Ultra-Low Voiding Halogen-Free No-Clean Lead-Free Solder Paste for Large Pads

Li Ma, Fen Chen, and Dr. Ning-Cheng Lee

Indium Corporation
Clinton, NY
mma@indium.com; fchen@indium.com; nclee@indium.com

Abstract
The miniaturization trend is driving industry to adopting low standoff components. The cost reduction pressure is pushing telecommunication industry to combine assembly of components and electromagnetic shield in one single reflow process. As a result, the flux outgassing is getting very difficult for devices. This resulted in more large voids. For a properly formulated flux, there is less outgassing at temperature above melting temperature of solder or the flux can be expelled out from interior of solder joints due to good wetting ability. Either approach will reduce the voids. In this work, a new halogen-free no-clean flux chemistry, F, has been developed. The solder paste using 96.5Sn3.0Ag0.5Cu and Alloy A exhibited ultra-low voiding and virtually zero solder beading performance. The low voiding performance on Alloy A solder paste is particularly crucial since the automotive industry has been ailing by the poor voiding performance of this 6-element solder alloy system. The halogen-free F virtually enables the automotive to migrate toward full adoption of high reliability 6-element alloy system. Furthermore, the hot slump, wetting, solder balling, and graping performance are all acceptable. The printing performance of F showed excellent transfer efficiency under various printer setup and pad design conditions, indicating this flux system is a very robust system for SMT fine-pitch applications.

Key Words
No-clean, flux, QFN, SAC305, 6-element solder alloys, 90.95Sn3.8Ag0.7Cu3Bi1.4Sb0.15Ni, halogen-free, voiding, large thermal pad, low standoff, solder beading

Introduction
The electronic industry is evolving rapidly toward miniaturization, with major emphasis on thin product profiles. To facilitate the implementation of thin profile, use of thin components such as Land Grid Array (LGA) and Quad Flat No-lead (QFN) becomes mandatory. Quad Flat No Leads (QFN), see Fig. 1, has a number of benefits including (1) small size, such as a near die-sized footprint, thin profile, and light weight; (2) easy Printed Circuit Board (PCB) trace routing due to the use of perimeter I/O pads; (3) reduced lead inductance; and (4) good thermal and electrical performance due to the adoption of exposed copper die-pad technology [1]. But, due to the large coverage area, large number of thermal via, and low standoff, voiding control at QFN assembly becomes a major challenge. The presence of voids will affect the mechanical properties of joints [2] and deteriorate the strength, ductility, creep and fatigue life [3, 4]. It can also produce spot overheating, hence reduce the reliability of joints.

As we all know, some of the causes affecting voiding are related to the materials, such as flux type, board, stencil and components design, while others are dependent on process parameters in the printing and reflow process, circuit board contamination, or human factors [5]. Among all, the primary cause is mainly attributable to the flux outgassing within the solder joints when the solder is at molten state. Apparently, the solder paste is the most critical element in regulating the voiding for the large pads design [6].

On the other hand, government regulations and environmental initiatives are driving the electronics industry away from the use of lead and halogen, among other things, at soldering. Accordingly, a major developmental effort has been conducted for this quest. As a result, a new halogen-free lead-free no clean solder paste, F, has been developed. The performance was assessed, including the wetting, voiding, solder beading, slump and solder ball, and the results are presented and discussed below.

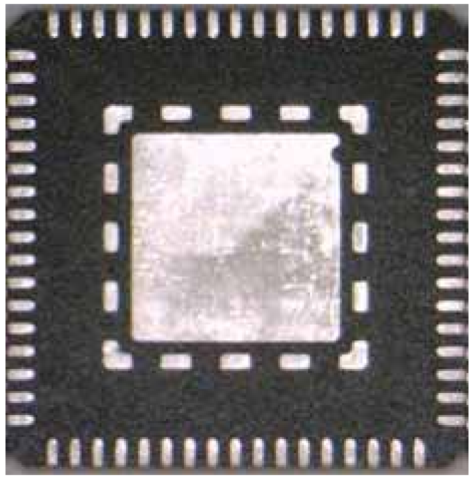


Figure 1. QFN component bottom view

EXPERIMENTAL I

1. Materials

Six solder pastes were tested, including the newly developed halogen-free no-clean solder paste F and five conventional solder pastes as controls. The characteristics of those six solder pastes are shown in Table 1. All solder pastes employed 96.5Sn3.0Ag0.5Cu (SAC305), type 4 (20-38 microns) solder powder. Pastes A to E are Surface Mount Technology (SMT) no-clean lead-free solder paste materials available from the market. The powder size of E is not available.

Table 1. Characteristics of solder pastes evaluated.

Flux	Characteristics	Metal load
A	Halogenated, no-clean	SAC305 T4 88.5%
B	Halogenated, no-clean	SAC305 T4 88.5%
		Alloy A T4 88.5%
C	Halogen-free, no-clean	SAC305 T4 88.75%
		Alloy A T4 88.5%
D	Halogenated, no-clean	SAC305 T4 88.5%
E	Halogen-free, no-clean	SAC305 T4 88.5%
F	Halogen-free, no-clean	SAC305 T4 88.5%
		Alloy A T4 88.5%
G	Halogen-free, no-clean	Alloy A T4 88.5%

Note: Alloy A exhibits the composition as 90.95Sn3.8Ag0.7Cu3Bi1.4Sb0.15Ni.

