

## Study Of Alternate Surface Finishes For Quad Flat Packs

**Muffadal Mukadam /State University of New York at Binghamton, NY.**  
**Michael Meilunas/Universal Instruments Corporation, Binghamton, NY.**  
**K. Srihari/ State University of New York at Binghamton, NY.**

**Abstract:** The purpose of this study is to evaluate three different QFP lead finishes using steam age preconditioning. This evaluation is based on solder joint strength measured by lead pull test. The effects of steam age preconditioning on solder voiding, wetting, fillet formation, and solder joint strength is included. This paper also summarizes the details of the QFP assembly build and process characterization using visual inspection, X-ray, and cross-sectional analysis. Furthermore, microscopic examination of the fracture surfaces following the lead pull tests was performed.

### Introduction

The electronics industry is actively pursuing the move to Pb-free assembly. At the board level, alternatives such as Copper OSP and immersion Ag have already begun replacing Sn/Pb HASL. Various Sn/Ag/Cu alloys are beginning to replace Sn/37Pb solder in BGA and CSP devices and have also found favor in solder paste and wave applications. However, there is no front-runner in the race to remove lead from plating on leaded devices such as QFPs, SOICs, and TSOPs. Several plating finishes have been proposed, but only a handful are readily available. This study evaluated two Pb-free QFP lead finishes, Sn and SnCu, assembled with both Sn/37Pb and Sn/3.0Ag/0.5Cu pastes, and compared the results to the Sn/Pb baseline plating.

Historically, the lead pull test method was used to evaluate the solder joint strength of through-hole components. However, in this case, the lead pull test method was used to compare the solder joint strength of QFP components with three different lead finishes.

In practice, the solder joint strength of otherwise identical assemblies varies due to differences in fillet formation (mainly heel fillet), solder voiding (which determines the load bearing area), and lead to bulk solder bond strength (the intermetallic strength). These factors may be directly affected by lead surface finish and have been considered in this paper.

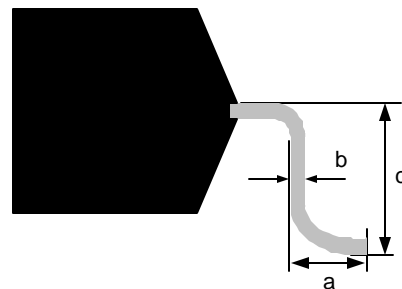
### Test Matrix

Fig. 1 provides the test matrix. Three QFP component lead finishes (i.e. Sn, SnCu, and SnPb), two solder alloys (Sn/37Pb and Sn/3.0Ag/0.5Cu), and three different steam age preconditioning levels (0 hr, 1 hr, and 8 hr) were evaluated.

A 62-mil thick FR-4 based printed circuit board with MacDermid immersion Ag pad finish was used throughout the study. Three QFP components were assembled on each test board. All the three QFP sites contained non-solder mask defined pads measuring 12 mils x 80 mils.

The QFPs evaluated were 0.5mm pitch, 208 I/O devices with gull wing leads. Dimensional variations between the lead designs are summarized in Table 1. The Sn (100%Sn) and SnCu (98.5%Sn, 1.5%Cu) plated components contained Cu as the leadframe base metal, while the SnPb plated devices contained alloy 42 (Ni/Fe).

**Table 1: QFP Component Lead Dimensions**



	a	b	c	Composition
Sn	23.6	8.0	86.0	100% Sn
SnCu	22.4	7.4	89.6	98.5%Sn, 1.5%Cu
SnPb	22.4	8.3	86.4	85%Sn, 15%Pb

All dimensions in mils

### QFP Assembly

The QFPs were steam age preconditioned according to IPC/EIA J-STD-002A. The components were steam aged

in a temperature / humidity chamber. The temperature at the preconditioning level was maintained at  $93\pm 3^{\circ}\text{C}$  and the relative humidity was maintained at 98%. The components were placed in a “Dead Bug” position to expose the leads to the aging environment and to allow condensate to drain away from the leads (Fig. 2).



**Fig. 2: Component Dead Bug Position**

QFP assembly was performed through solder paste deposition, component placement, and reflow soldering.

Solder paste was stencil printed over the test vehicles. A 5 mil thick laser cut stencil with apertures measuring 77.5 mils x 9.5 mils was used. The stencil printer was equipped with 60° metal squeegees and a board support was used to minimize flexing of the test vehicles during the print process. Each print was visually inspected using an optical microscope to determine the quality of the paste deposits. In general, the paste deposits were well defined with no apparent bridges.

