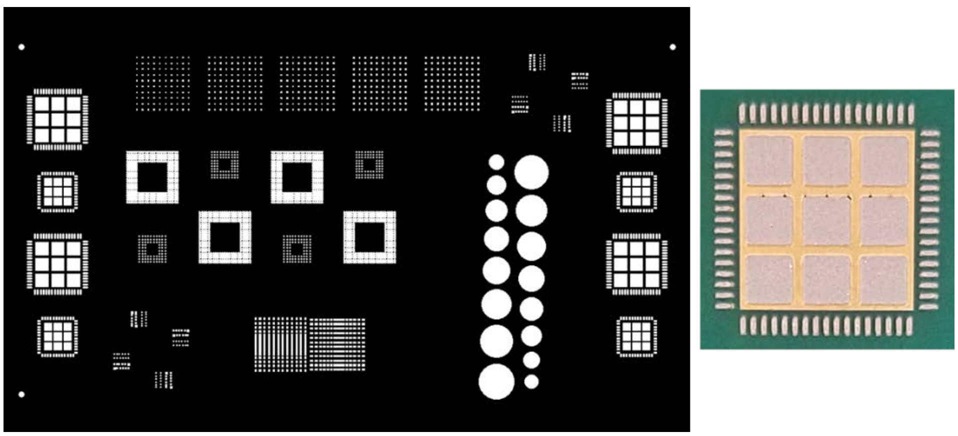


Figure 14 –Stencil Design for QFN Thermal Pads

The QFN thermal pad stencil design was a “window-pane” type with 9 panes. The web width of the QFN window panes was 0.51 mm (20 mils). 4 QFN components were placed on each of 5 circuit boards for a total of 20 QFNs and 20 void area measurements per solder paste. Statistical analysis was used to compare voiding performance for each solder paste.

Standard Solder Paste Tests

Several industry standard solder paste tests were run to compare and contrast performance of the solder pastes. Viscosity using both T-bar spindle and spiral pump, slump and solder balling were all run per J-STD-005 [1]. The data from these industry standard tests was compared and contrasted for each solder paste, mainly to illustrate basic differences in the solder pastes.

Stability - Tack Force

Tack force testing was run per JIS Z 3284 [11] on freshly prepared coupons. Additional tack force coupons were printed and placed in a controlled environment at 21-24 °C (70-75 °F) and 50-55% relative humidity. The tack force coupons were stored and tack force was measured after hold times of 24, 48 and 72 hours. Changes in tack force over time give some information about reactivity or stability of the solder paste. Ideal performance is no change in tack force over 72 hours.

Stability - Heat aging

The solder pastes were placed in sealed jars in an oven at 50-55 °C (122-131 °F) for 72 hours. This temperature is much higher than recommended for solder paste storage. The normal recommended storage temperature for most solder pastes is 5 to 10 °C (40-50 °F). Elevated temperatures tend to speed potential reactions within the solder paste. This may result in a loss of activity, thickening of the solder paste, and overall degradation in performance.

After heat aging, the solder pastes were printed on the PR test board and reflowed. Viscosity, solder balling, and tack force measurements were taken. These results were compared to the results from the fresh solder pastes (before heat aging). Stable solder pastes tend to show very little change in performance while more reactive solder pastes tend to show drops performance.

Statistical Analysis

Tukey Kramer honest significant difference (HSD) testing was done on the voiding data sets to compare and contrast the data. Tukey Kramer HSD analysis determines whether multiple data sets are significantly different, or statistically similar. This test is similar to Student's t-test used to compare means. The output of the Tukey Kramer HSD test is a chart that shows the data sets, several data calculations and reports (Figure 15).

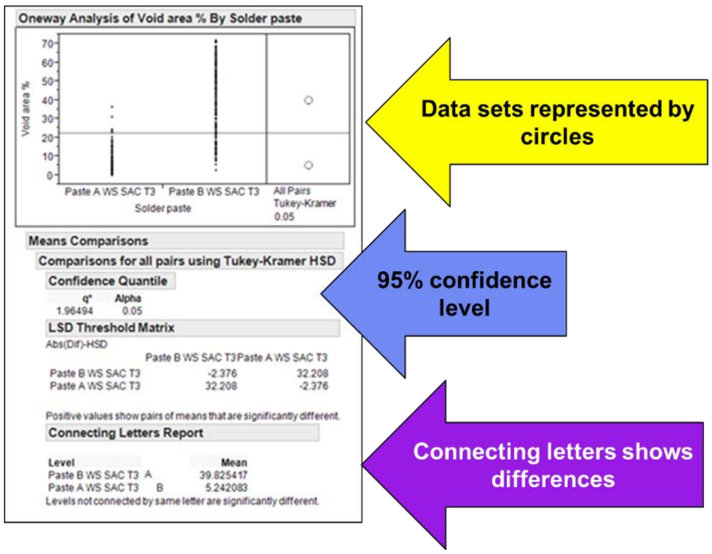


Figure 15 – Explanation of Tukey Kramer HSD Report

The Tukey Kramer HSD analysis shows whether the data sets under comparison are significantly different. This analysis is used to draw general conclusions and show trends in performance.

RESULTS AND DISCUSSION

Standard Solder Paste Tests

The viscosity of each solder paste was measured using the T-bar spindle and spiral pump methods from J-STD-005 [1]. The results are shown in the graphs below (Figure 16).

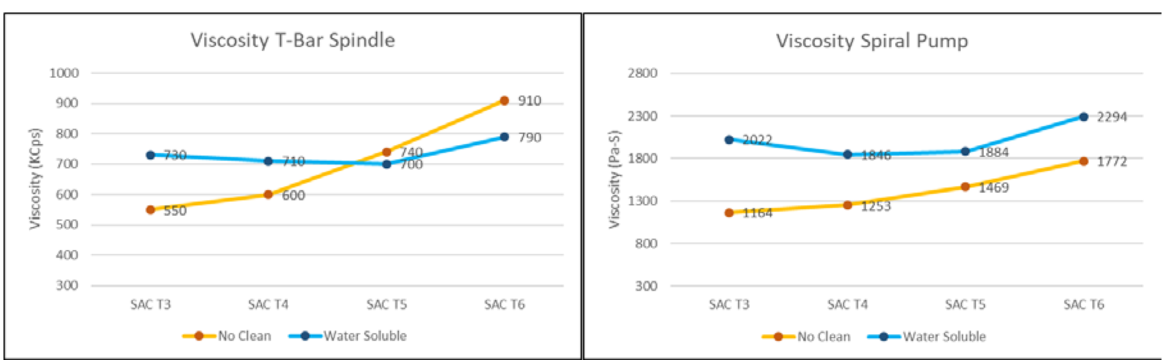


Figure 16 – Viscosity of Each Solder Paste Using both T-Bar Spindle (Left) and Spiral Pump Methods (Right)

The viscosity of the no clean solder paste increased with decreasing solder powder size for both the T-bar spindle and spiral pump methods. The viscosity of the water-soluble solder paste was more stable with respect to solder powder size regardless of the method used. The T-bar spindle method gave a higher viscosity for the no clean SAC type 5 and type 6 solder pastes than for the water-soluble solder pastes, while this was not true for the spiral pump method.

The slump of each solder paste was measured according to IPC-J-STD-005 methods. The pass and fail results are shown below (Table 5).

Table 5 – IPC Slump Pass and Fail Results for Each Solder Paste

	No Clean		Water Soluble	
	Cold Slump	Hot Slump	Cold Slump	Hot Slump
SAC T3	Pass	Pass	Pass	Pass
SAC T4	Pass	Pass	Pass	Pass
SAC T5	Pass	Pass	Pass	Fail
SAC T6	Pass	Fail	Pass	Fail

All solder pastes passed cold (25 °C) slump but there were some failures with hot slump (180 °C). The no clean type 6 and the water-soluble type 5 and 6 solder pastes failed hot slump. These solder pastes were formulated originally for use with type 3 and 4 solder powders and are not necessarily optimized for the smaller solder powders.