2. Testing

Wetting Test

Prepare a three-hole stencil, with a hole diameter of 6.35 mm (0.25 inch), and a thickness of 0.12 mm (5 mil). Print the paste onto the substrate with surface finishes Organic Solderability Preservative (OSP), Oxidized OSP (by pre-conditioning OSP substrate in 200ºC oven for 2 hours), and Electroless Nickel Immersion Gold (ENIG), respectively. The substrate with printed paste was then sent through oven under air atmosphere with reflow profile shown in Figure 2. The reflowed coupon was then examined for wetting behavior.

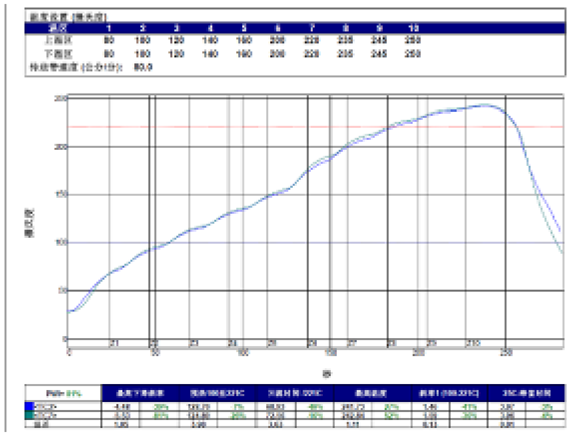


Figure 2. Reflow profile used for paste wetting test.

For Alloy A wetting test, a test coupon with 10 track lines (track length 9.5mm) was used. On each track line, 14 segments of paste were printed. A stencil of thickness 127μm was used, with a set of apertures with 0.25mm x 0.40mm opening and a symmetrically distributed gradually increasing spacing, 0.1mm, 0.15mm, 0.2mm, 0.25mm, 0.3mm, 0.35mm, and 0.4mm. The total spacing number is 130. After paste was printed, the board was reflowed with profile shown in Figure 2. The number of remaining non-bridged spacing was tallied, and expressed as percentage of total original spacing number for each paste. Figure 3 showed an example of test coupon with paste printed and reflowed. Here no bridge was observed.

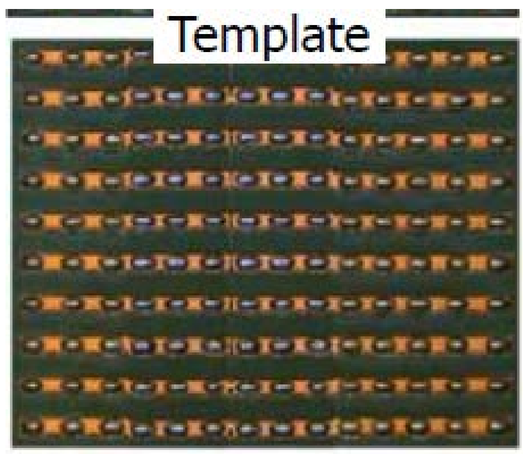


Figure 3. Test board with paste printed and reflowed with gradually increasing spacing.

<u>Hot Slump Test</u>

The IPC slump pattern was used, as shown in Figure 4. The paste was printed, then conditioned at 180C for 10 minutes on hot plate, then examined for paste bridging. Out of the 4 rows printed, the bridges formed on both ends were recorded as I, J, K, L, M, N, O, and P. The total bridges formed out of the 4 rows was tallied as X. A smaller number X reflects a lower hot slump tendency.

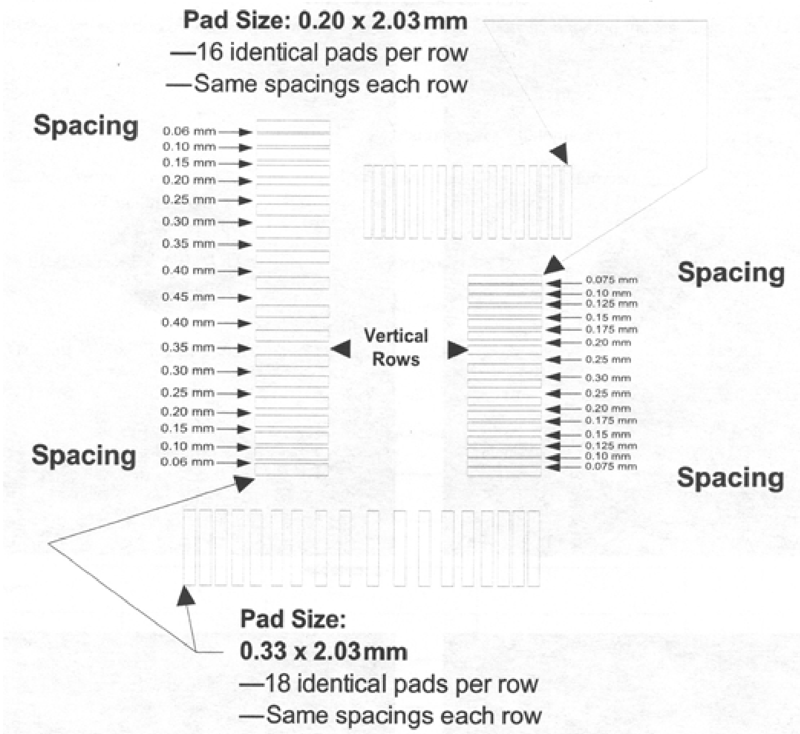


Figure 4. IPC J-STD-005 Slump test pattern. Slump test stencil thickness 0.1mm (top) the slump data chart (bottom)

