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QUAD FLAT NO-LEAD PACKAGE WITH DIFFERENT THERMAL PROFILES AND SOLDER PAD FINISHING FOR VOID MINIMIZATION

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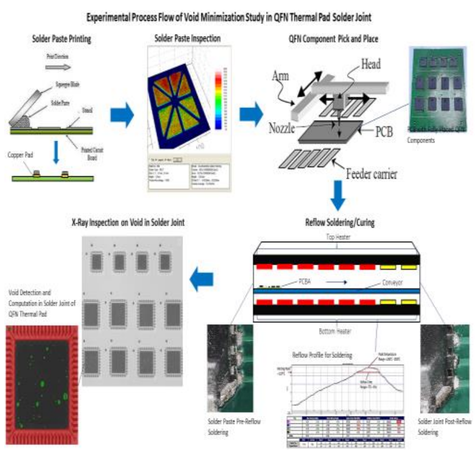
Graphical abstract



Abstract

Voiding in solder joints is a common problem that occur in electronic packaging, specifically for bottom terminated component (BTC). Quad Flat No-Lead (QFN) is a good example of BTC component that susceptible to void. Thus, QFN component thermal pads were used as the test vehicle in this voiding assessment. The objectives of this study are to analyze the influence of the variables from every parameter evaluated in the experiment on voiding area in QFN thermal pad solder joint and obtain the best combination of variables that can minimize the total void area percentage inside QFN thermal pad solder joint down to below 5%. In this study, several variables and their impacts on voiding based on the literature review were studied. No clean lead-free solder paste of SAC305 composition was employed in this experiment. Various stencil patterns were tested, including Window-Pane, Round, and Triangle/Polygon. The influence of pad surface finishing of the test board on the voiding reduction was analyzed in this study. The effects of convection reflow of various profiles and atmospheres were also considered. All the variables were setup for the experiment execution which begins by solder paste printing, solder paste inspection, component pick & place, convection reflow soldering, Xray inspection, void data extraction & analysis, and finally void results compilation. The results shown that reflow profile Ramp-To-Spike (RTS) Long Reflow Time High Peak Temperature gave lesser void area % than Ramp-Soak-Spike (RSS) Long Soak and RTS Normal profiles. Reflow with nitrogen atmosphere found to yield lesser void area % than air. It was shown that Organic Solder Preservatives (OSP) and Immersion Silver (Im-Ag) PCB pad finishes gave much lesser void area % than Electroless Nickel Immersion Gold (ENIG) finish. The stencil designs of window-pane, round and triangle/polygon shown that all three of them have insignificant difference of impact on void area %. From the results, it can be proposed that combining the pad finishing with OSP and Im-Ag, RTS Long Reflow time high peak temperature reflow profile, and nitrogen atmosphere can significantly reduced the void, regardless of the stencil design used.

Keywords: Voids, solder joints, reflow profile, solder powder, stencil design

Abstrak

Lompang udara dalam sambungan pateri adalah masalah biasa yang berlaku dalam pakej elektronik, khususnya untuk komponen terminal bahagian bawah (BTC). Pakej empat segi rata tanpa kaki (QFN) ialah contoh yang baik bagi komponen BTC yang mudah terdedah kepada lompang udara. Oleh itu, pad haba komponen QFN digunakan sebagai peralatan ujian dalam analisa kelompangan udara ini. Dalam kajian ini, beberapa pembolehubah dan kesannya terhadap lompang berdasarkan kajian literatur telah diselidiki. Pateri bebas plumbum tanpa bersih bagi komposisi SAC305 digunakan dalam eksperimen ini. Pelbagai reka bentuk stensil terdiri daripada segiempat sama, bulat dan segitiga/poligon telah diuji. Pengaruh pelbagai kemasan permukaan pad papan ujian terhadap pengurangan lompang telah dianalisis dalam kajian ini. Kesan pengaliran semula perolakan pelbagai profil dan atmosfera turut dipertimbangkan. Keputusan menunjukkan bahawa lompang berkurangan dengan ketara dengan gabungan kemasan pad dengan Organic Solder Preservatives (OSP) dan rendaman perak (Im-Ag), profil aliran semula puncak tinggi dan dengan atmosfera nitrogen. Pengesyoran untuk reka bentuk stensil, kemasan permukaan pad, dan profil aliran semula serta suasana juga dicadangkan.

Kata kunci: Lompong udara, sambungan pateri, profil aliran semula, serbuk pateri, reka bentuk stensil

1.0 INTRODUCTION

Voiding in solder joints is among the common issues for electronic devices especially for bottom terminated component (BTC) devices [1]. Quad Flat No-Lead (QFN) is one of the BTC devices that is susceptible to the voiding due to the physical of the device having low vertical gap and large solder paste area coverage at the thermal pad [2]-[4]. As a result, air bubbles or moisture in solder paste have a limited path to escape during reflow before the joint develops [2]. Having void in solder joints can potentially deteriorate the performance of the devices in terms of electrical signal transfer, solder joint reliability, and thermal dissipation [3]. Thus, QFN is a suitable component to be used in the voiding study. The aim of this study is to analyze the influence of the variables from every parameter evaluated in the experiment on voiding area in QFN thermal pad solder joint and obtain the best combination of variables that can minimize the total void area percentage inside QFN thermal pad solder joint down to below 5%.

2.0 LITERATURE REVIEW

According to Lentz *et al.*, (2020) stencil design, Printed Circuit Board (PCB) surface polish, ambient conditions, reflow profile, PCB design, and solder paste are all potential causes of voiding in solder joints [7]. The previous related works conducted for void reduction of solder joint for QFN components, the stencil design commonly used for QFN thermal pad is window-pane design with various solder coverage area, by different number of windows, window size and spacing [2-6]. There were also void study that used stencil design of diagonal stripes circular and triangular openings on thermal pad [7,8,9]. Lentz *et al.,* (2017) reported the findings in their studies that stencil designs of cross hatch (window-pane) and cross hatch rotated 45˚ with solder area coverage on thermal pad approximately 65% have lower void area % compared to diagonal stripes and circular designs [4,7]. Herron *et al.,* (2011) reported the findings in their study that window-pane stencil design with 9 square openings yielded the lowest void area %, followed by triangle design with 8 openings, triangle with 4 openings and window-pane with 4 square openings [9]. Smith *et al.*, (2019) published the findings in their study that window-pane designs with standard web and furthest distance from perimeter openings yielded the lower void area % compared to largest openings gap (web) and most panes opening [5]. They also reported the findings that stencil designs with 70% and 80% solder area coverage on thermal pad yielded lower void area % compared to 50% and 60%.

