`THE INFLUENCE OF ASPECTS OF SOLDER PASTE FORMULATION AND SOLDERING PROCESS FACTORS ON VOIDING UNDER LARGE QFN DEVICES

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ABSTRACT

When QFN and other bottom-terminated devices are soldered using solder paste at atmospheric pressure, some voiding is always observed. The process of void formation during reflow is dynamic; voids, primarily formed from volatilized flux materials and soldering reaction products, grow, coalesce and then vent at the margins of the solder joint while the solder is molten. As flux materials are an underlying cause of void formation, then solder paste formulation has considerable potential to influence the degree of voiding finally observed. This paper summarizes some studies concerned with the influence of an aspect of solder paste formulation – solvent choice - in conjunction with some process factors on voiding under a large (12 mm x 12 mm) QFN device.

A range of three solder pastes with different solvent systems were evaluated for voiding during multiple tests; these results were aggregated and show the effect of formulation and two process factors (profile and aperture design) on voiding. Following this, a general factorial experiment was used to more formally evaluate a similar range of pastes and process factors, also including three common board finishes.

Key words: Voiding, BTC, QFN, Solder Paste, Reflow, X-ray.

INTRODUCTION

The choice of solvent in a solder paste flux is an important consideration and, generally, high boiling point organic solvents are chosen. The solvent must be capable of dissolving the resins and other materials used in the flux at a concentration acceptable for the required application, but must also meet several other requirements. One of these requirements is that it should have a relatively low evaporation rate at room temperature to achieve acceptable open time and ensure the product is sufficiently robust to printer pause time (abandon time) where the paste is intended for application by open-squeegee printing. It is also known that the solvent selection influences voiding performance. This paper describes research concerned with the influence of solvent selection on voiding, specifically under QFN components.

Recently, a number of studies have investigated the reflow process under packages and QFNs using near real-time[1] X-ray analysis. These investigations serve to give insight into the dynamic nature of void formation and dissipation under such devices.

The results of two studies were used by the authors to gain understanding of voiding progression under packages. One study presented work conducted at the Electronics Packaging Lab, Technische Universität Dresden, Germany [1,2]. The second study presented similar work undertaken by Henkel in conjunction with Dage, which manufactures a heating chamber (heated stage reflow simulator) which can be fitted into an X-ray machine to follow the soldering process. Using this equipment in conjunction with a Dage Quadra 5 X-ray inspection system, the soldering of large (12 mm square) QFNs was imaged during reflow.

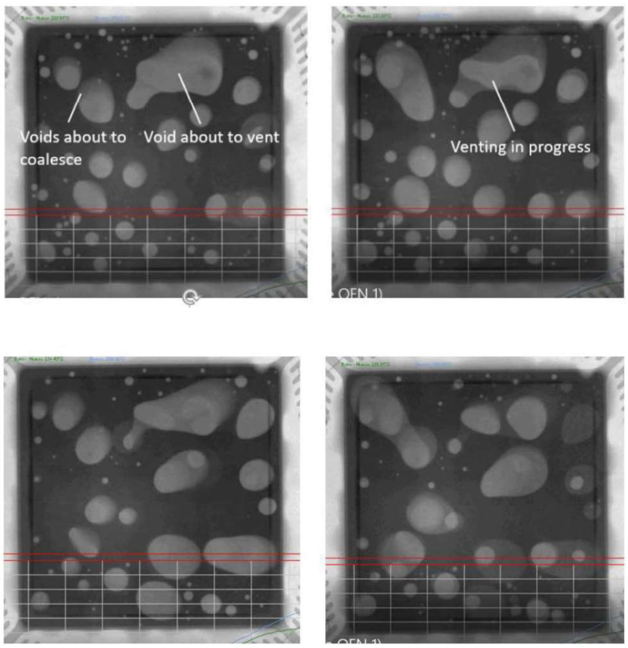
When soldering QFNs using a typical solder paste, several stages can be identified in the formation of the solder joint under the central pad. During preheating, some voids form in the solder paste prior to reflow and slowly grow; this void growth can lead to spreading of the paste deposits as pressure is exerted on the solder paste deposit. However, after some time, further void growth is not as readily observed; presumably, this stops once a pathway through the unreflowed solder paste has been established, allowing the gas to vent.