I: number of bridges on the left side of the top horizontal row
J: number of bridges on the right side of the top horizontal row
K: number of bridges on the top of the right side vertical column
L: number of bridges on the bottom of the right side vertical column
M: number of bridges on the right side of the bottom horizontal row
N: number of bridges on the left side of the bottom horizontal row
O: number of bridges on the bottom of the left side vertical column
P: number of bridges on the top of the left side vertical column
X: total number of bridges

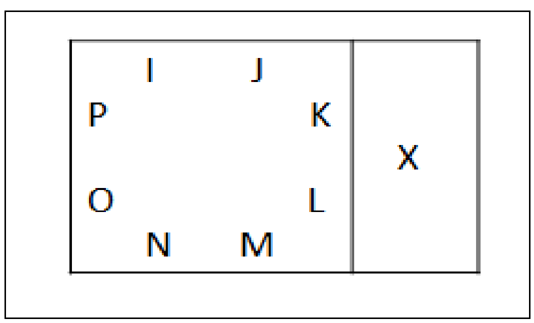


Figure 5. Quantitative expression on the slump performance of solder paste. I, J, K, L, M, N, O, P represent the bridge number. X is the sum of all bridges.

<u>Voiding， Solder ball Test</u>

The J test board [7] with QFN thermal pads was assembled as below (see Figure 6):

1) Place the J test board onto a production printer.
2) Print the paste onto the test board with immersion Sn surface finish using printer, with stencil and a thickness of 5 mil.
3) Place 4 dummy QFN components per board onto the paste
4) Send the board with components through production reflow oven with profile shown in Figure 7 under air reflow atmosphere
5) Examine the voiding with X-ray inspection equipment
6) Examine the solder ball, slump, and graping with optical microscope.

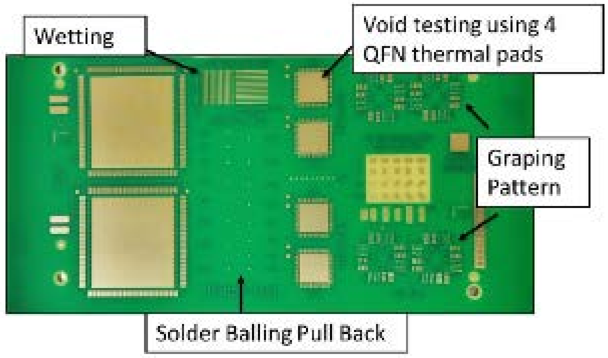
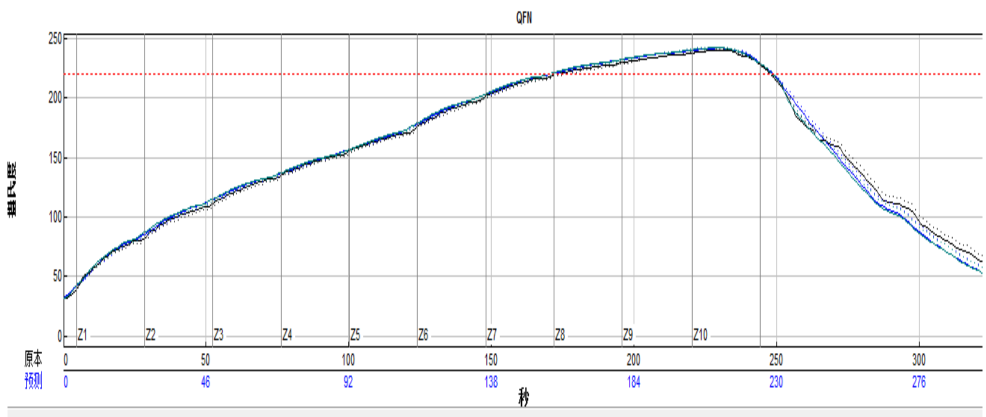


Figure 6. Picture of J test board with QFN thermal pads.



TCs	最高下降斜率		回流时间 /221C		最高温度		斜率1 (100-221C)		25C-峰值时间		温度对应时间 (上升) 100/22	
<TC3>	-3.10	-5%	79.55	30%	243.50	-44%	1.17	-42%	3.84	92%	132.42	24%
<TC5>	-3.09	-4%	75.68	5%	242.01	-78%	1.21	-40%	3.87	94%	133.80	38%
<TC7>	-3.20	-10%	79.50	30%	243.73	-39%	1.18	-41%	3.83	91%	133.38	34%
温差	0.11		3.87		1.72		0.04		0.04		1.38	

Figure 7. Reflow profile used for QFN voiding solder ball and graping test.