The QFPs were placed with a four spindle flex head General Surface Mount (GSM) machine. Components were supplied to the GSM in matrix trays and a force of 150 grams was used to place the devices on the test vehicles.

A 10-zone forced convection oven with an air atmosphere was used for reflow soldering. Two reflow profiles were developed: one for Sn/37Pb assembly and one for Sn/3.0Ag/0.5Cu assembly. Details of the reflow profiles are provided in Table 2.

**Table 2: Reflow Profile Parameters**

Profile	Ramp Rate	Dwell Temp	Dwell Time	Peak Temp	TAL
Sn/Pb	2°C/sec	140-160°C	92 sec	220°C	67 sec
Sn/Ag/Cu	1.88°C/sec	155-172°C	97 sec	245°C	55 sec

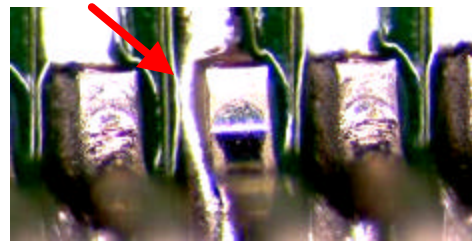
TAL = Time Above Liquidus

**Post Assembly Inspection**

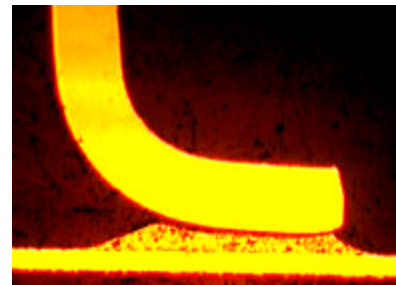
Post-reflow inspection determined that several assemblies contained offset leads. However, the off-centering was measured to be less than 25% of the lead width and was acceptable according to the IPC-A-610C standard. It is important to note that lead play, skew, and sweep are commonly encountered in QFP assemblies.

Several non-wetted leads were observed during visual inspection. The non-wetted leads physically contacted the soldered pads, but failed to form a strong metallurgical bond with the solder (see Fig. 3). Fig. 4 shows a cross-sectional image of a non-wetted lead. Fig. 5 shows an X-

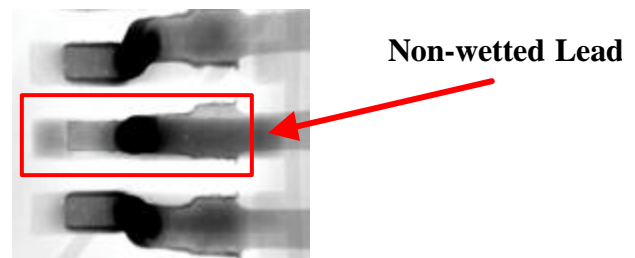
ray image of a non-wetted lead. The non-wetted lead is easily identified by a lack of solder around the foot of the lead.



**Fig. 3: Non-wetted Lead**

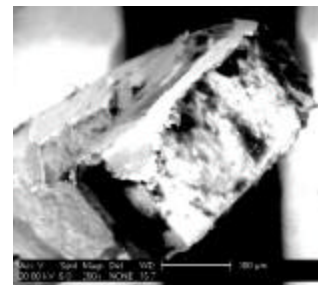


**Fig. 4: Cross-sectional Image of a non-wetted lead**



**Fig. 5: X-ray Image of a non-wetted lead**

An energy dispersion X-ray (EDX) analysis of the non-wetted lead surfaces discovered dark regions of high carbon content (see Fig. 6). This may be due to presence of impurity or presence of an oxide layer. The exact reasons are still unknown.



**Fig. 6: SEM Image of the bottom pad of an upside turned non-wetted lead**

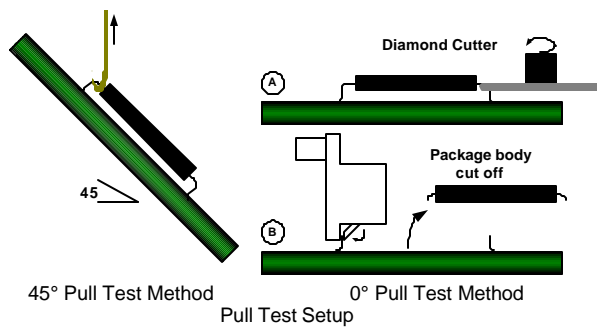
### Lead Pull Test Method

A literature review pertaining to lead pull testing suggests that two dominant methods exist: (1) 45° lead pull test method; and (2) 0° lead pull test method (as shown in Fig. 7) [1, 2, 3, 4, 5, 6, 7, 8, 9]. The most significant difference between the two test methods is that the 0° method requires cutting the QFP body from the leads and PCB, whereas the QFP assembly remains intact for the 45° method.