On reflow, the process generally becomes more dynamic. Voids form and grow within the molten solder and these

[1] Near real time as there are limitations on the frame rate due to the time required to capture a good-enough X-ray image

may then coalesce with nearby voids. As the voids coalesce and grow, they may reach the margin of the solder joint where they rapidly deflate as the gases are vented. The venting process is somewhat faster than the available video frame rate (about 30 frames per second), but the frame rate is sufficient to observe the disappearance of the voids as they reach the margin of the forming solder fillet. Some still images are shown in Figure 1 to illustrate the progression of this venting process.

Figure 1 Still Images of Voiding During Reflow



As soldering progresses the rate of void formation and of venting noticeably slow. This is presumably because less volatile flux material is available in the latter part of the reflow process to drive void formation (and hence coalescence and venting). The voids present at the end of this process form the final solder joint and are then frozen in place as the solder cools below the freezing point of the alloy. Some contraction of the voids is observed during the period where the solder is cooling above its freezing point as the gas within the void cools. Further work to use real-time X-ray analysis to investigate void formation will be undertaken in the future. However, for the purposes of this paper, the summary above has been included to provide background into the mechanism of void formation and dissipation observed.

Results of several separate tests on a wide range of solder pastes over many years indicated that voiding is influenced by solvent choice. Recently, work was conducted to gain additional understanding of the effects of solvent selection on voiding, particularly when soldering bottom-terminated components such as QFNs.

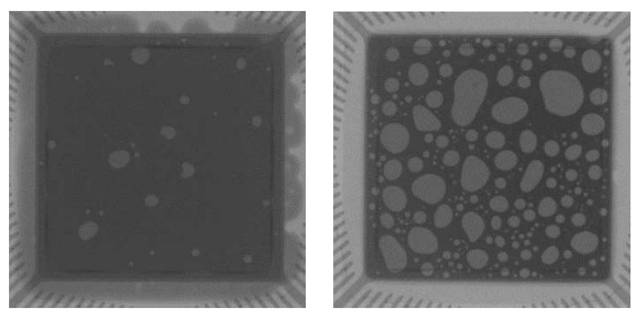
EFFECT OF SOLVENT ON QFN VOIDING

An illustrative study gives some idea as to the possible range of results. Using a solder paste formulation that was known to give very low voiding under packages and dies, a sample of this paste flux was prepared. Using a small-scale laboratory mixing method consistent with the original formulation, a modified material was formulated; the only alteration was the substitute of solvent for a higher-boiling solvent blend. The boiling point of the original solvent was approximately 230º C and the substituted solvent boiled over the range of 270° C to 305º C. Samples of SAC305 solder paste were prepared in the laboratory using the same batch of solder powder and these pastes were used to solder 12 mm square QFN100 devices to an OSP-finish copper test circuit board.

The QFNs used were tin-finish QFN100s supplied by Practical Components (part 30809) with an 8.2 mm square central pad. The solder paste was applied as a single rectangular deposit using a 100 µm thick stencil. The parts were soldered using a typical convection reflow oven using a linear profile (Figure 3.) in an aerobic atmosphere. The QFNs were inspected for voiding using a typical X-ray inspection machine, some representative images from this work are shown in Figure 2.

Figure 2 Examples of X-ray Inspection of QFN100

Left: orginal formulation, Right: high-bpt. solvent blend substituted.



Mean voiding (four trials): 4.2%

Mean voiding (four trials): 40.1%

This case illustrates that solvent potentially has a large effect. However, it must be noted that the original paste formulation is intended for application by dispensing. In this case, the selection of a lower boiling point solvent is feasible since solvent loss due to evaporation is minimal from the cartridges in which the paste is typically packed. The range of voiding achievable *by the method of solvent selection* in a practical solder paste for printing application is, perhaps, not so large due to considerations such as maintaining acceptable open time and response to printer pause. Other aspects of the formulation also influence voiding and compromise solutions are possible.