The reflow profiles normally used for the void evaluation are Ramp-To-Spike (RTS) and Ramp-Soak-Spike (RSS) [9,10,11] with variation on environment (air and nitrogen) and peak temperature (low and high) [3], [7], [12]–[14]. Herron *et al.,* (2019) reported the findings in their study that long reflow profile have the lowest void area %, followed by long cool profile, long hot profile and short profile [9]. Lentz *et al.,* (2017) reported the findings in their study that RTS profile with nitrogen (N2) reflow atmosphere yielded the lowest void area % compared to RTS, RTS with high peak temperature, RTS reflow twice and RSS [7]. Tudor, (2017) reported the findings in his study that RTS hot profile gave promising result in producing the void area % way lesser than RTS low profile [12]. Nguyen *et al.,* (2012) reported the findings in their study that both low and hot profiles have no significant impact on voiding but found that nitrogen reflow atmosphere helped in reducing the amount of voids compared to air [13]. Sweatman *et al.,* (2016) published the findings in their study that nitrogen atmosphere really helped in further reducing the void area % compared to air and high profile with long reflow time yielded much lower void area % than low profile with short reflow time [14].

The PCB surface finish commonly used by the researchers for this void evaluation are Electroless Nickel Immersion Gold (ENIG) and Organic Solder Preservatives (OSP) [4, 7,11]. Other surface finishes being tested as well are Hot Air Solder Leveling (HASL), Immersion Tin (Im-Tin) and Immersion Silver (Im-Silver) [15,16]. Lentz *et al.,* (2017) reported the findings in his studies that for the comparison between ENIG and OSP PCB finishes, ENIG gave lower void area % than OSP [4]. He also published the work where between OSP, Im-Silver and ENIG, OSP yielded the lowest void area %, followed by Im-Silver and ENIG [11]. Another work published by him shown that Im-Silver gave the lowest void area %, followed by HASL, Lead-Free HASL, OSP, ENIG and Im-Tin [15].

Lastly, the solder paste commonly being used for the void evaluation are lead-free solder pastes with different flux chemistries and solder powder sizes [2], [7], [11], [18], [19]. Leaded solder paste was tested as well for comparison with lead-free [15],[18]. Lentz *et al.,* (2017)(2019) reported the findings in their studies that no-clean flux chemistry of SAC305 solder paste gave lower void area % than water soluble flux chemistry [7,11]. In the other work he published, the findings shown that SAC305 alloy gave lower void area % than mixture of SAC305 90%/SN100C 10%, SN100CV alloy and SN100C alloy [4]. The findings also shown that type 4 solder powder size yielded lower void area % than type 3 and 5. Next, in the work he published on comparison between leaded Sn63Pb37 and lead-free SAC305 solder pastes, the findings shown that the leaded paste yielded much lower void area % than the lead-free [15]. He also published the work on different solder powder sizes where type 5, 4 and 3 produced lower void area % than type 6, and the no-clean flux chemistry solder paste produced lesser void area % than water soluble [17]. Briggs and Lasky, (2016) reported the findings in their study that the no-clean flux chemistry solder paste will always be better than water soluble chemistry in terms of voiding reduction due to the presence of rosins inside no-clean flux that protects the solder powder from oxidation during reflow process [20].

Based on the previous works, some of the parameters that have significant impact on voiding of QFN thermal pad were selected to be tested in the present study [2, 3, 5, 6, 11, 14, 21]. The list of parameters used in the present study are:

- Stencil design: Window-Pane, Round, Triangle and Polygon
- Surface finish of the printed circuit boards (PCB): Electroless Nickel Immersion Gold (ENIG), Organic Solder Preservative (OSP) and Immersion Silver (Im-Ag)
- Convection reflow profiles: Ramp-To-Spike (RTS) Normal-Air, RTS Normal-N2, RTS Long Time Above Liquidus (TAL) High Peak-Air, RTS Long TAL High Peak-N2, Ramp-Soak-Spike (RSS) Long Soak-Air and RSS Long Soak-N2

Analysis of the void formation was done using color coded in the bar chart. Color coded was used to distinguish the void values that are below and above 5%. The chart is also used to analyze the consistency of the void trend for every sets of variables. It is found that the void is significantly reduced with the combination of the pad finishing, reflow profile and with nitrogen atmosphere.

3.0 METHODOLOGY

Figure 1 is shown the process flow of the QFN void experiment which consists of Surface Mount Technology (SMT) processes. Whereas Table 1 and 2 shown the parameters setup for the experiment execution.

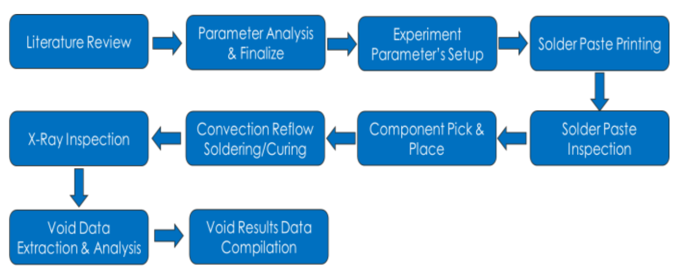


Figure 1 Flow chart of quad flat no-lea d void minimization experiment process flow

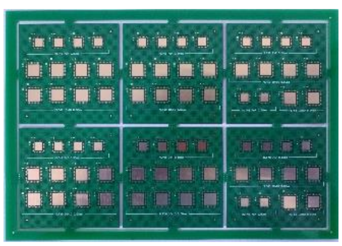
Table 1 Parameter setup for experiment

No.	Parameters	Capability Values
1	Flight time (minute)	15
2	Take-off weight (kg)	<2.0
3	Altitude (m)	100 – 300
4	Payload (kg)	0.250
5	Radio System Frequency (GHz)	2.4