The IPC J-STD-005 solder balling test was run using frosted glass slides and a hot plate set to 245 - 250 °C. The results are tin the table below (Table 6).

Table 6 – IPC Solder Balling Results for Each Solder Paste

	No Clean		Water Soluble	
	Initial	After 4 Hrs	Initial	After 4 Hrs
T3	Acceptable	Acceptable	Acceptable	Acceptable
T4	Acceptable	Acceptable	Acceptable	Acceptable
T5	Acceptable	Ac - UnAc	Acceptable	Acceptable
T6	Unacceptable	Unacceptable	Unacceptable	Unacceptable

All of the Type 3, 4 and 5 solder pastes gave acceptable solder balling results. The no clean Type 5 solder paste gave borderline acceptable / unacceptable results. All of the Type 6 solder pastes gave unacceptable results showing rings of solder balls and clumps of solder balls (Figure 17).

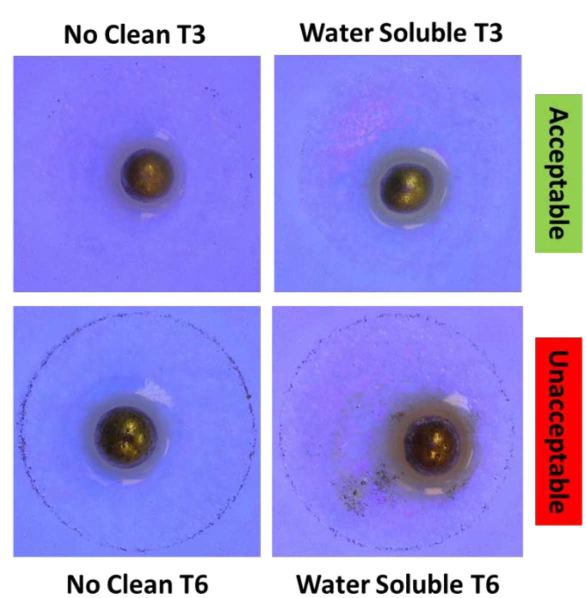


Figure 17 – IPC J-STD-005 Solder Balling Pictures of Acceptable and Unacceptable Results

<u>Printing Area Ratio Limits</u>

The printing patterns on the PR test circuit board are challenging for solder pastes. The aperture sizes in the print patterns range from 6 mils (0.152 mm) up to 10 mils (0.254 mm) and the stencil is 5 mils (127 µm) thick. This corresponds to aspect ratios of 1.2 up to 2.0 and area ratios of 0.30 up to 0.50 respectively. The guidelines given in IPC-7525 [2] for acceptable solder paste printing are aspect ratios above 1.50 and area ratios above 0.66. The 0.30 and 0.35 area ratio apertures have aspect ratios of 1.2 and 1.4 respectively which are below the recommended guideline of 1.50. All of the area ratios are below the industry guideline of 0.66.

The printed solder paste transfer efficiency (TE%) values for these patterns typically range from 5% up to 60%. The transfer efficiencies for the printed solder paste broken out by area ratio are shown below (Figure 18).

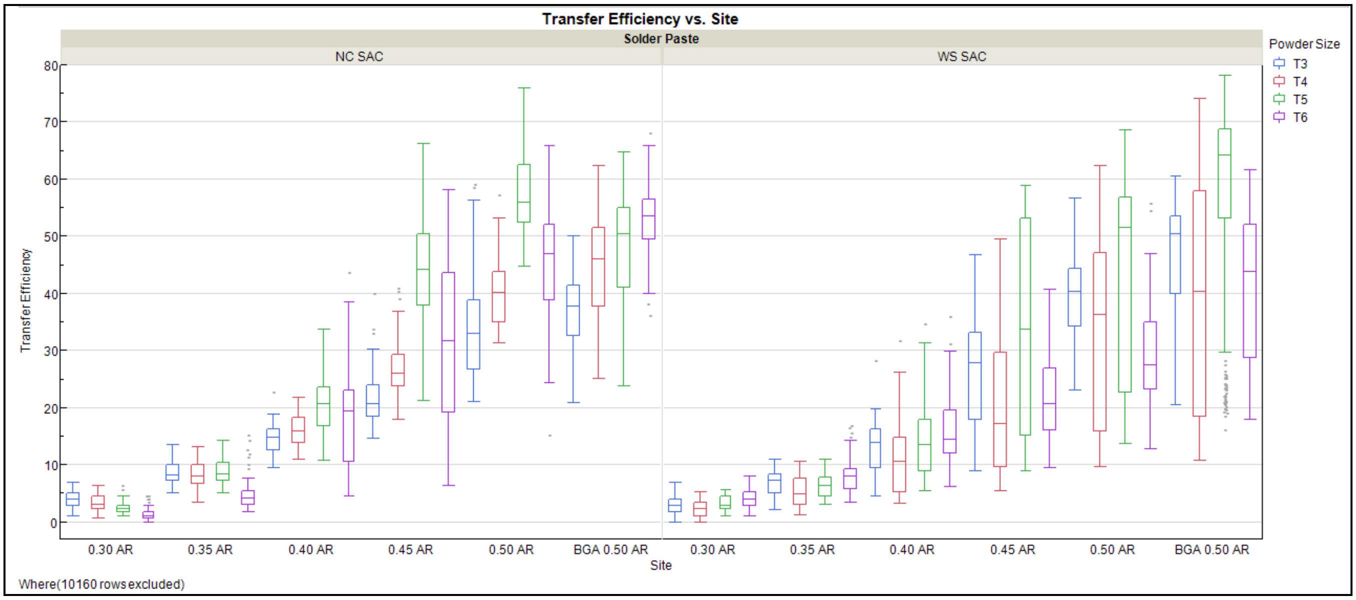


Figure 18 – Transfer Efficiency Box Plots for Each Solder Paste by Area Ratio

These transfer efficiency numbers are well below the generally accepted industry limit of 80% which is normal for this stencil design. Generally speaking the transfer efficiencies increase with decreasing solder powder size. There are some anomalies in this data that do not follow that trend. The no clean type 6 solder paste gave lower transfer efficiencies for the 0.30 and 0.35 area ratios than the other solder powder sizes. This was an unexpected result. This same data set is shown as smooth curves below (Figure 19).

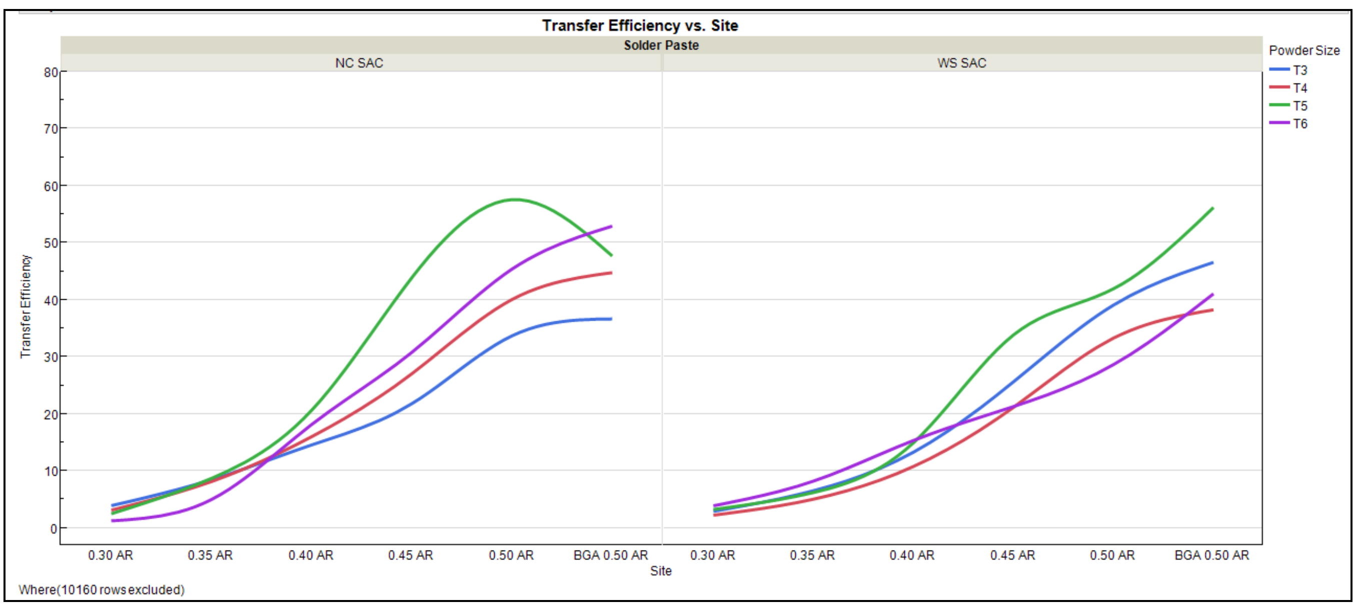


Figure 19 – Transfer Efficiency Curves for Each Solder Paste by Area Ratio

The transfer efficiency of the type 5 solder pastes was generally higher than all of the other solder powder sizes. This was an unexpected result. Type 6 solder paste was expected to give higher transfer efficiencies than the other solder powder sizes. The water-soluble type 6 solder paste gave some of the lowest TE% values.