VOIDING OF RELATED PASTE FORMULATIONS WITH DIFFERENT SOLVENTS

Several separate voiding tests using similar printing and reflow conditions were performed over a period of several months using three solder pastes, referred to here as pastes A to C. These pastes were all halogen-free, lead-free (SAC305 alloy, IPC Type 4 powder size) and were intended for application by printing. In each case, the formulations differed in the solvent systems used. A similar set of additional ingredients such as resins, activators and viscosity modifiers were used. However, some adjustment to the total solids content[2] of the fluxes was required to account for the varying solubility of these ingredients in the different solvent systems. The collected results include a number of batches of each paste.

The solvents were selected to cover a relatively wide boiling range while remaining practical formulations for application by printing. Open time evaluations were performed on the pastes at each extreme by carrying out a 1000-cycle print test lasting approximately 8 hours. The print performance of the pastes was assessed by printing 10 boards initially and at the completion of the 1000 cycle test. Printing was assessed by measuring the process capability of printing of several different aperture patterns. Data is presented below (Table 1) for a 0.5 mm pitch CSP device. Note that the pastes were tested separately on different printer models, so the Cpk values are not directly comparable and may represent process differences. There was no evidence of a change in Cpk following the 1000-cycle test for either paste.

Table 1 Open time (Process capability, 0.5 mm CSP) for Pastes A and C

Paste	Cpk (0.5 mm CSP) Initial	Cpk (0.5 mm CSP) After 1000 cycles
Paste A	1.9	2.1
Paste C	1.5	1.5

Two reflow profiles (refer to Figure 3 and Table 2) were used with a typical convection reflow oven (Heller 1826MKV). One of these was a relatively short linear profile intended to represent the sort of process used to solder a light assembly. The other was a longer profile with a substantial pre-heat soak intended to represent the assembly of a board requiring more thermal input during reflow. The profiles also represent different approaches sometimes used to modify voiding performance in real processes: a soak profile is sometimes used to counter voiding by the mechanism of volatilizing more of the flux ingredients- primarily the solvent- prior to reflow. These profiles were used throughout the work described in this paper.

Figure 3 Reflow Processes Used

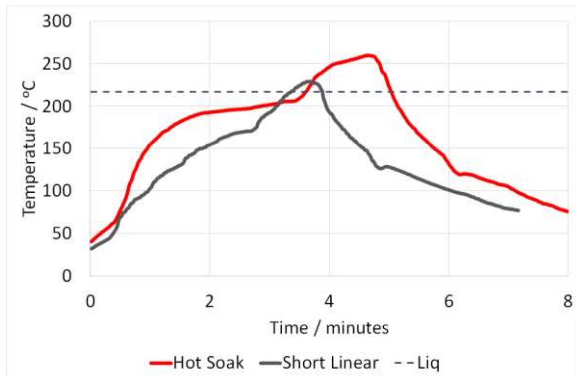


Table 2 Summary of Reflow Profiles

Atmosphere: air	**Linear**	**Soak**
Time above 217ºC /s	32	86
Time between 150ºC and 200ºC /s	77	100
Peak temperature /ºC	230	259
Time to peak /s	245	310