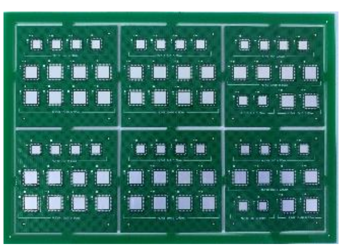
Table 2 Parameters setup for quad flat no-lead void experiment execution

Variables for QFN Void Experiment Evaluation / Fixed Parameters	PCB Surface Finish	Stencil Design	Reflow Profile	Reflow Atmosphere
PCB with OSP Pad Finish		✓	✓	✓
Solder Paste SAC305 No-Clean Type 4	✓	✓	✓	✓
2 QFN Packages: MLF48 7mm and MLF68 10mm	✓	✓	✓	✓
Convection Reflow Soldering with RTS Long TAL High Peak Profile	✓	✓		✓
Reflow Atmosphere using Nitrogen	✓	✓	✓	
4 mil Stencil Thickness	✓	✓	✓	✓
Window-Pane Stencil Design	✓		✓	✓

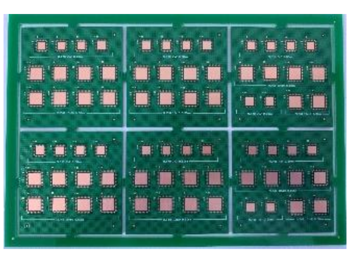
The test vehicle used for this experiment is as shown in Figure 2. The PCB is made of FR4 material, with 1 oz copper thickness and consists of ENIG, Im-Ag, and OSP pad Finishes as shown in Figures 2(a), 2(b), and 2(c), respectively. The QFN used in this experiment are dummy components with daisy chain and tin-plated leads, which are Micro-Lead Frame (MLF) of 7 mm x 7 mm body size with 48 perimeter pins and 0.5 mm pitch, and 10 mm x 10mm body size with 68 perimeter pins and 0.5 mm pitch as shown in Figures 3(a) and 3(b), respectively. Whereas, the PCB footprint for components MLF48 and MLF68 are as shown in Figures 3(c) and 3(d), respectively.



(a)

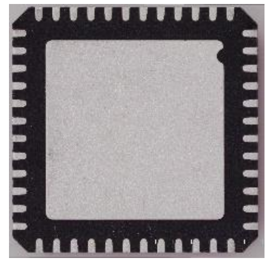


(b)

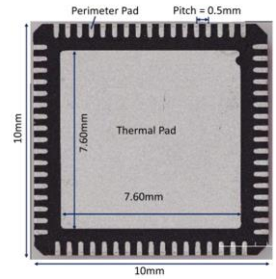


(c)

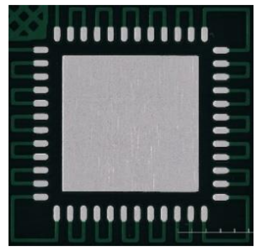
Figure 2 Quad flat no-lead printed circuit board of (a) electroless nickel immersion gold pad finish, (b) immersion silver pad finish, and (c) organic solder preservatives pad finish



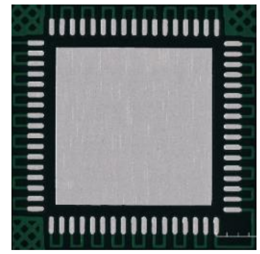
(a)



(b)



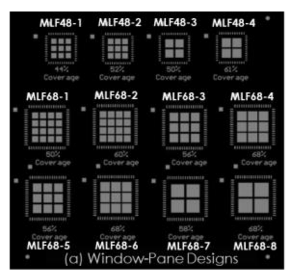
(c)



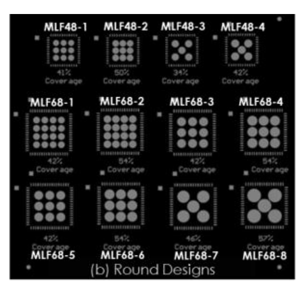
(d)

Figure 3 Quad flat no-lead components of (a) micro-lead frame 48 7x7mm, 0.5mm pitch (b) micro-lead frame 68 10x10mm, 0.5mm pitch, and the respective printed circuit board footprint (c) micro-lead frame 48 and (d) micro-lead frame 68

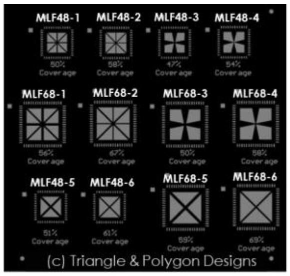
The stencil design for QFN thermal pad consists of three main designs which are window-pane, round, and triangle/polygon as shown in Figure 4(a), 4(b), and 4(c), respectively where each of the designs have various solder area coverage and label of the footprint locations across the individual board.



(a) Window-pane



(b) Round



(c) Triangle and polygon

Figure 4 Stencil layout with footprint labels of QFN PCB board for experiment (a-c)

The solder paste used in this experiment is no-clean SAC305 Type 4 by Alpha as designed for ultra-low solder voiding applications. In this study, various convection reflow profiles are used in the experiment which consist of RTS Normal, RTS Long TAL High Peak, and RSS Long Soak as shown in Figures 5, 6 and 7 respectively, and each of the profiles used in both air and nitrogen atmospheres. The oven settings of each reflow profile are shown in Table 3.

Figure 5 Reflow profile ramp-to-spike normal

Figure 6 Reflow profile ramp-to-spike long reflow time & high peak temperature

Figure 7 Reflow profile ramp-soak-spike long soak

Table 3 Convection reflow profile parameter settings

Settings	RTS-Normal Profile	RTS-Long TAL & High Peak Profile	RSS Long Soak
Max Rise Slope (˚C/s)	1.25 – 1.45	1.15 – 1.40	1.60 – 1.80
Soak Time (150˚C - 200˚C in seconds)	66 - 69	64 - 70	85 - 95
Reflow Time (>217˚C in seconds)	55 - 70	75 - 80	60 - 70
Peak Temperature (˚C)	235 - 240	245 - 250	235 - 240
Max Fall Slope (˚C/s)	2.00 – 2.35	2.00 – 2.45	1.80 – 2.15

X-ray inspection program has a void calculation feature to detect and compute the percentage of void in the target region which in this research study is the solder joint area on thermal pad. The feature will first define the region of thermal pad with solder coverage as shown in Figure 8 which is in grey color then proceed for void detection and percentage computation of total void area by capturing every single void area in green color spots with excluding the red color region outside of thermal pad from void detection.