There is a wide disparity in the test methods and test conditions (i.e. crosshead speeds) used for performing lead pulls. Hence, there is a need to develop standards for performing the lead pull tests because the proprietary test fixtures (and test methods) make it extremely difficult to compare and evaluate the different QFP surface finishes using mechanical tests such as lead pulls.

In the 45° lead pull test method, the base fixture is so designed that the board remains at angle of 45° to the base. In this test, a wire or hook is used to pull the lead. The shortcoming of this test method is the difficulty to pull each lead individually, especially for a fine pitch QFP.

The 0° test method requires the mechanical removal of the QFP body (in this case a low speed / low force diamond saw was used) before the leads may be pulled. A special fixture then grasps one lead at a time to perform the pull test.



**Fig. 7: Lead pull test methods**

A comparison study found that the 45° method required greater forces to pull the QFP leads due to the existence of shear forces not encountered in the 0° lead pull. The 0° test method was also found to be more repeatable than the 45° test method. Therefore, all the lead pull tests performed for this study used the 0° test method.

### Sample Preparation

The sample preparation procedure consisted of two steps: (1) separating the assemblies into 1.75" x 1.75"

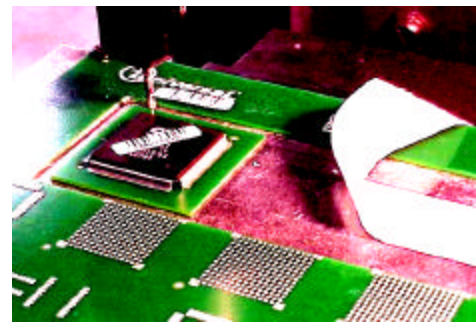
coupons; and (2) removing the QFP body from the coupon. The coupon cut out procedure was performed on a vertical milling machine using a machine drill (see Fig. 8). A double-sided tape was used to secure the boards to the milling fixture. This reduced the vibration during the cutting operation. The QFP removal procedure was also performed on the vertical milling machine using a low speed diamond saw (see Fig. 9). A very low feed rate was used to minimize vibration during the cutting process.

In a few cases, particularly for the alloy 42 (SnPb plated) QFPs, lead bending was observed during the package cutting operation. Also, the non-wetted leads were automatically detached during the package cutting operation due to the lack of a metallurgical bond with the solder.

### Lead Pull Test Fixture

A lead pull test fixture was designed in-house for performing the tests. The fixture was designed such that one lead could be pulled at a time. The fixture consisted of a self-centering base and a pneumatic device (see Fig. 10). The self-centering base moved on precision ball bearings and could be adjusted to any point on the X-Y plane within a limited area. The base was used to align the QFP leads accurately beneath the pneumatic device. The pneumatic device contained two small "jaws" capable of grasping a single QFP lead with a clamping force of approximately 60 pounds.

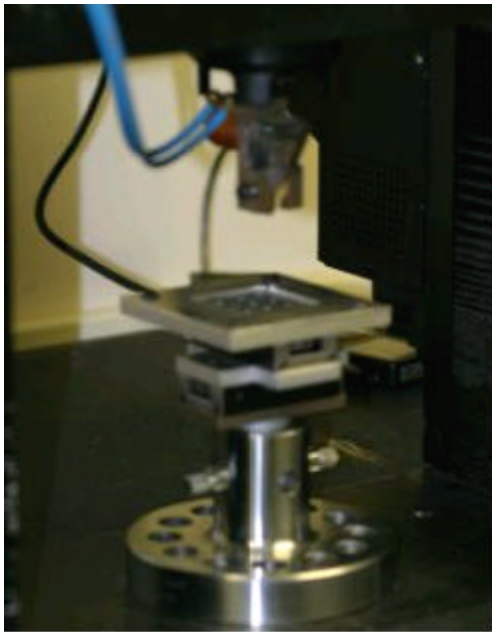
The pneumatic device was mounted directly to cross head containing a load cell. The crosshead was programmed to move in the Z-axis direction and the load cell recorded the force versus displacement data.