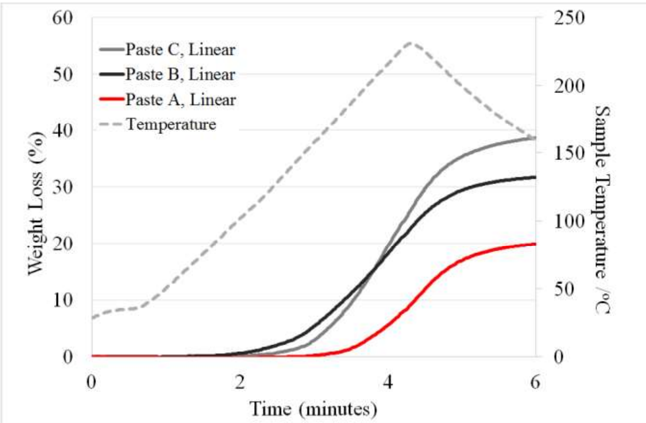
Thermogravimetric analysis (TGA) was performed on small samples of the solder paste fluxes (in the range 4 mg to 9 mg). The heating profiles used were created to simulate the linear and soak profiles used for the reflow test. The TGA weight loss curves are shown in Figure 4 and illustrate the different volatilization behavior of the three fluxes when heated to similar temperatures over a similar reflow process timescale.

Figure 5 shows an overlay of the measured reflow profiles used for assembly and the TGA heating profiles (sample temperature). Note that the TGA profile for the soak profile is a reasonable approximation during the preheat section. However, there is considerable divergence during the reflow section of the profile which is due to limitations on the heating rate achievable with the equipment used.

[2] The metal content of the pastes however was similar (88.5% wt.)

Figure 4 Weight loss (TGA) of fluxes from pastes A to C using simulated linear and soak reflow profiles

Weight loss (TGA) for Simulated Linear Profile



Weight loss (TGA) for Simulated Soak Profile

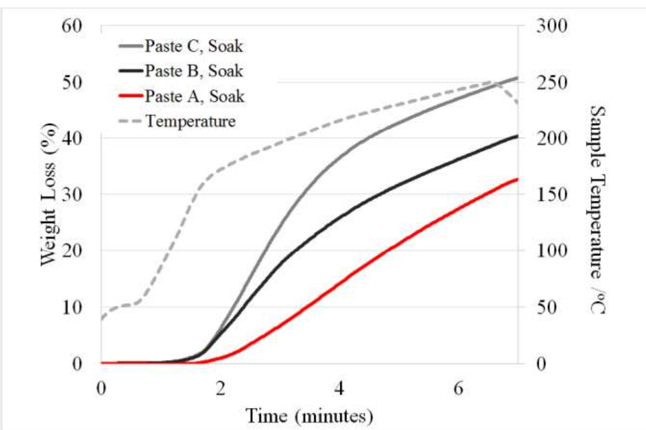
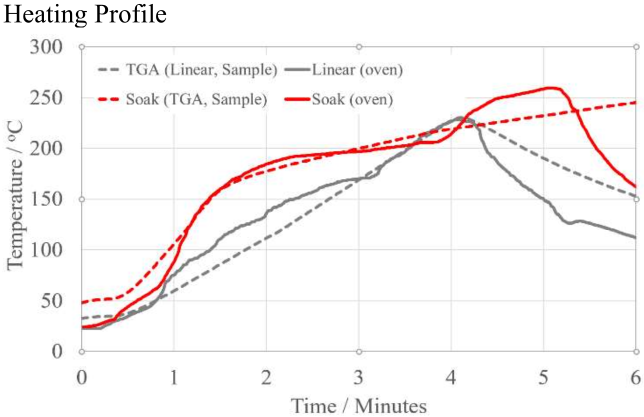
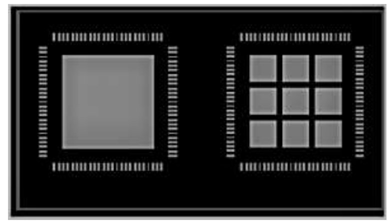


Figure 5 Comparison of TGA Heating Profile and Oven Heating Profile



The components used were the same 12 mm square QFN100 devices. Solder pastes were printed onto a test PCB with OSP copper finish[3] using a 100 µm thick stencil. Two different aperture designs were used; a rectangular aperture of the same size as the board pad and a 3x3 windowpane pattern with total coverage of about 75% of the board pad (Fig. 6).