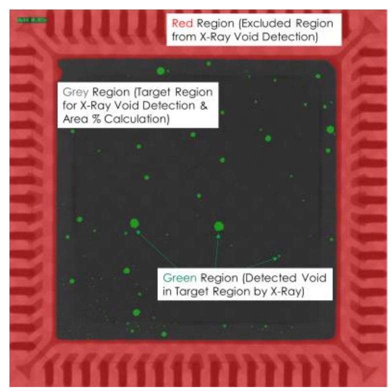


Figure 8 Sample x-ray image of void (green color spots) detection & area % calculation in solder joint on thermal pad (grey color region) of micro-lead frame68

The data of void percentage of every QFN location was generated and extracted from X-ray machine as Excel file that contained every single void detected in QFN thermal pad solder joint with the measured values of void area, void percentage with relative to the area of target inspection region (thermal pad), and total void percentage on thermal pad which is the summation of all the individual void percentage. Then, the data was analyzed and interpreted into statistical results.

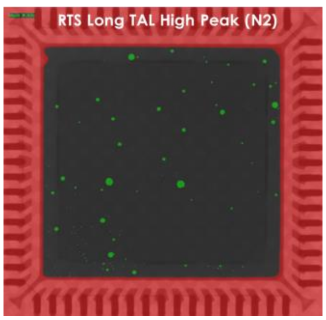
4.0 RESULTS AND DISCUSSION

The findings of the QFN void experiment are presented and discussed in this section with the effect of thermal profiles, stencil design and solder pad finishing.

4.1 Void Images of QFN Thermal Pad

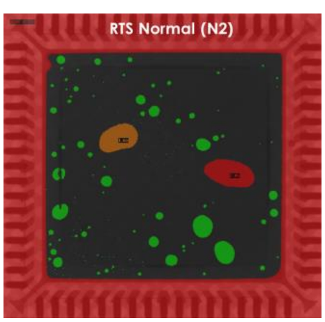
The sample images of void on QFN thermal pad solder joint generated by the x-ray inspection machine are presented in this subsection to show the void appearance and distinguish the different void area coverage.

Figure 9 shows photos of void on MLF68 thermal pad created by convection reflow profiles, with profile RTS Long TAL High Peak (N2 atmosphere) providing the least total void area coverage, followed by RSS Long Soak (N2 atmosphere), and RTS Normal (N2 atmosphere).



(a) Void= 0.83%

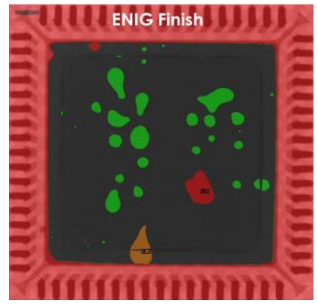
(b) Void= 4.66%



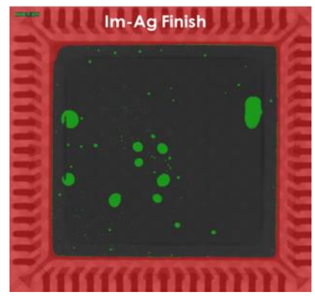
(c) Void= 8.32%

Figure 9 Sample of void area % on quad flat no-lead (micro-lead frame68) thermal pad based on organic solder preservatives pad finish, window-pane stencil design, and reflow profiles (a) ramp-to-spike long reflow time high peak temperature (n2), (b) ramp-soak-spike long soak, and (c) normal ramp-to-spike

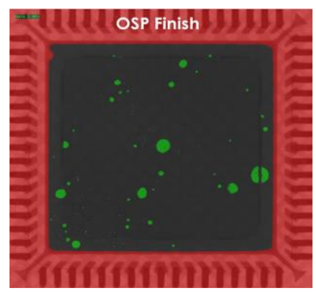
Figure 10 illustrates sample void pictures on MLF68 thermal pads by pad finishes, with OSP having the least overall void area coverage, followed by Im-Ag and ENIG.



(a) Void= 8.68%



(b) Void= 3.67%



(c) Void= 2.05%

Figure 10 Sample of void area % on quad flat no-lead (micro-lead frame68) thermal pad based on profile ramp-to-spike long reflow time high peak temperature (n2), round stencil design, and pad finishes (a) electroless nickel immersion gold, (b) immersion silver, and (c) organic solder preservatives

4.2 Effect of Reflow Profile on Total Void Area

Figure 11 shows the bar chart results for the QFN total void % by the effect of reflow profile where RTS Long TAL High Peak profile have most of the component footprints on PCB that yielded total void area below 5%, followed by RSS Long Soak and then RTS Normal profiles. This result was similar to the findings reported by Tudor, (2017) and Sweatman *et al.*, (2016) where the RTS Hot profile can helped further reduced the void area % lower than RTS Low profile [12] [14]. This proven that the void can be further reduced by prolong the reflow time and increase the peak temperature that allowed more time for the air bubbles in solder paste to escape during reflow stage.

Table 4 shows the tabulation results for the QFN total void % by the effect of reflow profile where RTS Long TAL High Peak profile have 9 out of 12 QFN footprints yielded total void area below 5%, followed by RSS Long Soak profile with 5 out of 12 QFN footprints below 5% total void area and RTS Normal profile with all the footprints have above 5% total void area. RTS Long TAL High Peak profile found to yield the lowest average total void area with 3.50%, followed by RSS Long Soak profile with 6.57%, and RTS Normal profile with 8.68%. In summary, only RTS Long TAL High Peak profile that yielded the average total void area of the whole QFN board footprints to be below 5%.