If we use a rule of 0.60 area ratio for the type 3 solder pastes, then the minimum area ratios for the other solder paste types can be estimated based on the TE differences in this study. These minimum area ratios are listed by solder paste below (Table 7).

Table 7 – Minimum Area Ratios for Each Solder Paste and Solder Powder Size

Solder Powder Size	Minimum Area Ratio No Clean	Minimum Area Ratio Water Soluble
Type 3	**0.60**	**0.60**
Type 4	**0.55**	**0.60**
Type 5	**0.50**	**0.55**
Type 6	**More work needed**	**More work needed**

These minimum area ratio rules are guidelines based upon the print patterns used in this evaluation. More work is needed to evaluate the print performance of the type 6 solder pastes. These rules do not take into account solder joint quality or reliability. Solder joint quality and reliability should be verified before using these rules in a production environment.

<u>Print and Pause Results and Stencil Life</u>

Print and pause testing is one way to determine the stability of solder pastes as they sit open to the air in the printer. Drops in transfer efficiency over time are a way to estimate stencil life. The transfer efficiency over time is shown for each solder paste below (Figure 20).

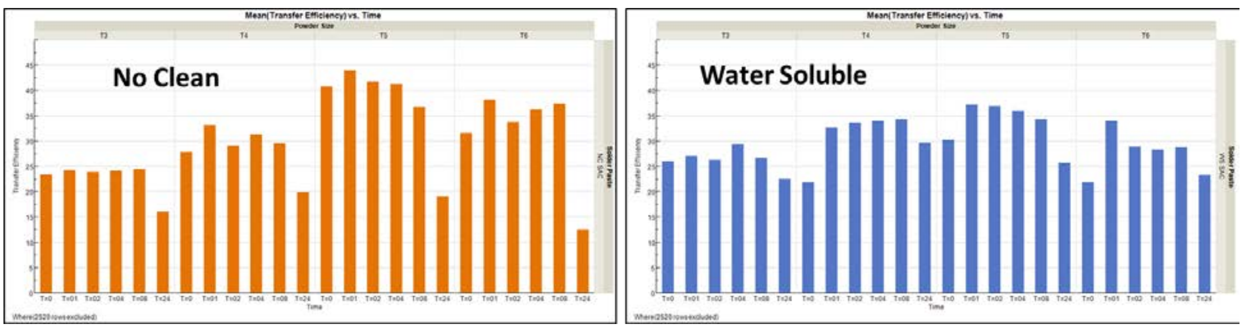


Figure 20 – Print and Pause Results for Each Solder Paste. No Clean (Left) and Water-soluble (Right)

The no clean solder pastes each showed similar performance in print and pause testing. The transfer efficiency was stable at time 0, 1 hour, 2 hours, 4 hours, and 8 hours. At a time of 24 hours there was a significant drop in transfer efficiency. The smaller solder powder sizes showed larger drops in transfer efficiency. The water-soluble solder pastes showed similar performance. There was a significant drop in TE% at a time of 24 hours. The TE% drops from the 8 hour time to the 24 hour time are summarized below (Table 8)

Table 8 – Transfer Efficiency % Drop from Time = 8 Hrs to Time = 24 Hrs

Solder Powder Size	Drop in TE% No Clean	Drop in TE% Water Soluble
Type 3	**8**	**5**
Type 4	**10**	**5**
Type 5	**18**	**8**
Type 6	**25**	**6**

Type 3 and 4 solder powders give a similar drop in transfer efficiency over time for each solder paste. Type 5 and 6 solder powder sizes show a larger drop in transfer efficiency over time for each solder paste. The no clean solder pastes are less stable with respect to decreasing solder powder size than the water-soluble solder pastes. The no clean solder pastes tend to "dry out" more while sitting on the stencil, especially with the smaller solder powder sizes.

Reflow Performance of the Solder Pastes

Wetting or spread percentage of each solder paste was measured using the PR test circuit board with ENIG surface finish. The results for wetting are shown below (Figure 21)

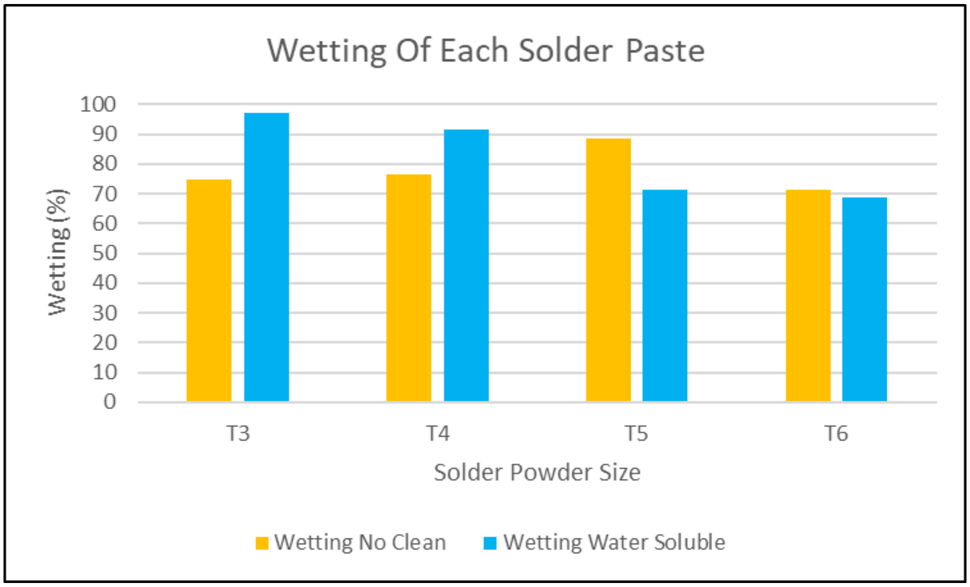


Figure 21 – Wetting or Spread of the Solder Pastes

The no clean solder pastes showed fairly stable wetting of about 70 to 75% regardless of solder powder size. The only anomaly in this trend is the wetting % for no clean type 5 solder paste which was near 90%. The water-soluble solder paste shows a trend in decreasing wetting as the solder powder size decreases. The wetting for the water-soluble type 3 solder paste was 97% and this decreased to under 70% for the type 6 solder paste (Figure 22).