Figure 6 Aperture Designs Used for QFN100



Left: 1x1 (rectangle, full coverage), Right 3x3 (windowpane, 75% area coverage)

Following the board builds, measurements of the voiding under the central pad of the QFNs were made using an X-ray inspection machine under similar conditions. Void results were expressed as the sum of the area of all voids as a percentage of the total area of the solderable pad. The voiding results are summarized in Tables 3, 4 and5 and Figures 7, 8 and 9.

Table 3 Total Observations for Aggregated Data

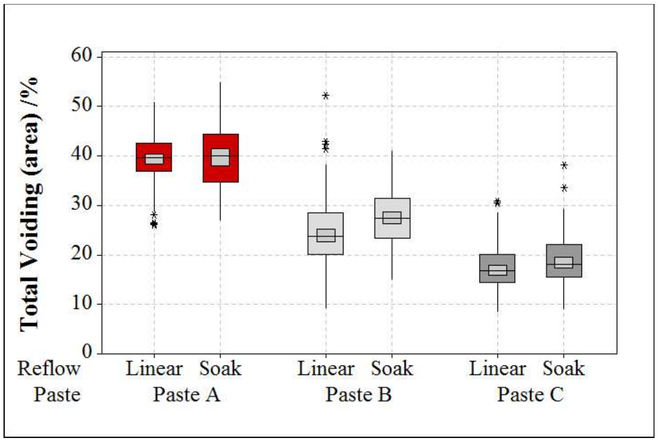
Paste	*Rectangular*	*3 x 3*	*Total*
A	78	78	156
B	136	136	272
C	144	144	288

Table 4 *ANOVA summary for aggregated data*

Factor	***F-value***	***p-value***
Paste (A, B, C)	767	<0.001
Reflow (Linear- Soak)	17	<0.001
Aperture (1x1, 3x3)	7	0.002
Lack-of-fit		0.25
R^2 (model) 0.69		

[3] Glicoat SMD-F2(LX) was used throughout.

Figure 7 Boxplots of Voiding, by Paste and Profile



Inset boxes represent 95% CI for the median. Refer to Table 3 for n.

Figure 8 Boxplots of Voiding, by Paste and Aperture

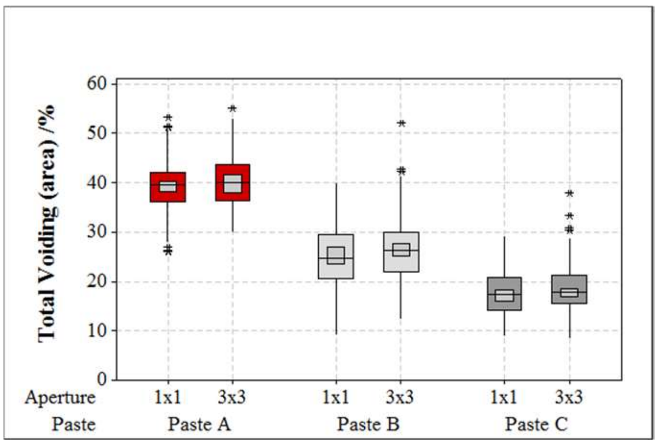


Figure 9 Main Effects Plots of Voiding

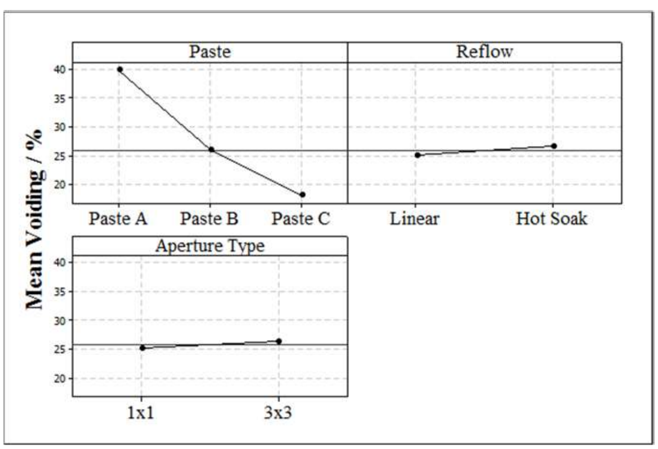


Table 5 Summary of Effect Sizes

Factor	Max. difference between means	Cohen's *d*	Size of effect
Paste	21.8%	3.4	Very large
Reflow profile	1.7%	0.2	Small
Aperture	1.1%	0.1	Small