<u>Solder Beading Test</u>

1) Print solder paste using 5mil thick stencil
2) Place 0805 capacitor by pick & place equipment (360 capacitors for one test board, see Figure 8)
3) Reflow test board in production reflow oven using reflow profile as below (see Figure 9)

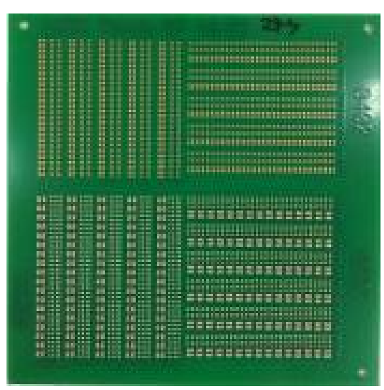
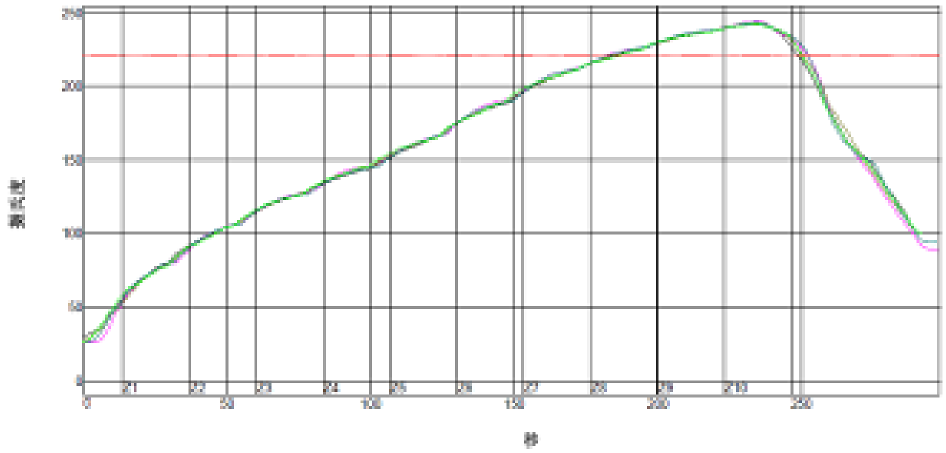


Figure 8. The LCK Tomb solder beading test board



[illegible]	[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	
<TC3>	69.65	-34%	243.77	73%	1.15	15%	0.44	-56%			3.88	77%	0.94	-70%
<TC4>	65.35	-64%	243.09	57%	1.09	9%	0.44	-56%			3.93	85%	0.93	-72%
<TC5>	63.79	-75%	242.23	38%	1.07	7%	0.43	-57%			3.90	84%	0.93	-72%
<TC7>	69.58	-36%	243.28	62%	1.09	9%	0.44	-56%			3.89	78%	0.94	-70%
<TC9>	63.71	-75%	242.12	41%	1.09	9%	0.45	-55%			3.90	80%	0.93	-71%
[illegible]	6.15		1.54		0.08		0.02				0.05		0.01	

Figure 9. Reflow profile used for solder beading test.

Graping Test

Solder paste was printed to square and round pads with gradually decreasing dimension, followed by reflow, as shown in Figure 10. The total number of solder domes was 384. Solder domes with graping symptom, as shown in Figure 11, were tallied, and expressed as percentage of total solder domes.

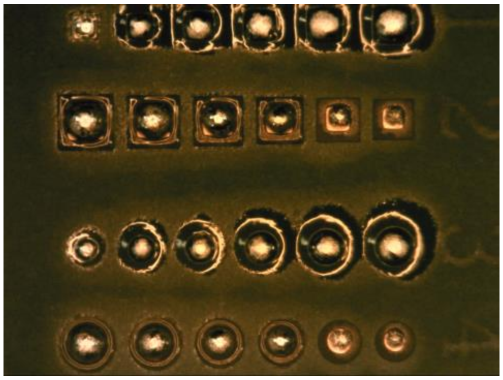


Figure 10. Test pattern of solder beading

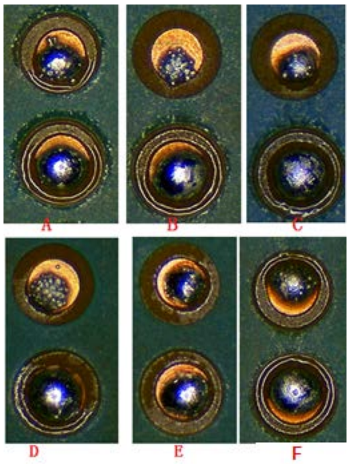


Figure 11. Example of solder domes with graping symptom.

Printability Test

A production printer was used with the following printer and PCB board pad parameter settings.

1) Stencil separation speed: 2mm/sec, 5mm/sec, fast
2) Squeegee pressure: 3, 3.6, 4, 4.5 Kg
3) Squeegee speed: 25, 50, 100, 150 mm/sec
4) PCB pad dimension: 9, 10, 11, 12, 14, 16 mils
5) PCB pad shape: circle, square
6) PCB pad vs solder mask: solder mask defined (SMD), non-solder mask defined (NSM)

RESULTS

1. Wetting

Stencil design pattern: the spacing from center to edge.

Reflowed under air, all solder pastes wet well on fresh OSP and ENIG substrates, and no difference can be discerned.

On oxidized OSP, the wetting behavior of those pastes can be differentiated. Figure 12 shows the SAC305 solder spread appearance on various substrates. The halogenated pastes B and D showed good wetting, but A showed dewetting. For the halogen-free solder pastes C, E, and F, C wetted well, E wetted well but has colorful residue. Paste F wetted well on the oxide OSP. That is paste F wetted well on fresh OSP, oxide OSP and ENIG, thus is expected to meet industry need for air reflow condition.