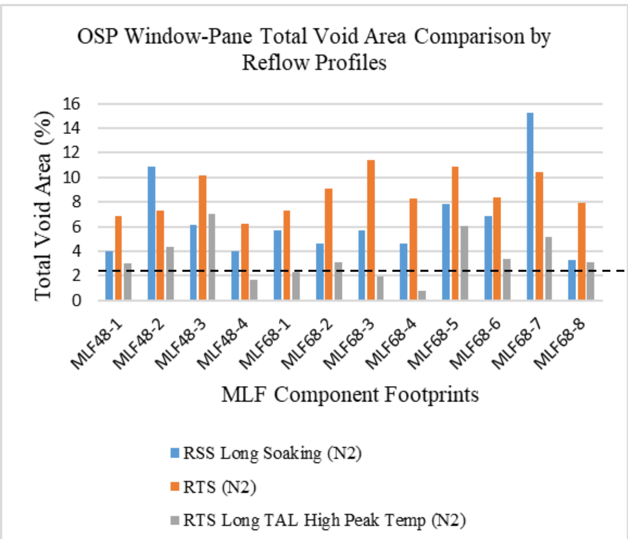


Figure 11 Bar chart of reflow profile effect on total void area % of quad flat no-lead thermal pad using window-pane stencil design, and organic solder preservatives pad finish for all quad flat no-lead footprints

Table 4 Data of reflow profile effect on total void area % of quad flat no-lead thermal pad using window-pane stencil design, and organic solder preservatives pad finish for all quad flat no-lead footprints

	Total Void Area (%)		
Stencil Design	Window-Pane		
Pad Finish	OSP		
Reflow Profiles / Footprint Locations	RSS Long Soaking (N2)	RTS (N2)	RTS Long TAL High Peak Temp (N2)
MLF48-1	3.96	6.88	3.04
MLF48-2	10.88	7.28	4.35
MLF48-3	6.11	10.14	7.04
MLF48-4	4.03	6.26	1.69
MLF68-1	5.72	7.28	2.34
MLF68-2	4.6	9.05	3.07
MLF68-3	5.71	11.39	1.96
MLF68-4	4.66	8.32	0.83
MLF68-5	7.81	10.85	6.05
MLF68-6	6.87	8.41	3.41
MLF68-7	15.22	10.39	5.16
MLF68-8	3.3	7.89	3.1
Mean	6.57	8.68	3.50

Legend

Total Void % =< 5%

Total Void % > 5%

4.3 Effect of Reflow Atmospheres and Pad Surface Finish on Total Void Area

Figure 12 shows the results of the QFN total void area by reflow atmosphere and pad surface finish, utilizing a window-pane stencil design and the RTS Long TAL High Peak profile. The results revealed that OSP pad finish have most of the component footprints on PCB that yielded total void area below 5%, followed by Im-Ag and then ENIG pad finishes. Both nitrogen and air atmospheres shown the same pattern. This result was similar to the findings reported by Lentz *et al.*, (2019) where OSP yielded the lowest void area %, followed by Im-Silver and ENIG [11]. The majority of the footprints with total void area above 5% by using ENIG finish can be explained due to the tendency to produce 'black pad' defect on the pad which described as a Nickel corrosion [22]. This corrosion indicates that some area of Nickel surface that is not protected by Gold due to contamination during plating process, is exposed to oxidation which may results in void and black spots formation.

For the void analysis by the effect of reflow atmosphere, nitrogen resulted in more component footprints on PCB that yielded total void area of less than 5% and also lower total void area for most of the footprints compared to air, independent of pad finishes utilized. This result was similar to the findings reported by Lentz *et al.*, (2017), Nguyen *et al.*, (2013) and Sweatman *et al.*, (2016) where nitrogen significantly reduced the void area % compared to air [7, 13, 14]. This can be explained due to the less amount of air presence when using nitrogen atmosphere during reflow that helped to minimize the oxidation effect on the surface to be soldered [14].

Table 5 shows the tabulation results of the QFN total void area by reflow atmosphere and pad surface finish, utilizing a window-pane stencil design and the RTS Long TAL High Peak profile where OSP (N2) and Im-Ag (N2) both have 9 out of 12 QFN footprints yielded total void area below 5%, followed by OSP (air) with 8 out of 12 QFN footprints below 5% total void area, both ENIG (N2) and Im-Ag (air) with 4 out of 12 QFN footprints below 5% total void area, and lastly ENIG (air) with only 1 out of 12 QFN footprints below 5% total void area. OSP finish (N2 atmosphere) found to yield the lowest average total void area with 3.50%, followed by Im-Ag finish (N2 atmosphere) with 3.87%, OSP finish (air atmosphere) with 4.22%, Im-Ag finish (air atmosphere) with 5.81%, ENIG finish (N2 atmosphere) with 6.21%, and ENIG finish (air atmosphere) with 8.27%. In summary, only OSP and Im-Ag finishes under nitrogen atmosphere and OSP finish under air atmosphere that yielded the average total void area of the whole QFN board footprints to be below 5%.

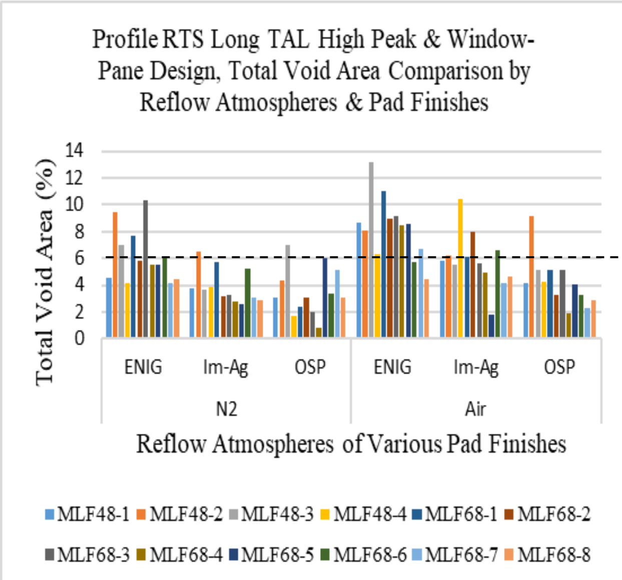


Figure 12 Bar chart of pad finish and reflow atmosphere effects on total void area % of quad flat no-lead thermal pad using window-pane stencil design, and profile ramp-to-spike long reflow time high peak for all quad flat no-lead footprints