**Fig. 8: Coupon separation procedure**



**Fig. 9: QFP removal procedure**

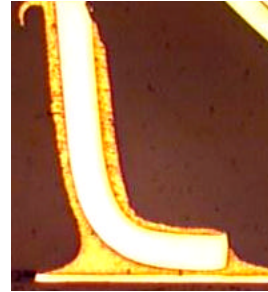


**Fig. 10: Lead pull test fixture**

Individual leads were grabbed at a height of approximately 5 mils above the PCB. A relatively low crosshead speed of 20 mils/min was used to pull the leads. References show use of markedly different pull speeds (or crosshead speeds) varying from 0.01"/min to 0.78"/min [1, 2, 3, 4, 5, 6, 7, 8]. The crosshead speed can significantly affect the resulting fracture surface with high crosshead speeds leading to 'brittle' fracture whereas low crosshead speeds tend to produce ductile failures.

#### Cross-sectional Analysis

Cross-sections were performed after the QFP bodies were cut from the coupons for each solder paste, lead finish, and steam age preconditioning combination. In general, the non-steam aged samples resulted in greater lead wetting than their 8-hour steam aged counterparts (see Fig. 11 and 12). Fig. 13 shows a schematic of the heel fillet wetting observed for the different steam age preconditioning levels.

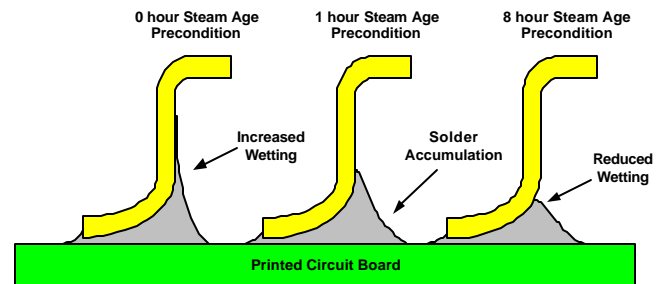


**Fig. 11: SnPb lead finish on Sn/37Pb solder paste with no steam aging**



**Fig. 12: SnPb lead finish on Sn/37Pb solder paste with 8 hour steam aging**

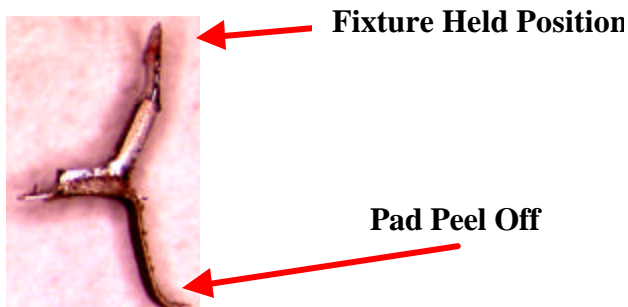
The cross-sectioned leads were also analyzed for minimum heel fillet criteria as per IPC-A-610C. In most cases, the minimum heel fillet was found to be acceptable for the class 3 (i.e. high performance electronic products) parameters provided in the standard.



**Fig. 13: Different wetting conditions**

#### Lead Pull Tests

30 leads were pulled per component. However, in a few cases, PCB pad peel off was observed during the test (see Fig. 14). Pad peel off indicates that the adhesive bond between the PCB pad and PCB substrate was weaker than the solder joint strength and therefore all pad peel offs were excluded from the analysis. The design of experiment required three components to be tested per combination. However, in some cases, the sample size was reduced to two components.



**Fig. 14: Pad peel off case**

The maximum pull force, in lbs, required to break each lead was recorded for each component. Fig. 15, Fig. 16, and Fig. 17 present the lead pull results for every SnCu, Sn, and SnPb plated QFP assembled with Sn/37Pb and Sn/3.0Ag/0.5Cu (SAC) solder pastes for the three steam age preconditions.

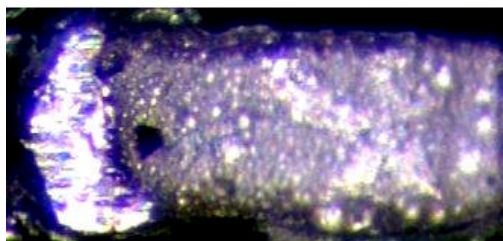
Fig. 15, Fig 16 and Fig 17 further separate the lead pull data into horizontal (H) leads and vertical (V) leads which are defined by their orientation on the PCB. The distinction between the lead orientation is important because solder paste transfer efficiency will vary based on print direction and these variations may alter the maximum lead pull force.