For Alloy A alloy, the wetting performance reflected by the number of remaining gaps is ranked in the following order: B > G > F > A, as shown in Figure 13. Regardless, F showed satisfactory wetting of 0.25 inch diameter print on surface finishes OSP, Au, ENIG, and Ag.

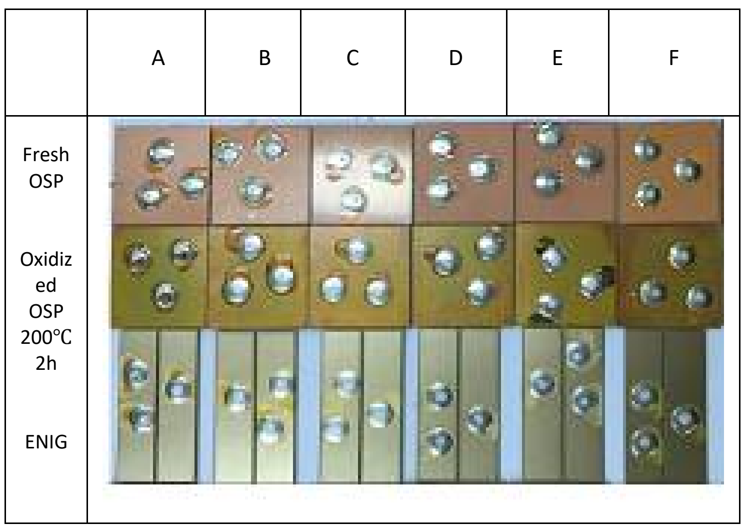


Figure 12 Wetting of SAC305 solder pastes under air on various substrates.

	C	B	G	F
gaps number remaining	126	80	87	108
gap % remaining	97%	61%	67%	83%

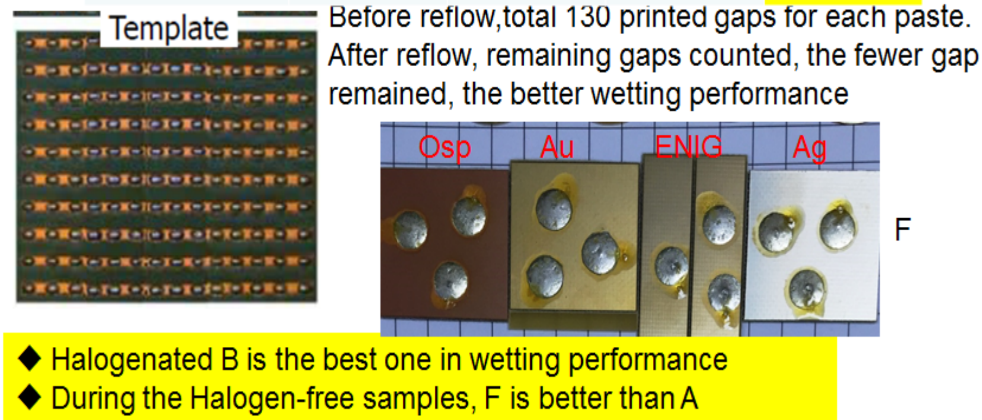


Figure 13. Wetting of Alloy A solder pastes under air on various substrates.

2. Voiding

The voiding performance of each SAC305 paste is shown in Table 2. The halogen-free paste F exhibits the lowest voiding, almost half of the halogenated paste B, which exhibited the lowest voiding in the field among all pastes prior to this study. The same conclusion can be seen from Figure 14 directly.

Table 2. Voiding performance (area %) of various SAC305 solder pastes

No.	Largest void (%)	SD	All voids (%)	SD
A	9	2	30	4
B	7	2	20	6
C	6	1	25	3
D	11	2	24	6
E	7	1	28	2
F	7	2	12.7	5

Note: the largest void is the largest void among all the test coupons, and the data “all voids” is the average of all test coupons

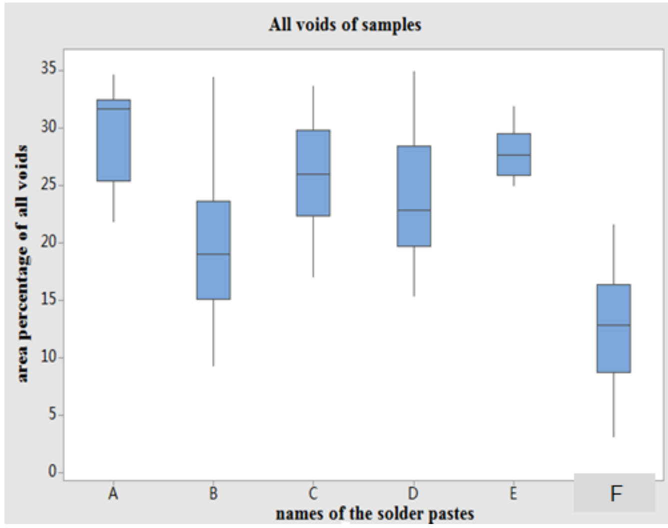


Figure 14. The chart of all voids performance of the SAC305 samples (area %)