Table 5 Data of Pad Finish and Reflow Atmosphere Effects on Total Void Area % of Quad Flat No-Lead Thermal Pad using Window-Pane Stencil Design, and Profile Ramp-To-Spike Long Reflow Time High Peak for all Quad Flat No-Lead Footprints

	Total Void Area (%)					
Stencil Design	Window-Pane					
Reflow Profile	RTS Long TAL High Peak Temp					
Reflow Atmospheres	N2			Air		
Pad Finishes / Footprint Locations	ENIG	Im-Ag	OSP	ENIG	Im-Ag	OSP
MLF48-1	4.57	3.8	3.04	8.64	5.78	4.17
MLF48-2	9.4	6.47	4.35	8.07	6.16	9.19
MLF48-3	6.95	3.7	7.04	13.2	5.55	5.16
MLF48-4	4.14	3.83	1.69	6.29	10.46	4.29
MLF68-1	7.66	5.7	2.34	11.01	6.15	5.11
MLF68-2	5.78	3.16	3.07	9	7.97	3.3
MLF68-3	10.33	3.22	1.96	9.19	5.61	5.08
MLF68-4	5.5	2.81	0.83	8.47	4.94	1.86
MLF68-5	5.5	2.56	6.05	8.59	1.84	4.08
MLF68-6	6.15	5.26	3.41	5.68	6.57	3.22
MLF68-7	4.18	3.06	5.16	6.72	4.11	2.27
MLF68-8	4.41	2.86	3.1	4.42	4.6	2.87
Mean	6.21	3.87	3.50	8.27	5.81	4.22

Legend

Total Void % =< 5%

Total Void % > 5%

Figure 13 shows the results for QFN total void area by reflow atmosphere and pad surface finish, using a round stencil design and the RTS Long TAL High Peak profile. The results revealed that OSP pad finish have most of the component footprints on PCB that yielded total void area below 5%, followed by Im-Ag and then ENIG pad finishes. This pattern was the same for both nitrogen and air atmospheres. This result shown its consistency and repeatability with respect to the result of same void analysis using window-pane stencil design and similar to the findings reported by Tony *et al.*, (2019) where OSP yielded the lowest void area %, followed by Im-Silver and ENIG as ENIG tends to produce 'black pad' defect on the pad which resulted in pad oxidation [11, 22].

For the void analysis by the effect of reflow atmosphere, both nitrogen and air had the same number of component footprints on PCB that yielded total void area below 5%, for all three pad finishes. However, for majority of component footprints, nitrogen had a somewhat lower total void area than air, particularly for Im-Ag and OSP finishes. This result pattern was similar to the findings reported by Tony *et al.*, (2017), Nguyen *et al.*, (2012) and Sweatman *et al.*, (2016) where nitrogen significantly reduced the void area % compared to air due to the less amount of air presence during reflow that helped to minimize the oxidation effect on the surface to be soldered [7, 13, 14].

Table 6 shows the tabulation results of the QFN total void area by reflow atmosphere and pad surface finish, utilizing a round stencil design and the RTS Long TAL High Peak profile where OSP (both N2 & air) have 8 out of 12 QFN footprints yielded total void area below 5%, followed by Im-Ag (both N2 & air) with 7 out of 12 QFN footprints below 5% total void area, and ENIG (both N2 & air) with none of 12 QFN footprints below 5% total void area. OSP finish (N2 atmosphere) yielded the lowest average total void area with 3.71%, followed by OSP finish (air atmosphere) with 4.34%, Im-Ag finish (N2 atmosphere) with 4.40%, Im-Ag finish (air atmosphere) with 5.90%, ENIG finish (N2 atmosphere) with 8.34%, and ENIG finish (air atmosphere) with 8.66%. In summary, only OSP and Im-Ag finishes under nitrogen atmosphere and OSP finish under air atmosphere that yielded the average values of total void area of the whole QFN board footprints below 5%, which was the same result pattern as the same void analysis using window-pane stencil design.

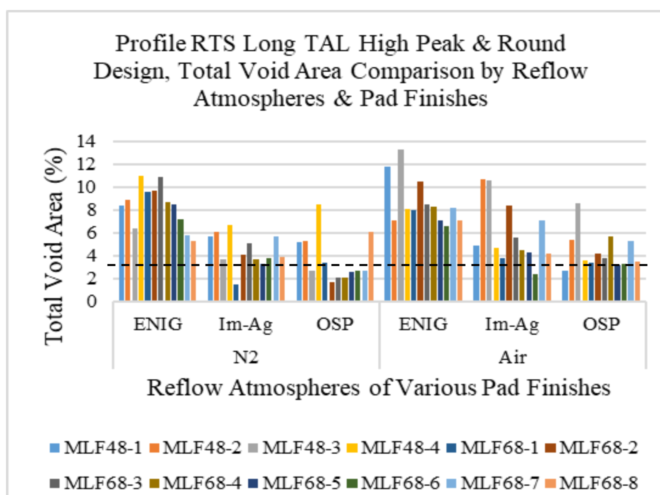


Figure 13 Bar Chart of Pad Finish and Reflow Atmosphere Effects on Total Void Area % of Quad Flat No-Lead Thermal Pad using Round Stencil Design, and Profile Ramp-To-Spike Long Reflow Time High Peak for all Quad Flat No-Lead Footprints

Table 6 Data of pad finish and reflow atmosphere effects on total void area % of quad flat no-lead thermal pad using round stencil design, and profile ramp-to-spike long reflow time high peak for all quad flat no-lead footprints