The data indicates that Sn and SnCu lead finishes produced higher lead pull forces with Sn/3.0Ag/0.5Cu solder than with Sn/37Pb solder. These results were not surprising given that the Sn/3.0Ag/0.5Cu alloy is a stiffer material.

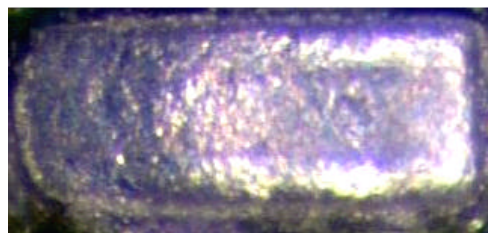
However, the pull forces obtained for the SnPb plated leads assembled with the Sn/3.0Ag/0.5Cu alloy were lower than those obtained using the Sn/37Pb paste. Figure 18 shows the fracture surface of a Sn/37Pb solder joint previously assembled to a SnPb lead. The shiny area at the heel of the joint indicates a ductile failure mode in that region. However, the remaining fracture surface is littered with voids, which may have reduced the strength of the joint. Figure 19 shows the fractured pad surface of a Sn/3.0Ag/0.5Cu solder joint previously assembled to a SnPb lead finish. The fracture surface is dull and grainy and is typical of a brittle failure.

SnCu lead finish showed higher lead pull forces for the 1 hour steam age precondition as compared to the other two preconditioning levels. This may be due to the solder accumulation at the heel side making the joint stronger (as explained in Fig. 13). Overall lower lead pull forces were seen with 8 hr steam age preconditioning especially with Sn/37Pb solder paste. This may be due to the solder wetting issues. SnPb lead

finish showed no trends with respect to steam age preconditioning and results were found to be variable. This may be due to the extensive voiding and solder wetting issues. Also, SnPb lead finish used alloy 42 as the leadframe base metal, which tends to bend more than Cu base metal leads during the package cutting operation.



**Fig. 18: Fractured Pad of Sn/37Pb solder previously assembled with SnPb Lead Finish**

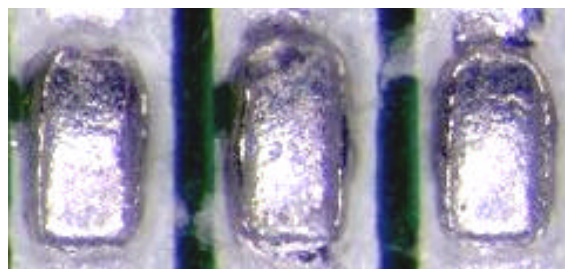


**Fig. 19: Fractured Pad of SAC solder previously assembled with SnPb Lead Finish**

#### Microscopic Examination of Fractured Surface

A microscopic examination of the fracture surfaces was performed following the lead pull tests. A fractured surface clearly shows the load bearing area associated with the joint. Voids, non-wet regions, and partial pad peel offs, which reduce the load bearing area, are visible and may be characterized.

The fracture surface of every lead tested was characterized. Voiding was categorized as minimal, moderate, or numerous. Fig. 20 and 21 show examples of minimal and numerous solder voiding.



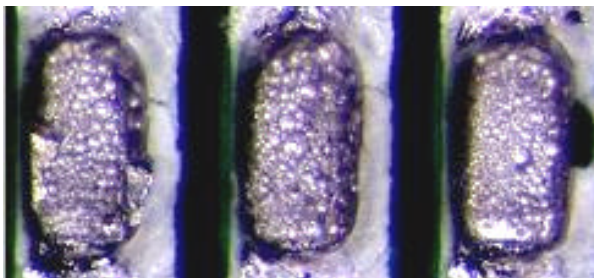
**Fig. 20: Minimal voiding**

Table 3 summarizes solder voiding, pad peel offs, and non-wetting cases for the different lead finish, solder paste, and steam age preconditioning combinations.

The size and frequency of solder voids varied significantly from component to component. Analysis indicates that voiding was not significantly affected by steam aging, solder paste, or lead finish with the exception of the Sn/Pb QFPs which produced less voiding with the Sn/3.0Ag/0.5Cu solder paste.