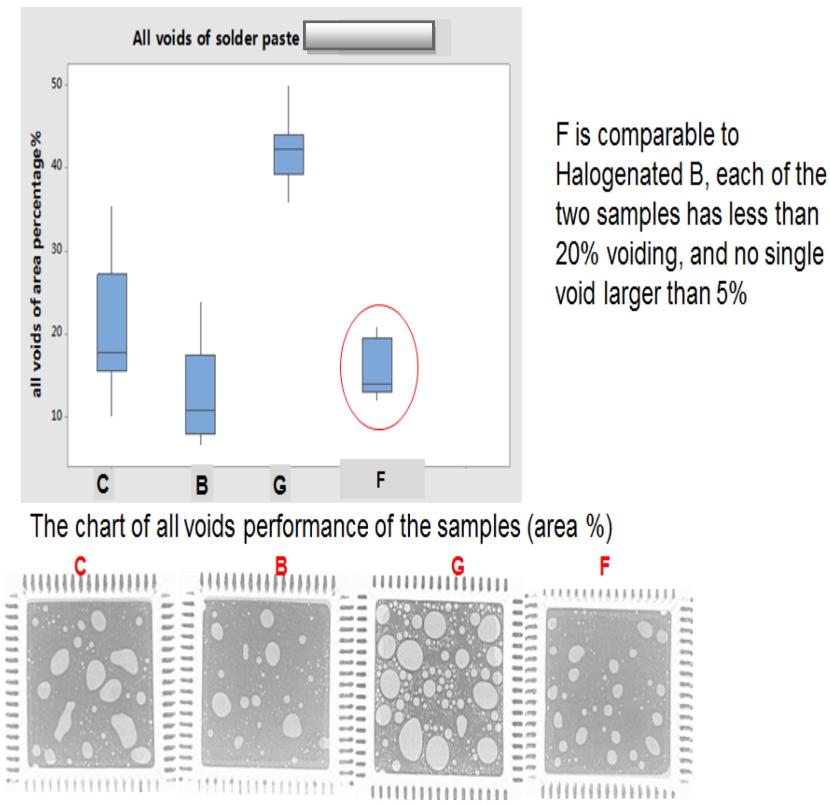


Figure 15. QFN Voiding performance of Alloy A solder pastes

For Alloy A , the halogenated B showed the lowest voiding, with halogen-free F being very close to B, as shown in Figure 15. Both pastes were significantly lower than the other two halogen-free pastes C and G, and no single void was larger than 5% for these two pastes.

The low voiding performance of halogen-free F on the 6-element solder alloy system 90.95Sn3.8Ag0.7Cu3Bi1.4Sb0.15Ni is particularly crucial for the automotive industry. The 6-element alloy system, including quite several versions of altered compositions, has demonstrated very promising reliability at high service temperature needed by automotive industry. In the meantime, halogen-free flux chemistry is becoming mandatory due to ROHS regulation and reliability consideration. However, up to this moment, all 6-element halogen-free solder pastes available on the market suffer very poor voiding performance. As a result, adoption of the 6-element solder paste occurred only at non-critical applications in automotive industry. The outstanding low voiding performance of F virtually enables the automotive to migrate to full adoption of the high reliability 6-element solder alloy system.

3. Solder Balling

Figure 16 shows the solder ball performance of the studied SAC305 pastes. F showed no difference from all the other pastes which have been accepted by industry. Table 3 showed the solder ball performance of Alloy A solder pastes. Again, all paste showed acceptable solder ball performance.

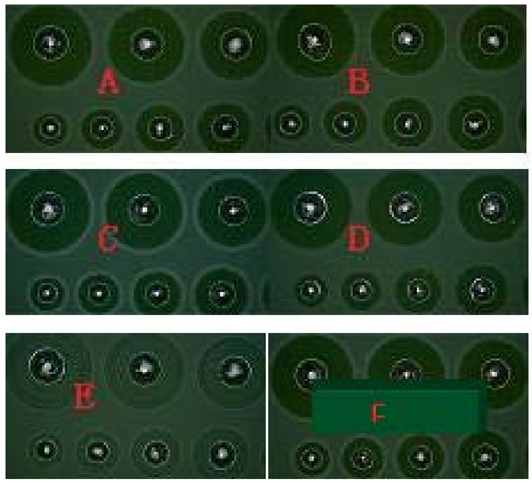


Figure 16. solder ball performance of the SAC305 samples

Table 3. Solder ball performance of Alloy A solder paste

Paste	C	B	G	F
Solder ball number	< 10	< 10	< 10	< 10

4. Hot Slump

Figure 17 shows the hot slump performance of the studied pastes. The order of hot slump resistance is shown below: D > F > A > B, E > C.