The findings illustrate that the effect of paste, reflow and aperture were significant, although only the effect of paste was large. A summary of the sizes of the effects are shown in Tables 4 and 5 above. The effect of profile was small, with the mean voiding being a little higher for the soak profile. It should be noted that the pastes used in this work were of a generally similar type. Other studies [3] have shown that profile may interact with paste type.

GENERAL FACTORIAL DoE TO EVALUATE PASTES A-C

Results on pastes A, B and C showed that the effect of paste formulation was large. However, the results were collected over several months, measured on separate occasions and aggregated for analysis. A general factorial DoE was designed to test these same pastes in a more systematic manner using the same two reflow profiles and three PCB finishes- OSP copper, immersion tin and immersion gold over electroless nickel (ENIG).

The experimental design chosen was a split-plot general factorial design replicated three times (54 runs). The experimental runs were generated using a commercial software package for experimental design. Pastes A, B and C were the same solder paste types for which data was collected and the results already described but, in this case, the three pastes were from a single batch of each.

For each experimental run, a single test board was printed with the required paste through a 100 µm thick stencil and components were mounted using a pick and place machine. For each board, two QFN100 components and two smaller QFN28 components were placed. Two different aperture types were used within each board - a single rectangular aperture and a 3x3 'windowpane' aperture design as previously described. (Figure 6)

Due to the slow response of the reflow oven to profile changes, the reflow profile was cumbersome to randomize. A split-plot experimental design was chosen where paste and board finish were randomized, but the profiles used were split into three blocks. A summary of the experimental matrix is shown in Table 6.

The responses analyzed for the experiment were as follows: for each run there was one value- the total voiding measured for the QFN component with each aperture design. (In this experiment, the aperture design was not a factor. However, responses for the two aperture designs were analyzed separately.)

Response	Description
1	QFN100 area voiding rectangular aperture
2	QFN100 area voiding 3x3 windowpane aperture
3	QFN28 area voiding combined results

Table 6 DoE Matrix

Factor	a: Profile	B: Paste	C: Finish
Levels	2	3	3
HTC[4]?	Yes	No	No
Level 1	Short linear	A	OSP
Level 2	Hot soak	B	Imm. Sn.
Level 3		C	ENIG

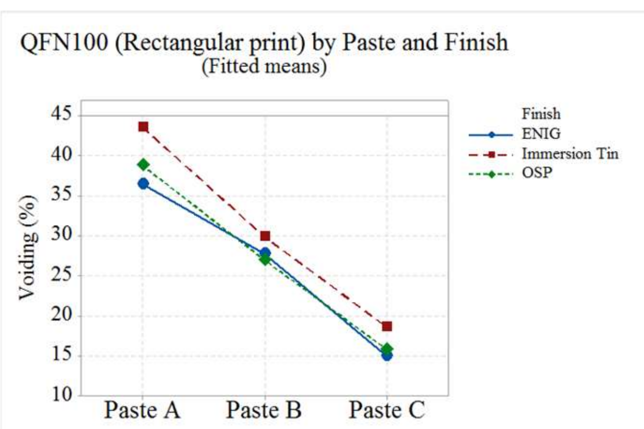
Summary of Results for QFN100 Component

Table 7 ANOVA summary for Voiding, Rectangular Aperture

Effect	*F*-value	*p*
B- Paste	103	<0.0001
C- PCB Finish	4	0.024

R^2 (model) =0.80

Figure 10 Summary Plot for Voiding, Rectangular Aperture (Paste and PCB Finish)



[4] Hard-to-change

Table 8 ANOVA summary for Voiding, Windowpane Aperture

Effect	*F*-value	*p*-value
B- Paste	59	<0.0001
C- PCB Finish	9	0.001
aC (profile – board finish)	4	0.025