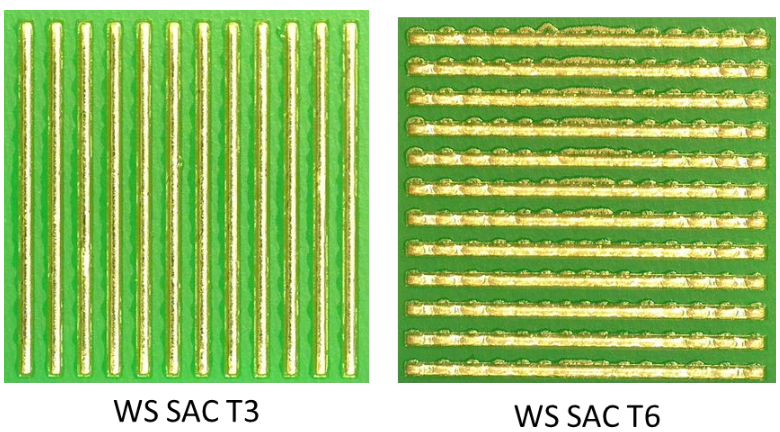


Figure 22 – Wetting for WS SAC Type 3 and Type 6 Solder Pastes

Solder balling was measured using the pullback patterns on the PR test board. The largest overprint percentages that gave 0 solder balls, less than 5 solder balls and less than 10 solder balls were recorded for each solder paste. The maximum overprint percentage in each category is 1250%. The results for the solder pastes that were measurable with this criteria are shown below (Table 9).

Table 9 – Solder Balling Performance of Solder Pastes That Fell Within the Measurement Criteria

Solder Paste	Overprint with 0 Solder Balls	Overprint with < 5 Solder Balls	Overprint with < 10 Solder Balls
No Clean Type 3	750%	1200%	1200%
Water-soluble Type 3	None	1200%	1250%
Water-soluble Type 4	None	500%	1200%

The solder balling was greater than 10 on all patterns for the solder pastes that are not shown in Table 9. Representative pictures of the solder balling in the overprint patterns are shown below (Figure 23).

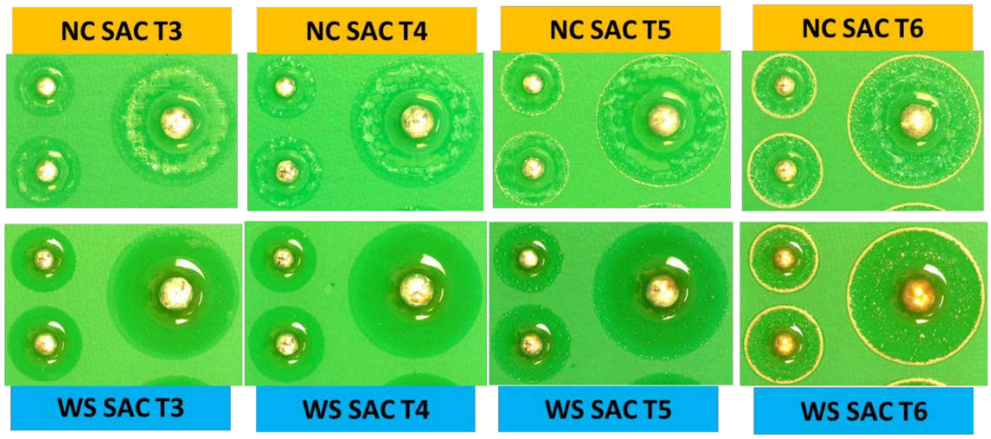


Figure 23 – Solder Balling in the Overprint Patterns

These overprint levels are fairly extreme and would not normally be used in typical surface mount technology (SMT) designs. The solder balling generated by the type 3 and 4 solder pastes was low and would be considered acceptable on most electronic assemblies. It is evident from these pictures that type 5 and type 6 solder powders create excessive solder balling with the no clean solder paste. The water-soluble type 5 solder paste gave better solder balling than the no clean type 5. This is likely due to the relative activity levels of these solder pastes. The water-soluble solder paste has a higher activity level than the no clean solder paste and therefore the water-soluble solder paste gives less solder balling with the smaller solder powder sizes. Both the no clean and water-soluble type 6 solder pastes gave excessive solder balling.

The graping levels of the solder pastes vary with solder powder size (Figure 24).

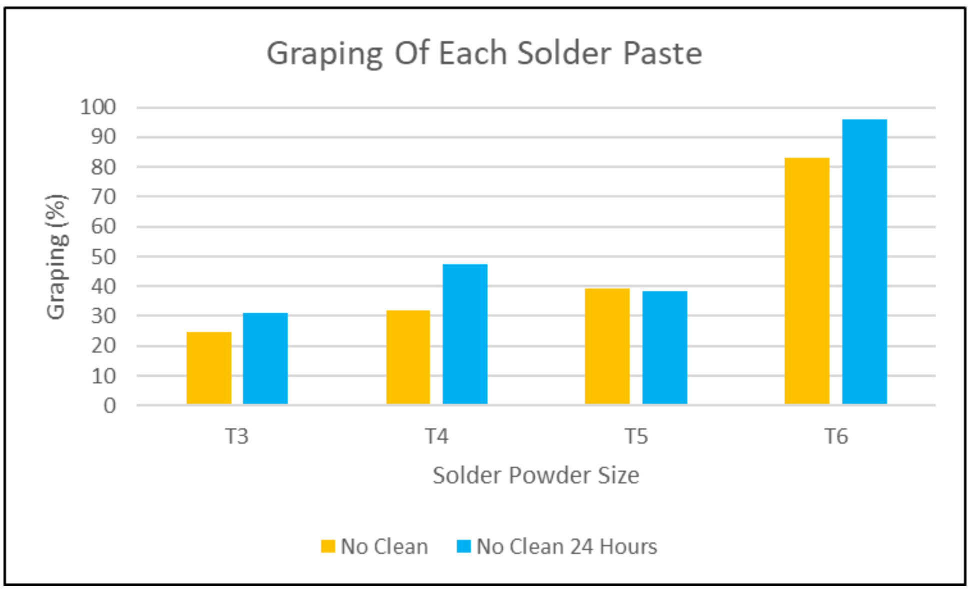
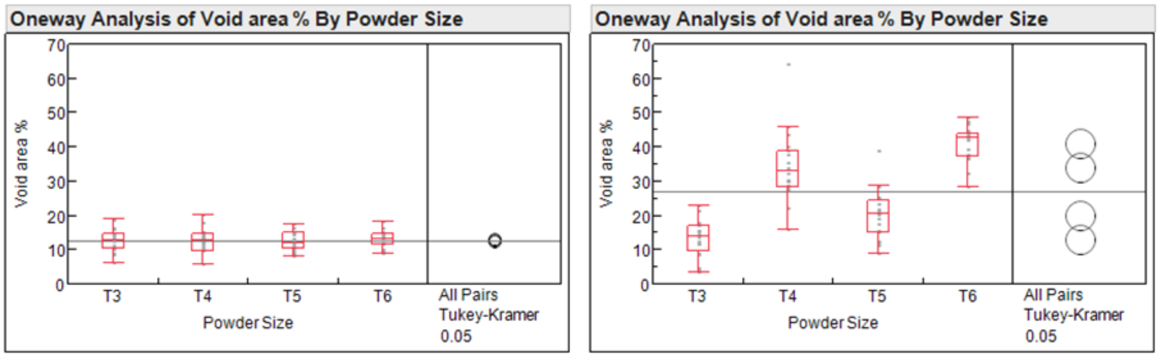


Figure 24 – Graping for Each Solder Paste

The graping levels for the no clean and water-soluble solder pastes were very similar for the type 3, 4, and 5 solder powders. Overall the graping was very high for the type 6 solder pastes. The water-soluble solder paste gave higher graping than the no clean solder paste with type 6 powder.

Voiding was measured for each solder paste using the QFN/BTC thermal pads. The voiding data is shown below (Figure 25).



Excluded Rows 80

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

Level		Mean
T6	A	13.3
T3	A	12.9
T4	A	12.7
T5	A	12.5

Levels not connected by same letter are significantly different.

Excluded Rows 80

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

Level					Mean
T6	A				41.2
T4		B			34.3
T5			C		20.4
T3				D	13.3

Levels not connected by same letter are significantly different.