	Total Void Area (%)					
Stencil Design	Round					
Reflow Profile	RTS Long TAL High Peak Temp					
Reflow Atmospheres	N2			Air		
Footprint Locations \ Pad Finishes	ENIG	Im-Ag	OSP	ENIG	Im-Ag	OSP
MLF48-1	8.37	5.61	5.12	11.71	4.88	2.68
MLF48-2	8.9	6.03	5.23	7.03	10.69	5.4
MLF48-3	6.37	3.62	2.62	13.25	10.57	8.55
MLF48-4	10.93	6.66	8.48	8.07	4.63	3.53
MLF68-1	9.57	1.5	3.34	7.92	3.8	3.32
MLF68-2	9.68	4.06	1.67	10.49	8.38	4.13
MLF68-3	10.88	5.1	2.06	8.42	5.53	3.75
MLF68-4	8.68	3.67	2.05	8.25	4.46	5.61
MLF68-5	8.47	3.25	2.54	7.08	4.25	3.15
MLF68-6	7.17	3.75	2.7	6.6	2.37	3.24
MLF68-7	5.79	5.67	2.64	8.12	7.07	5.26
MLF68-8	5.23	3.88	6.01	7.02	4.18	3.48
Mean	8.34	4.40	3.71	8.66	5.90	4.34

Legend

Total Void % =< 5%

Total Void % > 5%

Figure 14 shows the findings for QFN total void area by reflow atmosphere and pad surface finish, using triangle/polygon stencil design and RTS Long TAL High Peak profile. The results shown that OSP pad finish have most of the component footprints on PCB that yielded the total void area below 5%, followed by Im-Ag and then ENIG pad finishes for nitrogen atmosphere. For air atmosphere, both OSP and Im-Ag finishes have the same number of component footprints resulted in total void area of less than 5%, with ENIG having the least. This shown the consistency and repeatability of the result pattern with respect to the result of same void analysis using window-pane and round stencil designs and similar to the findings reported by Lentz *et al.*, (2019) where OSP yielded the lowest void area %, followed by Im-Silver and ENIG as ENIG tends to produce 'black pad' defect on the pad which resulted in pad oxidation [11, 22].

For the reflow atmospheric void analysis, nitrogen shown to have consistently yielded more component footprints on PCB that having total void area of less than 5% and also lower total void area for most of the footprints compared to air, independent of pad finishes utilized. This result pattern was the same as the previous same void analysis using window-pane and round stencil designs, and similar to the findings reported by Lentz *et al.*, (2017), Nguyen *et al.*, (2012) and Sweatman *et al.*, (2016) where nitrogen significantly reduced the void area % compared to air due to the less amount of air presence during reflow that helped to minimize the oxidation effect on the surface to be soldered [7,13,14].

Table 7 shows the tabulation results of the QFN total void area by reflow atmosphere and pad surface finish, utilizing a triangle/polygon stencil design and the RTS Long TAL High Peak profile where OSP (N2) have 9 out of 12 QFN footprints yielded total void area less than 5%, followed by Im-Ag (N2) with 7 out of 12 QFN footprints less than 5% total void area, ENIG (N2), OSP & Im-Ag (both air) three of them have 5 out of 12 QFN footprints yielded total void area less than 5%, and ENIG (air) with 4 out of 12 QFN footprints less than 5% total void area. OSP finish (N2 atmosphere) found to yield the lowest average total void area with 3.69%, followed by Im-Ag finish (N2 atmosphere) with 4.95%, OSP finish (air atmosphere) with 5.06%, ENIG finish (N2 atmosphere) with 5.64%, Im-Ag finish (air atmosphere) with 5.90%, and ENIG finish (air atmosphere) with 6.31%. In summary, only OSP and Im-Ag finishes under nitrogen atmosphere that yielded the average values of total void area of the whole QFN board footprints to be less than 5%.

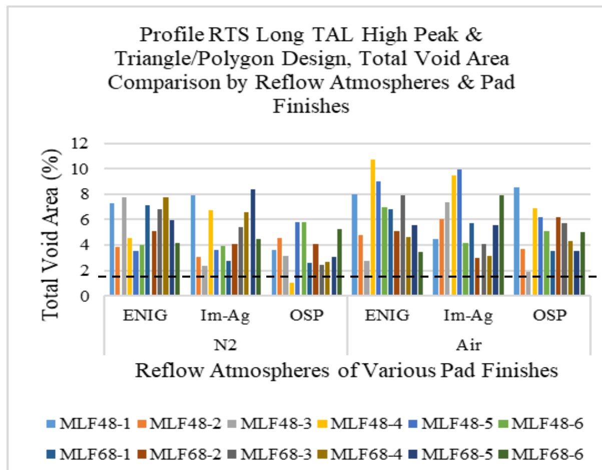


Figure 14 Bar chart of pad finish and reflow atmosphere effects on total void area % of quad flat no-lead thermal pad using triangle/polygon stencil design, and profile ramp-to-spike long reflow time high peak for all quad flat no-lead footprints

Table 7 Data of Pad Finish and Reflow Atmosphere Effects on Total Void Area % of Quad Flat No-Lead Thermal Pad using Triangle/Polygon Stencil Design, and Profile Ramp-To-Spike Long Reflow Time High Peak for all Quad Flat No-Lead Footprints

	Total Void Area (%)					
Stencil Design	Triangle/Polygon					
Reflow Profile	RTS Long TAL High Peak Temp					
Reflow Atmospheres	N2			Air		
Footprint Locations \ Pad Finishes	ENIG	Im-Ag	OSP	ENIG	Im-Ag	OSP
MLF48-1	7.26	7.88	3.58	7.99	4.49	8.53
MLF48-2	3.83	3.08	4.58	4.8	6.03	3.67
MLF48-3	7.72	2.38	3.19	2.77	7.34	1.89
MLF48-4	4.52	6.77	1.08	10.71	9.47	6.87
MLF48-5	3.51	3.58	5.78	8.99	9.91	6.23
MLF48-6	4	3.96	5.84	6.97	4.18	5.11
MLF68-1	7.14	2.79	2.6	6.79	5.71	3.56
MLF68-2	5.09	4.09	4.1	5.1	2.99	6.18
MLF68-3	6.78	5.44	2.46	7.9	4.08	5.7
MLF68-4	7.74	6.55	2.71	4.64	3.15	4.32
MLF68-5	5.94	8.39	3.1	5.57	5.56	3.55
MLF68-6	4.2	4.49	5.27	3.44	7.93	5.05
Mean	5.64	4.95	3.69	6.31	5.90	5.06

Legend

Total Void % =< 5%

Total Void % > 5%

5.0 CONCLUSION

In this study, the evaluation of void formation for different reflow profiles, reflow atmospheres, solder pad finishing and stencil patterns were carried out. The percentage void area on QFN thermal pad with varying reflow profiles & atmospheres, solder pad finishing and stencil patterns was compared and analyzed. It is found that convection reflow profile of RTS Long TAL High Peak gave promising result in further minimized the void area down to less than 5% of the QFN thermal pad solder joint compared to RSS Long Soak and RTS Normal profiles. This can be due to the prolonged reflow time and increased peak temperature that allowed more time for the air bubbles in solder paste to escape during reflow stage.