R^2 (model) =0.75

Figure 11 Main Effects Plot for QFN100, Windowpane Aperture

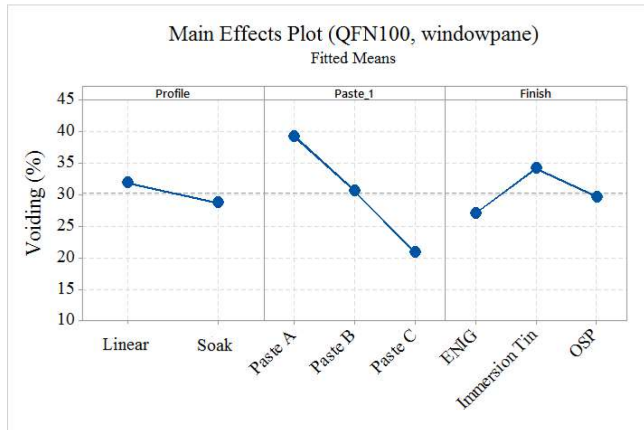
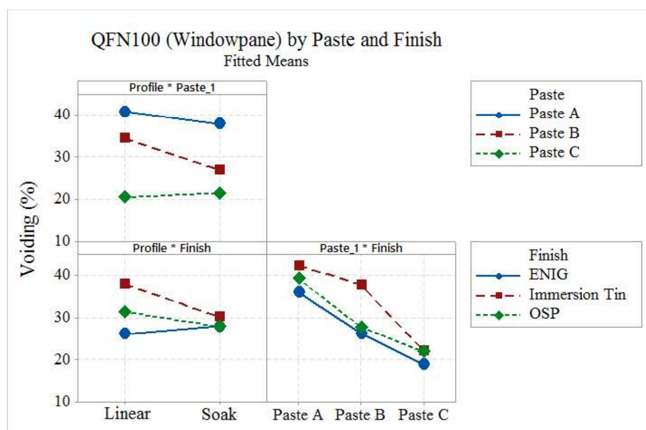


Figure 12 Interaction Plot for QFN100, Windowpane Aperture (Paste, PCB Finish and Profile)



Discussion (QFN100)
For the larger QFN100 device with a simple rectangular print pattern, there was good evidence of a large paste formulation effect and a smaller PCB finish effect, most of which is explained in this case by the slightly higher voiding obtained with immersion tin finish (Table 7, Figure 10). It is more likely that this small effect is due to some aspect of this batch of boards rather than a generalizable result. Another published study suggested that OSP copper tended to give higher voiding than a tin finish [3].

Where a 3x3 windowpane aperture pattern was used, the relative size of the effect of PCB finish was somewhat larger and there was a significant interaction between the reflow profile and the board finish (Table 8, Figures 11 and 12). One possible explanation is that where more complex print patterns are used, paste wetting behavior tends to have more influence on the final voiding result.

Summary of Results, QFN28 Component

Table 9 ANOVA Summary for Voiding

Effect	*F*-value	*p*-value
B- Paste	8	<0.001
a- Profile	8	0.05
aC (profile – board finish)	5	0.01
aB (profile- paste)	20	<0.001

R^2 (model) =0.62

Figure 13 Main Effects Plot for QFN28 Component.