Figure 25 – Voiding for Each Solder Paste in the QFN/BTC Thermal Pads. No Clean (Left) and Water-soluble (Right)

The no clean solder paste showed statistically identical voiding behavior for each solder powder size. The water-soluble solder paste showed some differences in voiding by solder powder size. The largest solder powder (type 3) gave the lowest voiding while the highest voiding was generated by the no clean type 6 solder paste. One possible explanation for this is the difference in rosin content of the no clean and water-soluble solder pastes. The no clean solder paste contains rosins which help to protect the solder powder from oxidation during reflow. It is theorized that the byproducts of the reaction of the flux with the solder oxides can lead to voiding. With the added protection that rosins give, the amount of oxide generated during reflow is much lower for the no clean than for the water-soluble solder paste. This may explain the voiding behavior observed in this work.

<u>Stability of the Solder Pastes - Tack Force Over Time</u>

The tack force was measured for each solder paste using the JIS method [11]. The tack force coupons were printed and stored in a chamber at room temperature and 50-55% relative humidity over a 72-hour period. Tack force was measured with the freshly printed solder paste, after 24 hours, 48 hours and 72 hours (Figure 26).

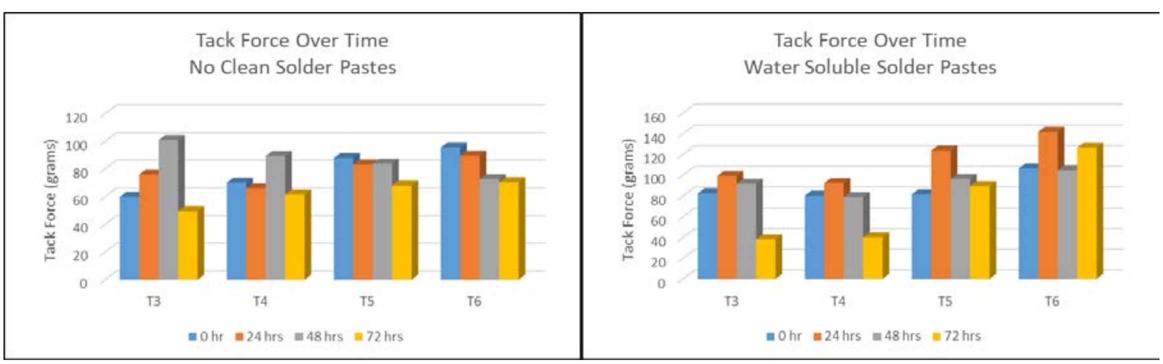


Figure 26 – Tack Force of No Clean (Left) and Water-soluble (Right) Solder Pastes Over Time.

In general, the tack force decreases over time for each type of solder paste and each solder powder size. The tack force drops significantly at 72 hours for most of the solder pastes. This is not true for the water-soluble type 5 and type 6 solder pastes. The water-soluble type 5 solder paste showed relatively stable tack force over the 72-hour time period. The water-soluble type 6 solder paste showed an increase in tack force at the 72-hour time. This difference in the water-soluble paste performance is likely related to the increased flux content for the smaller solder powder types.

<u>Stability of the Solder Pastes - Reflow Performance After a 24-Hour Hold Time</u>

The reflow performance of each solder paste was measured with freshly printed PR test boards and again with test boards that were printed and stored open to the air for 24 hours. Storing the printed solder paste open to the air can increase the solder oxide levels and deplete the activity of the solder paste. This test is one way to show the stability of the solder paste and to determine if that stability is lessened with smaller solder powders. The wetting results are shown below (Figure 27).

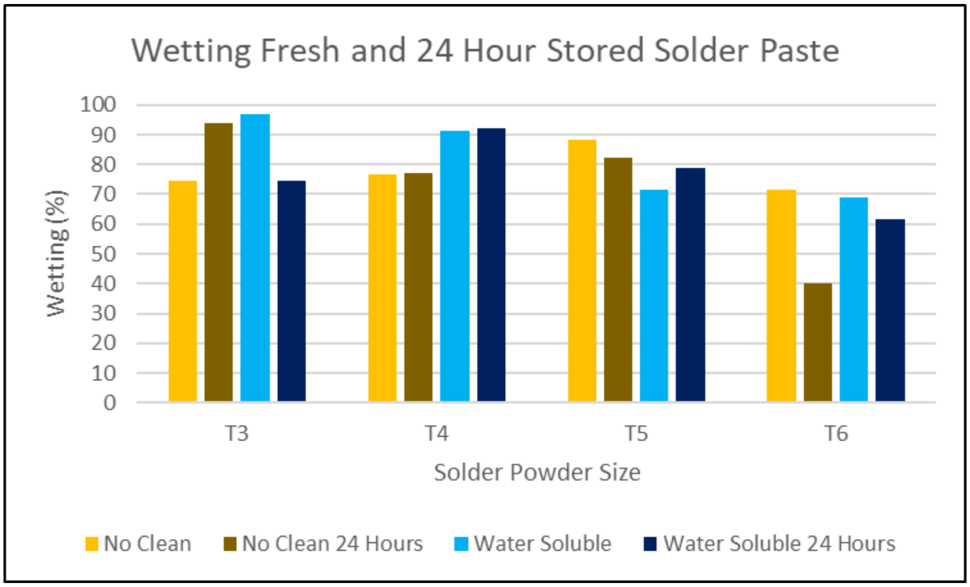


Figure 27 – Wetting Results of Solder Pastes Before and After 24 Hour Storage

The wetting for the freshly printed no clean solder pastes and the no clean solder pastes stored for 24 hours were similar for every solder powder size except type 6. The no clean type 6 solder paste showed a decrease in wetting when stored open to the air for 24 hours. The water-soluble pastes showed similar wetting when fresh and after 24 hours, except for the type 3 solder paste which showed a drop in wetting with storage.

Solder balling was measured using the overprint patterns in the PR test board with freshly printed solder paste and again with printed boards stored for 24 hours (Table 10).

Table 10 – Solder Balling Performance of Solder Pastes Before and After 24 Hour Storage

Solder Paste	Overprint with <5 Solder Balls	Overprint with <10 Solder Balls	Overprint with <5 Solder Balls After 24 hours	Overprint with <10 Solder Balls After 24 Hours
No Clean Type 3	1200%	1200%	600%	1000%
Water-soluble Type 3	1200%	1250%	1150%	1250%
Water-soluble Type 4	500%	1200%	None	500%

The overprint percentages decreased as the printed solder pastes were stored over 24 hours. This indicates a general increase in random solder balling with storage. The increase in random solder balling was worse for the smaller solder powder sizes. Representative pictures of the solder balling before and after the 24 hour storage are shown below (Figure 28).

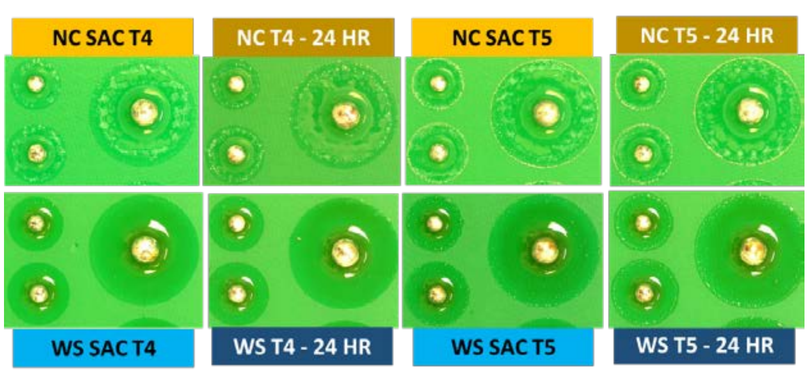


Figure 28 – Solder Balling of Solder Pastes Before and After 24 Hour Storage

The graping percentages were measured before and after 24 hour storage (Figure 29).