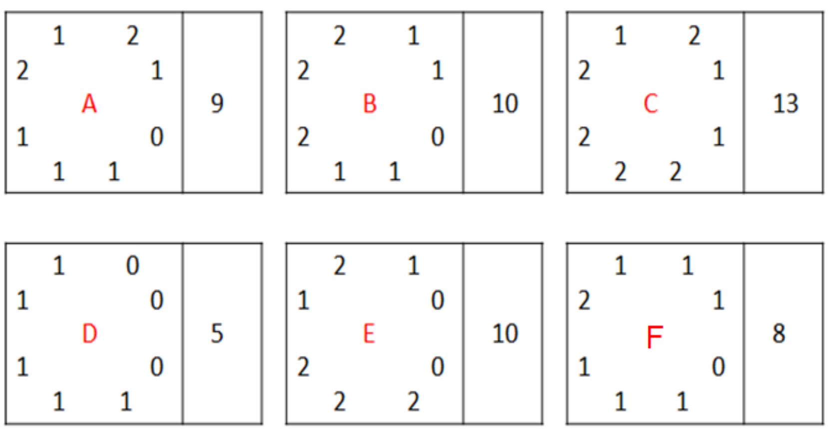


Figure 17. Hot slump performance of the SAC305 pastes

5. Graping

For SAC305 pastes, the graping results are shown in Table 4. F ranked in the middle of pastes tested.

Table 4. Graping performance of the SAC305 samples

Paste	A	B	C	D	E	F
Graping (%)	35	22	9.4	44.5	18.7	27

For Alloy A solder pastes, the results are shown in Table 5. Again, paste F performance ranked in the middle of pastes tested, with its graping occurred at 7 mils dot size or below.

Table 5. Graping performance of theAlloy A solder pastes

Paste	C	B	G	F
Graping (%)	9%	14%	15%	12%

6. **Solder Beading**

Among the SAC305 paste A, B, C, D, and E which have been used widely in industry, D is the best paste in solder beading performance. Under the same test condition, F was comparable with D, almost have no solder beads, as shown in Table 6.

Table 6. Solder beading performance of various SAC305 solder pastes

	A	B	C	D	E	F
Number	108	37	108	0/8	57	0/13
Percent	30%	10%	30%	1.1%	16%	1.8%

For Alloy A solder pastes, as shown in Table 7, F showed a much lower solder beading rate than all other samples.

Table 7. Solder beading performance of various Alloy A solder pastes

Paste	C	B	G	F
Solder Beading (%)	20%	10%	10%	0.5%

<u>Summary of Soldering Performance</u>

The soldering performance of SAC305 and Alloy A solder pastes are shown in Table 8 and Table 9, respectively. In both alloy systems, F was the only one performed best on voiding and solder beading, and was acceptable for the rest features tested.

Table 8 Summary of SAC305 solder paste soldering performance

Paste	Wetting (air)	Solder Ball	Solder Beading	Voiding	Hot Slump	Graping
A	X	√	X	X	√	O
B	√	√	X	X	√	O
C	√	√	X	X	√	√
D	√	√	√	X	√	O
E	√	√	X	X	√	O
F	√	√	√	√	√	O

Legend: √ good; O acceptable; X unacceptable

Table 9. Summary of Alloy A solder pastes soldering performance

Paste	Wetting (air)	Solder Ball	Graping	Solder Beading	Voiding
C	√	√	√	X	O
B	√	√	√	X	√
G	√	√	√	X	X
F	√	√	√	√	√

Legend: √ good; O acceptable; X unacceptable

Printing Performance of F

The printing performance of F SAC5 paste for 0201 pads under various printer setup conditions was shown in Figure 18. Regardless of stencil separation speed, squeegee pressure, and squeegee speed, virtually 100% transfer efficiency was always observed. The area ratio was 0.6548 for the 0201 pads during stencil printing.

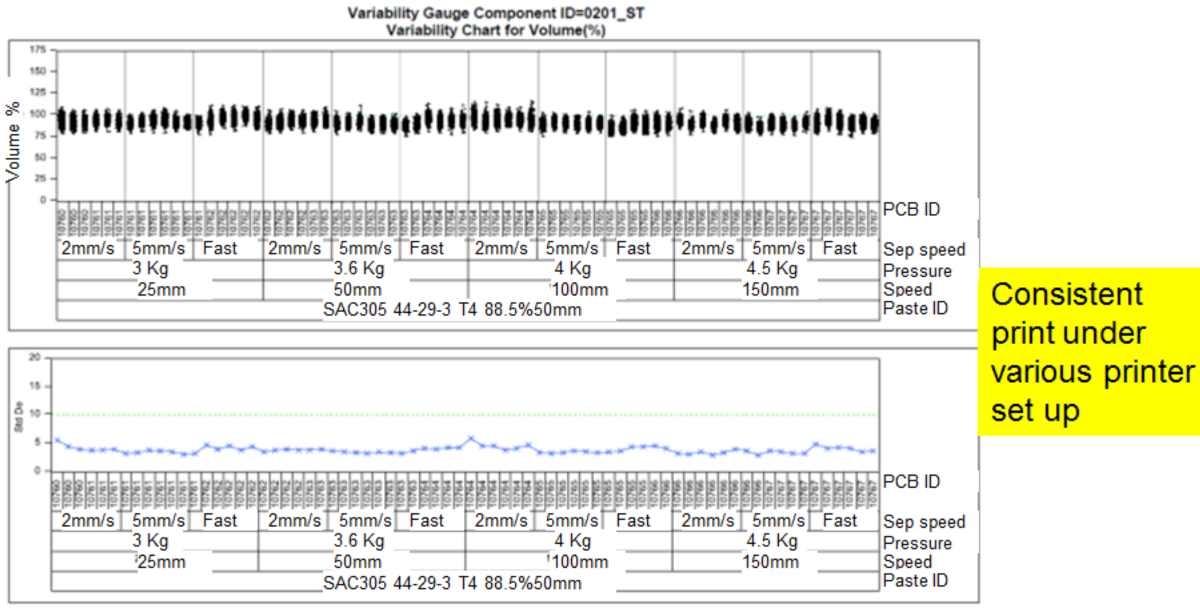


Figure 18. The printing performance of F SAC5 paste for 0201 pads under various printer setup conditions

The printing performance of F paste at various pad shape designs are shown in Figure 19. In all instances, the transfer efficiency was always higher than 90%. The stencil design involved in Figure 19 is shown in Table 10 below.