For the voiding evaluation by stencil design, it is found that all the three designs have statistically insignificant difference in void area reduction based on their average values obtained for all the footprints on PCB. For the voiding evaluation by pad surface finish, OSP and Im-Ag finishes shown to provide significant reduction in void area for most of the footprints on PCB regardless of the stencil designs used compared to ENIG finish. This can be due to the tendency of ENIG finish to produce 'black pad' defect on the pad which described as a Nickel corrosion that can resulted in oxidation [22]. For the voiding evaluation by reflow atmosphere, Nitrogen shown to yield better results in void area reduction regardless of pad finishes and stencil designs used compared to air atmosphere. This was due to the less amount of air presence when using nitrogen atmosphere during reflow that helped to minimize the oxidation effect on the surface to be soldered [14].

Using RTS Long TAL High Peak profile, with the combinations of Nitrogen atmosphere, and both OSP and Im-Ag finishes produced promising results on void area reduction with average value of less than 5% for the whole QFN board footprints for all the three stencil designs used.

The main conclusions are as follows:

1. The effects of the stencil pattern on void formation are found to be insignificant for void reduction.
2. The results demonstrated that the reflow profile with RTS Long TAL high peak profile has provided lowest void percentage below 5% for almost all configurations.
3. The lowest void percentage with below 5% also obtained for the pad finishing with OSP and Im-Ag.
4. The nitrogen atmosphere has provided less void formation compared to the air atmosphere during the reflow process.

The outcome from these results suggested that the proper stencil pattern, pad surface finishing, reflow profile and atmosphere conditions have significant effects in reducing void formation during reflow process. This work also demonstrated the benefits of using pad surface finishing, proper reflow thermal profile and with nitrogen atmosphere can be explored further in reducing the void formation for future study.

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References

[1] Nguyen, J., Marin, H., Geiger, D., Mohammed, A. and Kurwa, M. 2014. Reliability Study of Bottom Terminated Components. *Ipc Apex Expo*.
[2] Gadepalli, H., Dhanasekaran, R., Ramkumar, S. M., Ny, R., Jensen, A. and Briggs, E. 2009. Influence of Reflow Profile and Pb-Free Solder Paste in Minimizing Voids for Quad Flat Pack No-Lead (QFN) Assembly 2016 Electronic Components and Technology Conference. *IEEE Electron. Components Technol. Conf*. 9.
[3] Tony Lentz, G. S. 2020. Fill the Void V - Mitigation of Voiding for Bottom Terminated Components. *IPC APEX Expo*. 35.
[4] Tony Lentz, P. C. and Byers, JB. 2017. Fill The Void III. *IPC APEX Expo*.
[5] Tony Lentz, G. S. 2019. Root Cause Stencil Design for SMT Component Thermal Lands. *SMTA International*. 7.
[6] Nguyen, J., Geiger, D. and Mohammed, A. 2016. The Impact of Via and Pad Design on Qfn Assembly. *SMTA Proceedings.* 8.
[7] Tony Lentz, P. C., Byers, J. B. 2017. Fill the Void II: An Investigation into Methods of Reducing Voiding. *Ipc Apex Expo*. 17.
[8] Bright, L. and Caswell, G. 2013. Understanding The Criticality of Stencil Aperture Design and Implementation for a QFN Package.
[9] Herron, D., Liu, Y. and Lee, N. C. 2011. Voiding Control for QFN Assembly. *Pan Pacific Symposium Proceedings.* 11.
[10] Briggs, E., Ronald, C. and Lasky, P.E. 2013. Best Practices Reflow Profiling for Lead-Free SMT Assembly. *Indium Corporation*. 8.
[11] Lentz, T. 2019. The Effects of Surface Finish on Solder Paste Performance - The Sequel Tony Lentz. *SMTA International.* 11.
[12] Tudor, C. 2017. Minimizing Voiding Indium Corporation's Business. 1-38.
[13] Nguyen, J., Geiger, D. and Shangguan, D. 2012. Assembly Challenges of Bottom Terminated Components. *IPC APEX EXPO Proceedings.* 29.
[14] Sweatman, K., Nishimura, T., Sugimoto, K. and Kita, A. 2016. Controlling Voiding Mechanisms in the Reflow Soldering Process. *Proc. IPC APEX Expo*.
[15] Lentz, T. 2018. How Does Surface Finish Affect Solder Paste Performance ?. *SMTA International.* 13.
[16] Bernard, D. 2004. Does PCB Pad Finish Affect Voiding Levels in Lead-Free Assemblies? 5.
[17] Lentz, T. 2019. Size Matters - The Effects of Solder Powder

Size on Solder Paste Performance. 23.
[18] Bradley, E. 2003. Lead-free Solder Assembly : Impact and Opportunity. *IEEE Xplore*. 1-6.
[19] Seelig, K. F. Lead Free Alloy Development. 1-7.
[20] Briggs, E. and Lasky, R.C. 2016. Process Guidelines to Ensure Optimal SMT Electronics Assembly. *Indium Corporation Tech Paper*. 13.
[21] Lentz, T. and Smith, G. 2016. Fill the Void. *Proc. SMTA Int*. 7.
[22] Ramanauskas, R., Selskis, A., Juodkazyte, J. and Jasulaitiene, V. 2013. PCB Failure Analysis Related to the ENIG Black Pad Problem. *Circuit World*. 39(3): 124-132. DOI: 10.1108/CW-05-2013-0013.