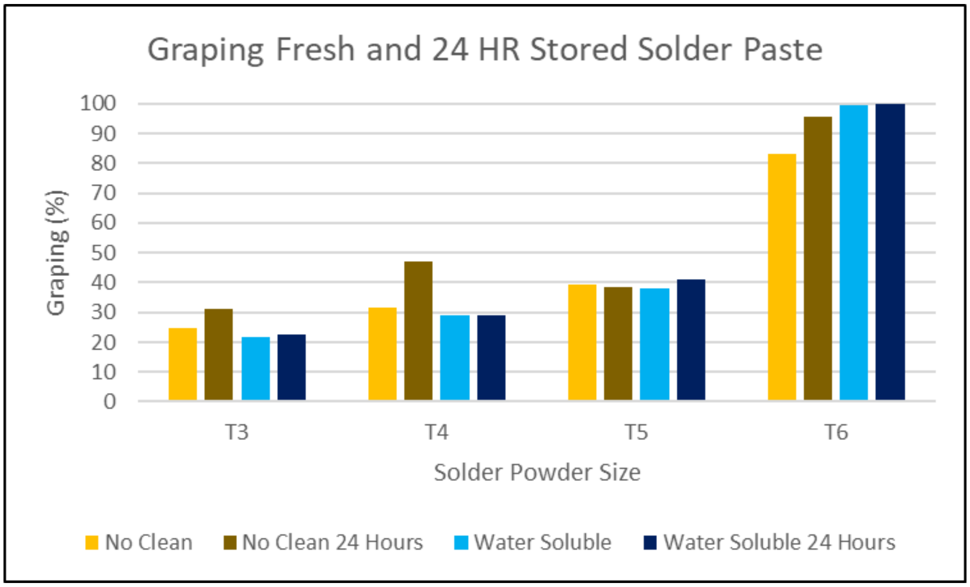


Figure 29 – Graping Results of Solder Pastes Before and After 24 Hour Storage

The no clean solder paste showed increases in graping for the type 3, 4 and 6 solder powder sizes when stored for 24 hours. The increases in graping were 6% for type 3, 16% for type 4 and 13% for type 6. The type 5 solder pastes were unaffected by 24-hour storage. The water-soluble solder paste showed the same levels of graping before and after the 24 hour hold time. The graping with the no clean solder paste shows increasing sensitivity to hold times with the smaller solder powder sizes.

<u>Stability of the Solder Pastes - Heat Aging</u>

The solder pastes were sealed in their containers and heat aged in an oven at 50 °C (122 °F) for 3 days. After heat aging viscosity, IPC solder balling, tack force, and print and reflow performance were measured. These results were compared to the results from the fresh solder pastes. The viscosity results before and after heat aging are shown below (Figure 30).

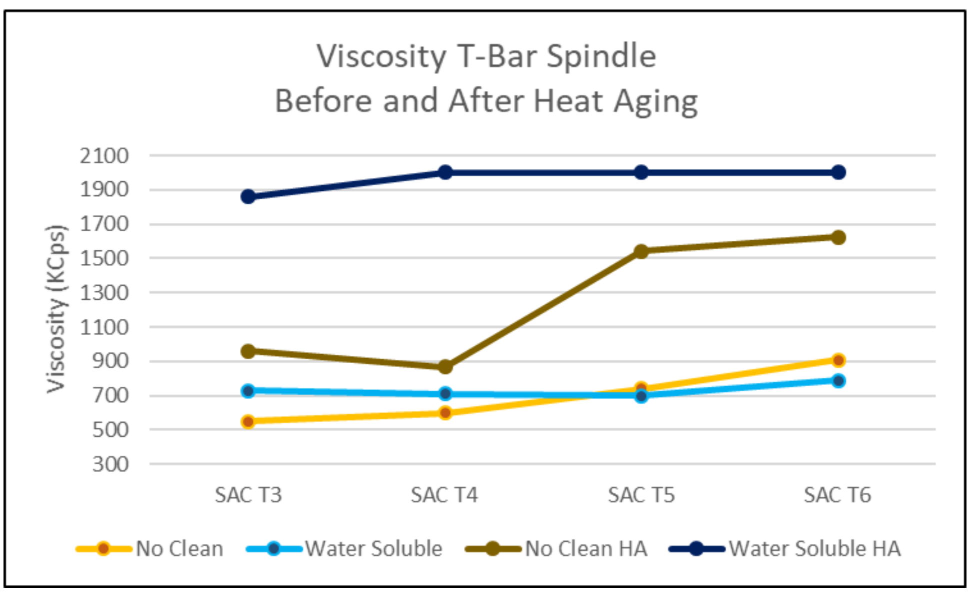


Figure 30 – Viscosity T-Bar Spindle Results Before and After Heat Aging

The viscosity of the water-soluble solder pastes increased dramatically with heat aging. The water-soluble solder pastes all reacted to the point of being unusable. The no clean solder pastes showed some stability in this test. The no clean type 3 and 4 solder pastes increased in viscosity roughly 40 to 70% but were still usable. The no clean type 5 and 6 solder pastes increased in viscosity by more than 100%. These solder pastes were thick but printable with an increase in blade pressure.

The IPC solder balling test was run on the heat aged solder pastes and the results are shown below (Table 11)

Table 11 – IPC Solder Balling Performance of Solder Pastes After Heat Aging

	No Clean		Water Soluble	
	Initial	After 4 Hrs	Initial	After 4 Hrs
T3	Acceptable	Acceptable	Acceptable	Acceptable
T4	Acceptable	Acceptable	Acceptable	Unacceptable
T5	Acceptable	Unacceptable	Acceptable	Unacceptable
T6	Unacceptable	Unacceptable	Unacceptable	Unacceptable

Initially the fresh solder pastes gave acceptable solder balling for all solder powder sizes except type 6 which was unacceptable. After heat aging, the solder the type 5 and 6 no clean solder pastes gave unacceptable results. The type 4, 5, and 6 water-soluble solder pastes gave unacceptable results. It is clear from this testing that the smaller solder powder sizes are more susceptible to reaction over time, which may lead to a shorter usable shelf life.

The JIS tack force was measured on the heat aged solder pastes. The tack force data for the fresh and heat aged solder pastes is shown below (Figure 31).

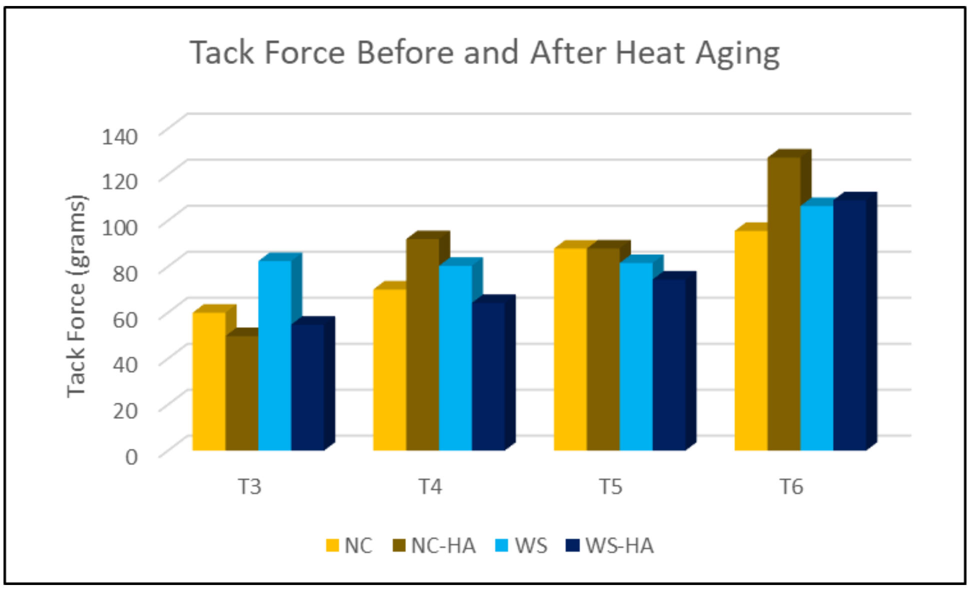


Figure 31 – JIS Tack Force Before and After Heat Aging

The no clean type 3 solder paste decreased slightly in tack force after heat aging. The type 4 and 6 no clean solder pastes increased in tack force with heat aging. The tack force of the type 5 solder pastes were stable with respect to heat aging. The water-soluble type 3 and 4 solder pastes showed a decrease in tack force with heat aging. The water-soluble type 5 and 6 solder pastes showed very little change in tack force with heat aging. This shows that tack force is not necessarily affected by heat aging and may not change through the shelf life.