Table 10 Stencil aperture description.

Aperture Size	0201	S09	S10	S11	S12	S14	S16	C09	C10	C11	C12	C14	C16
Area Ratio	0.6548	0.5625	0.625	0.6875	0.75	0.875	1	0.5625	0.625	0.6875	0.75	0.875	1

Note
0201: 0.25mm x 0.28mm
S = Square
C = Circle
Stencil Thickness: 0.004” (102 µm)

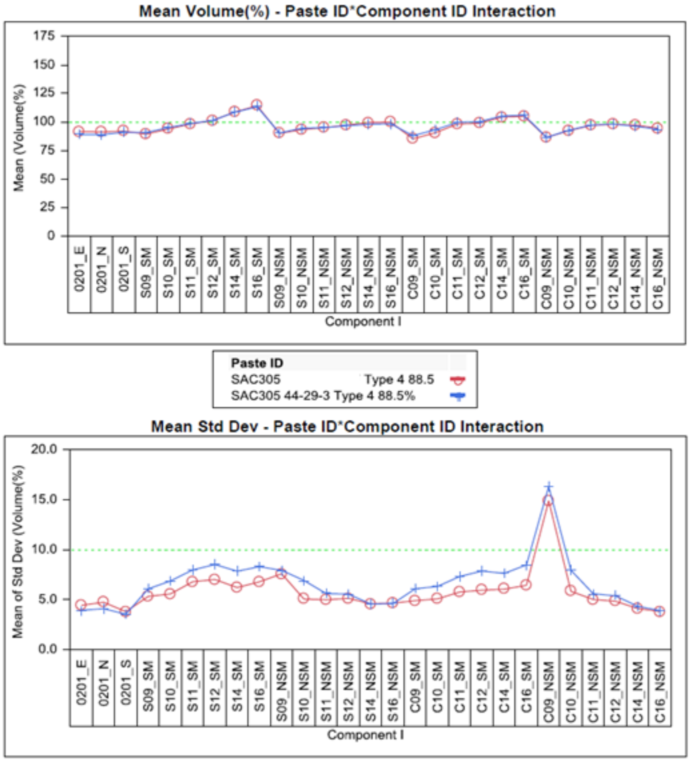


Figure 19. Printing performance of F at various pad designs.

Conclusions

The miniaturization trend is driving industry to adopting low standoff components. The cost reduction pressure is pushing telecommunication industry to combine assembly of components and electromagnetic shield in one single reflow process. As a result, the flux outgassing is getting very difficult for devices. This resulted in more large voids. For a properly formulated flux, there is less outgassing at temperature above melting temperature of solder or the flux can be expelled out from interior of solder joints due to good wetting ability. Either approach will reduce the voids. In this work, a new halogen-free no-clean flux chemistry, F, has been developed. The solder paste using SAC305 and Alloy A exhibited ultra-low voiding and virtually zero solder beading performance. The low voiding performance on Alloy A solder paste is particularly crucial since the automotive industry has been ailing by the poor voiding performance of this 6-element solder alloy system. The halogen-free F virtually enables the automotive to migrate toward full adoption of high reliability 6-element alloy system. Furthermore, the hot slump, wetting, solder balling, and graping performance are all acceptable. The printing performance of F showed excellent transfer efficiency under various printer setup and pad design conditions, indicating this flux system is a very robust system for SMT fine-pitch applications.

References

1. Derrick Herron, Dr. Yan Liu, and Dr. Ning-Cheng Lee, “Effect of Thermal Pad Patterning on QFN Voiding”, APEX 2011.
2. D. T. Novick, "A Metallurgical Approach to Cracked Joints," Welding J. Res. Suppl. 52, (4), 154S-158S(1973).
3. A. der Marderosian and V. Gionet, "The Effects of Entrapped Bubbles in Solder for The Attachment of Leadless Ceramic Chip Carriers'" in Proc. 21st IEEE International Reliability Physics Symposium, Phoenix, Arizona, pp.235-241 (1983).
4. V. Tvergaard,"Material Failure by Void Growth to Coalescence," in Advances in Applied Mechanics, Vol.27 (1989), Pergamon Press, pp. 83-149.
5. Guillermo Echeverria and Daryl Santos, “Effect of Lead-Free Assembly Processing on Solder Joint Voiding ”IPC/JEDEC International Conference on Lead Free Electronic Components and Assemblies. March 2004,
6. Wanda Hance and Ning-Cheng Lee, “Voiding Mechanisms in SMT”, China Lake’s 17th Annual Electronics Manufacturing Seminar, 1993
7. Tony Lentz,“Dispelling the Black Magic of Solder paste” IPC APEX EXPO 2015.