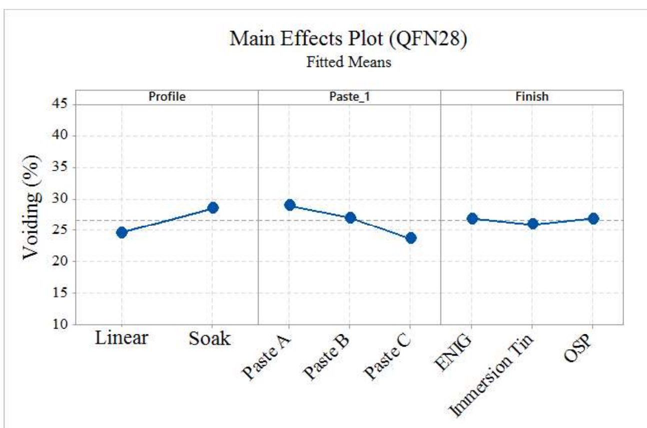
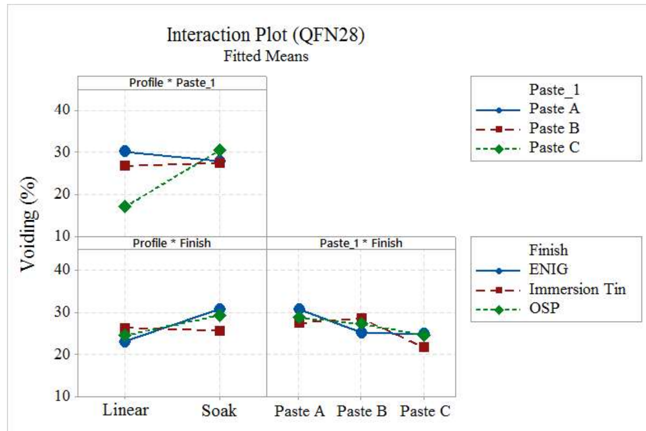


Figure 14 Interaction Plot for QFN28 (Paste, PCB Finish and Profile)



Discussion (QFN28)
Results are summarized for the QFN28 component in Table 9 and Figures 13 and 14. The effect of paste was smaller for the QFN28 device. Reflow profile and the profile-paste interaction were significant for this component. The profile-paste interaction had the largest effect, as paste C shows markedly reduced voiding following reflow with the linear profile. In this case, the pastes were indistinguishable following reflow with the hot soak profile.

CONCLUSIONS

Solder paste formulation was found to have a large effect on voiding under a large QFN component. For related paste formulations, solvent choice was shown to be particularly influential, leading to changes in voiding likely to have practical significance. Two separate studies on a similar range of pastes gave broadly similar conclusions. For the QFN100 device, the effect of profile and print pattern was, if statistically significant, small in comparison to the effect of the paste.

The relative effect of paste formulation- while significant- was smaller for a 5 mm square QFN28 component. This suggests that some aspect of the mechanism involved in void formation and dissipation under QFNs or other BTCs might differ for smaller components. One possibility is that, due to the shorter travel distance required for void venting, there may be an increased likelihood of successful venting from under a smaller component.

Discussion (Effect of Profile)

The effect of profile - if significant- was relatively small, which is an observation that is more difficult to explain. The TGA data show that more volatilization of a given flux occurs during the (simulated) soak-type profile and, since the fluxes themselves vary in this aspect, it might be expected that reflow using the soak profile would result in lower voiding.

Figure 5 shows that the TGA heating profiles approximate the preheat section of the reflow profiles used for assembly. The profile simulation for the linear profile was similar to the measured profile. However, the simulated soak profile was more difficult to achieve in practice: while the preheating part of the profile was closely approximated, the reflow section (above 217^{o} C) deviated substantially from the measured oven profile. This was a result of limitations of the heating rate achievable in the instrument.

A few general points can be stated. The soak profile- as expected- results in greater flux weight loss prior to reflow (217^{o}C), Table 10.

Table 10 Weight loss (preheat only), TGA.

	Weight loss (%) below 217^{o}C		
	Flux A	Flux B	Flux C
Wt. loss (linear)	6	19	21
Wt. loss (soak)	15	26	37

The fluxes lose more weight to volatilization in the order Paste A < Paste B < Paste C.

The time at which liquidus is achieved is similar for both profiles so pastes are entering the reflow phase at similar times, but with relatively more weight loss during preheat following the soak profile.

It may be that two or more competing mechanisms could explain the lack of profile effect. It is possible that more detailed information on the mechanisms involved might be obtained by making further use of near real-time x-ray analysis, which would be an interesting topic for further study.

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