Print performance was measured before and after heat aging. The water-soluble solder pastes were too viscous to print so the data below is only for the no clean solder pastes (Figure 32).

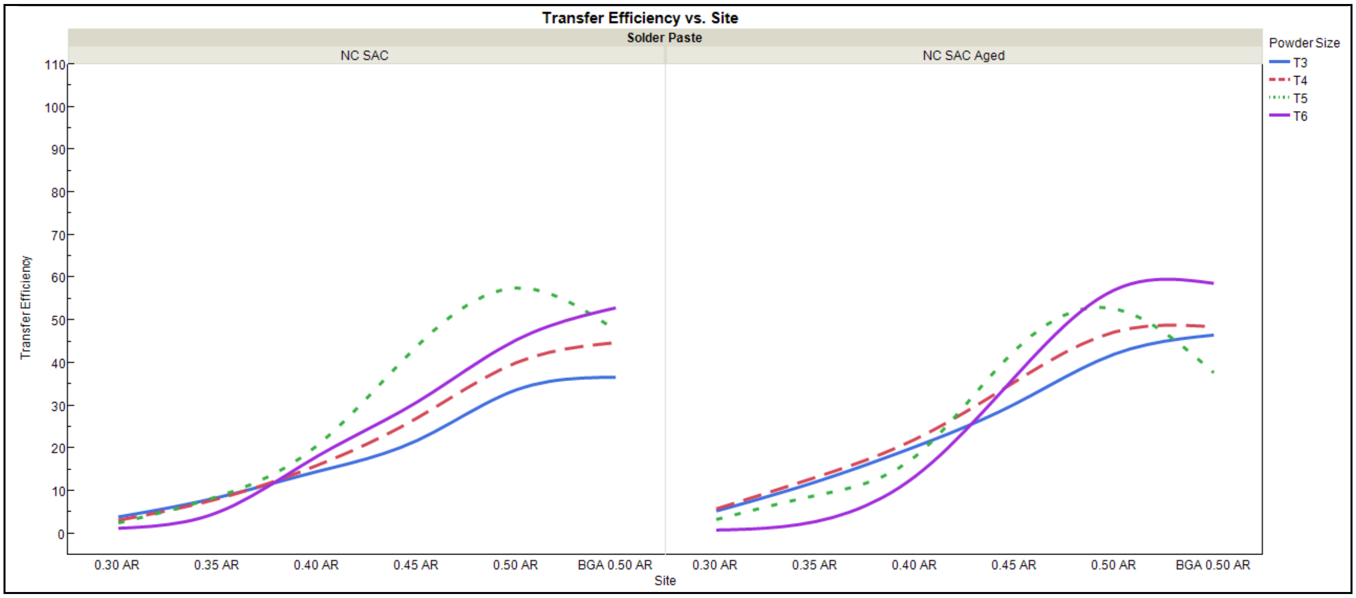


Figure 32 –Print Performance for the No Clean Solder Pastes Before and After Heat Aging

These transfer efficiency values are statistically the same before and after heat aging. Heat aging increased the viscosity of the no clean solder pastes but did not affect printability. By comparison heat aging increased the viscosities of the water-soluble solder pastes to the point where they were not printable.

The reflow performance of the no clean heat aged solder pastes was measured using the PR test board and compared to the fresh no clean solder pastes. The wetting data is shown below (Figure 33).

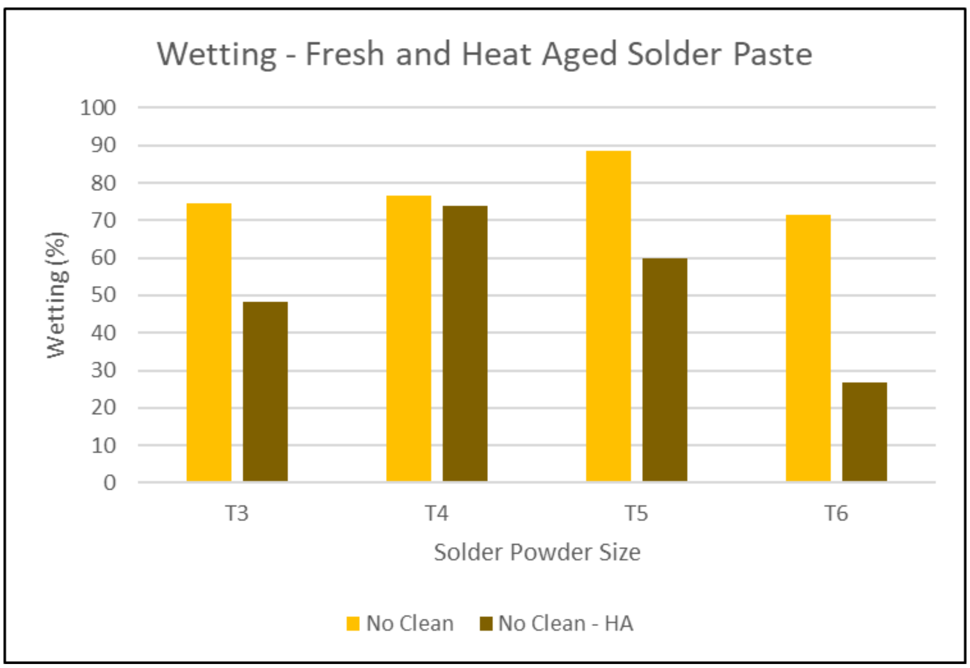


Figure 33 –Wetting for the No Clean Solder Pastes Before and After Heat Aging

Wetting performance decreased with heat aging for each of the no clean solder pastes. The largest decreases were with the type 5 and 6 solder pastes. Solder balling performance with respect to heat aging is shown below (Table 12).

Table 12 –Solder Balling Performance of Solder Pastes Before and After Heat Aging

Solder Paste	Overprint with <5 Solder Balls	Overprint with <10 Solder Balls	Overprint with <5 Solder Balls After Heat Aging	Overprint with <10 Solder Balls After Heat Aging
No Clean Type 3	1200%	1200%	1100%	1250%

The no clean solder pastes with type 4, 5, and 6 solder powders were not measurable with these criteria and therefore are not shown in this table. The solder balling performance did not change significantly with heat aging of the no clean solder pastes. Representative solder balling pictures are shown below (Figure 34).

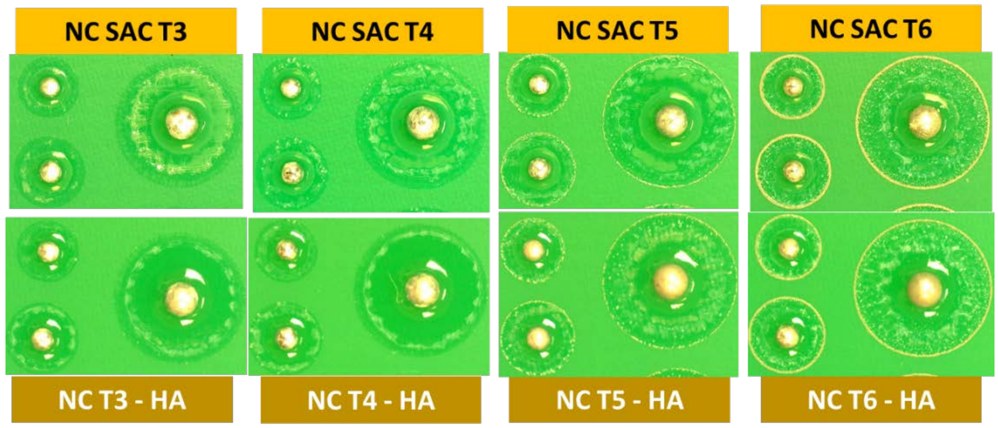


Figure 34 – Solder Balling of the No Clean Solder Pastes Before and After Heat Aging

The graping percentages were measured after heat aging and compared to the fresh no clean solder pastes (Figure 35).

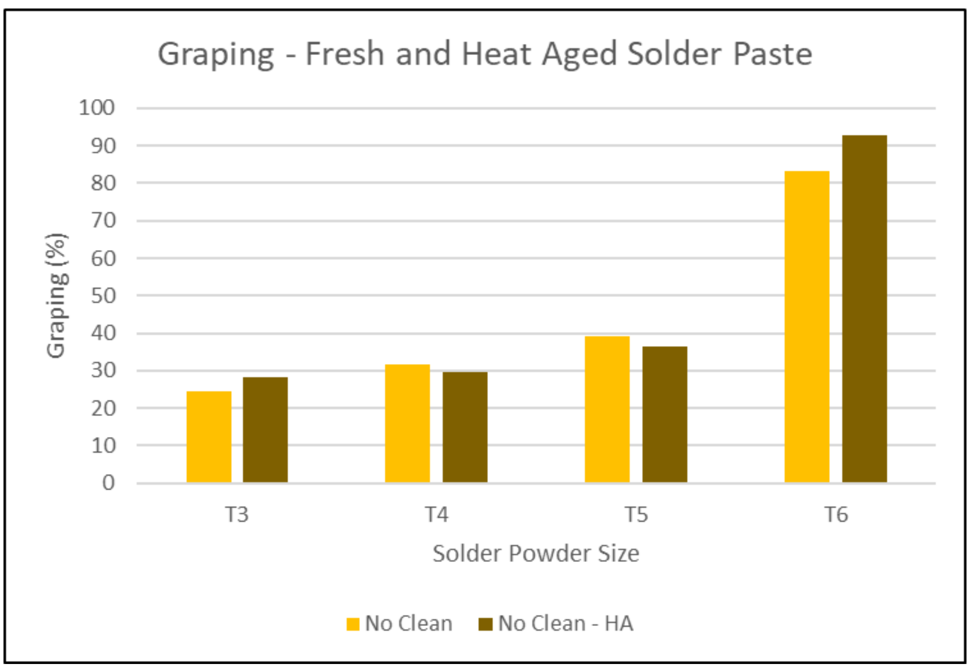


Figure 35– Graping of the No Clean Solder Pastes Before and After Heat Aging

The graping percentages were similar for the fresh and heat aged type 3, 4, and 5 no clean solder pastes. The type 6 no clean solder paste showed a slight increase in graping due to heat aging.

The decrease in wetting and graping performance with heat aging shows that the solder pastes with the smaller solder powder sizes loose activity more quickly than the larger solder powder sizes. The shelf life may be shortened for solder pastes made with smaller solder powder sizes.

Conclusions and Recommendations

Solder powder size certainly has an effect on solder paste performance. It is well understood that one cannot use every solder powder size with a particular solder paste. The solder paste must be formulated to work properly with the desired solder powder size. Here are recommendations for optimal use of each solder paste and solder powder size based on performance in this work.

Slump (IPC)

All of the solder pastes performed well in the IPC slump test except for the no clean type 6 and the water-soluble type 5 and 6 solder pastes which failed the hot slump test. The flux concentration of these solder pastes was significantly higher with the smaller solder powder sizes which changes the rheology of the solder pastes. This indicates that the smaller solder powder sizes may increase the potential for bridging during reflow.

Solder Balling (IPC)

The type 3, 4, and 5 water-soluble and no clean solder pastes gave acceptable solder balling in the IPC test. Both the no clean and water-soluble type 6 solder pastes failed the IPC solder balling test. Type 6 solder powders have a relatively large oxide content as compared to the other solder powder sizes. The type 6 solder pastes are more susceptible to solder balling than the other solder pastes.

Printing Minimum Area Ratio

In general, printed solder paste volume increased with decreasing solder powder size. The transfer efficiencies increased by roughly 5% for each decrease in solder powder size, which corresponded to a 0.05 change in area ratio. Here are the recommendations for minimum area ratio for each type of solder paste:

- Type 3 no clean solder paste: 0.60 AR
- Type 4 no clean solder paste: 0.55 AR
- Type 5 no clean solder paste: 0.50 AR
- Type 3 and 4 water-soluble solder paste: 0.60 AR
- Type 5 water-soluble solder paste: 0.55 AR

Please keep in mind that the print parameters, stencil technology and design will affect printability and these minimum area ratios.

Pauses in Printing and Stencil Life

The no clean type 5 and 6 solder pastes showed the largest drop in transfer efficiency after a pause of 16 hours on the stencil. The water-soluble type 5 and 6 solder pastes showed a smaller drop in transfer efficiency after a pause of 16 hours on the stencil. It is not recommended to print solder paste after a 16 hour pause and 24 hours total time on the stencil. All of the solder pastes tested responded well to pauses in printing of 1, 2, and 4 hours, and showed good printability through 8 hours on the stencil. Based on this work, the recommended stencil life for all of the solder pastes tested would be 8 hours. Environmental conditions, addition rate of fresh solder paste, and other factors will affect this stencil life.

Reflow Performance (PR Test Board)

The wetting or spread of the no clean solder pastes was consistent regardless of solder powder size. The wetting or spread of the water-soluble solder pastes decreased with decreasing solder powder size but was higher overall than the no clean solder pastes. The solder balling performance for the no clean and water-soluble type 3 and 4, and 5 solder pastes was acceptable for most electronic assemblies. The solder balling performance for the no clean and water-soluble type 6 solder pastes was excessive, as was seen in the IPC solder balling test. The graping performance for the no clean and water-soluble type 3, 4 and 5 solder pastes was very good. The graping was unacceptable for both of the type 6 solder pastes. Use of type 6 solder powder in a solder paste may lead to excessive solder balling and graping.

Voiding Performance

All of the no clean solder pastes showed identical low voiding behavior. The water-soluble solder pastes showed increasing voiding as the solder powder size decreased. Voiding is affected by solder powder particle size and a host of other factors. Voiding behavior may change with a change in solder powder size, and the process may require adjustments to minimize voiding.

Stability of the Solder Pastes

The tack force of all of the solder pastes was stable through 48 hours but dropped over 72 hours. The stability of the tack force is well beyond a normal amount of time between printing and reflow. The reflow performance after a 24-hour hold was stable for the type 3, 4 and 5 solder pastes.

The type 6 solder pastes gave questionable reflow performance both before and after the 24-hour hold. A 24 hour hold prior to reflow is not recommended, but shows that the type 3, 4, and 5 solder pastes were environmentally stable. More extreme environmental conditions will change the stability of the solder pastes.

Heat Aging of the Solder Pastes

The viscosity of the no clean type 3 and 4 solder pastes increased with heat aging, but they were easily printable. The viscosity of the type 5 and 6 no clean solder pastes increased significantly but they were printable by adjusting the print parameters. The viscosity of all of the water-soluble solder pastes increased dramatically with heat aging and the pastes were not printable. The print performance of the no clean solder pastes was essentially unchanged with heat aging. Heat aging caused failures in the IPC solder balling results for the no clean type 5 and 6 solder pates, and the water-soluble type 4, 5, and 6 solder pastes. The tack force was stable before and after heat aging for all of the solder pastes. Only the no clean solder pastes were printed and reflowed after heat aging. Heat aging caused the wetting performance to decrease for all of the no clean solder pastes. Solder balling performance for the no clean solder pastes worsened a little with heat aging. Graping performance was unchanged through heat aging of the no clean solder pastes.

These results show that the reactivity of the solder pastes increases as the solder powder size decreases. This indicates that the shelf life is shorter for solder pastes made with the smaller solder powder sizes, especially type 5 and 6 solder powders.

Summary

This work shows major differences in solder paste performance for no clean and water-soluble solder pastes using SAC305 type 3, 4, 5 and 6 solder powders. When solder pastes with smaller solder powder sizes are used, the users should be aware of these performance differences so that the SMT process can be tuned accordingly.

Solder paste manufacturers are looking ahead to the future needs of the electronics industry. Smaller solder powder sizes are becoming increasingly common for miniaturized electronic applications. Solder paste manufacturers are formulating products for use with the smaller solder powder sizes in order to address these needs.

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