Non-wetting cases were frequently observed with Sn/37Pb assemblies following 8-hour steam age preconditioning for the three lead finishes. Non-wets were also encountered with the SnPb lead finish and Sn/37Pb paste combination after 1 hour steam age preconditioning. Non-wets were not associated with any other test condition.

Pad peel offs were commonly encountered with the Sn and SnCu assemblies subjected to 0 or 1 hour steam age preconditioning for both solder alloys. A lower occurrence of pad peel offs was associated with the SnPb samples after 0 or 1 hour of preconditioning. No pad peel offs were observed for any finish / paste combination after 8 hours of preconditioning. This observation, along with the supporting pull test data, indicates that the solder joint strength decreased after 8 hours of aging to a point where the joint strength was consistently lower than the PCB pad adhesive bond.



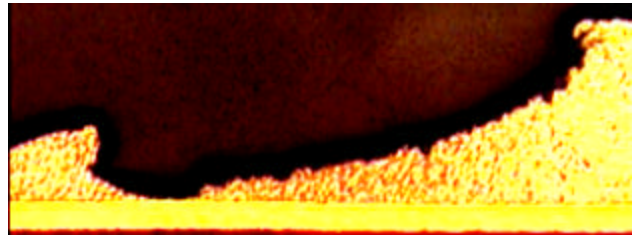
**Fig. 21: Numerous voiding**

#### Failure Mode Analysis

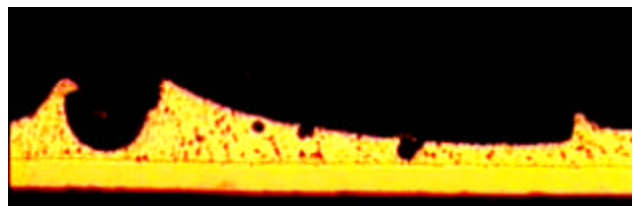
When performing the lead pull tests, the possible failure modes include fracture through intermetallic region, fracture through the bulk solder, lead breakage, and PCB pad peel offs. Fractured solder joints were cross-sectioned to determine the failure modes. Two types of failure modes were observed: (1) bulk solder failure and (2) intermetallic failure.

Typical bulk solder fracture is shown in Fig. 22. The fracture surface is characterized by its coarse shape and residual solder may be found on the lead (not shown). Fig. 23 indicates an intermetallic type failure. In this case, the fracture surface is smooth and flat and little solder remains on the lead. Bulk solder failures resulted in greater pull strength than similarly conditioned intermetallic failures.

The presence of voids in the fracture path, such as those shown in Fig. 23, reduced the maximum lead pull force by reducing the load bearing area. In general, packages with “minimal” voiding produced higher lead pull values than similar assemblies with “numerous” voids.



**Fig. 22: SnCu lead finish on Sn/37Pb solder paste with 1 hour steam age preconditioning (Average Lead Pull Force = 1.74 lbs, Std dev = 0.09)**



**Fig. 23: SnPb lead finish on SAC solder paste with 8 hour steam age preconditioning (Average Lead Pull Force = 1.45 lbs, Std dev = 0.17)**

#### Conclusions

A discussion of QFP assembly and lead pull study was presented in this paper. The combination of lead finish and solder paste does affect the lead pull forces. However, it is important to point out that a combination of lead play, off-centering, skew, coupon orientation, void formation, and sample preparation make it difficult to determine the exact reasoning for increase or decrease in lead pull force within the same lead finish (with same preconditioning and solder paste). Also, when comparing alternate surface finishes, the strength of the solder joint will vary depending on the component lead dimensions, solder modulus, intermetallic strength between the component and the solder, fillet formation, and amount of solder voiding, provided rest of the variables remain the same.

In this study, Sn and SnCu lead finishes showed higher lead pull forces with Sn/3.0Ag/0.5Cu solder paste whereas SnPb lead finish showed higher lead pull forces with Sn/37Pb solder paste. Sn and SnCu lead finishes showed comparable lead pull forces whereas SnPb lead finish showed lower lead pull forces compared to Sn and SnCu lead finishes. Non-wetting cases were observed with the 8 hr steam age preconditioned samples especially with the Sn/37Pb solder. Moreover, higher variation and lower lead pull

forces were observed for 8 hr steam age preconditioned samples. Higher solder voiding was observed for Sn/37Pb assemblies as compared to SAC assemblies. Pad peel offs were mainly observed for SAC assemblies.

**Acknowledgements**

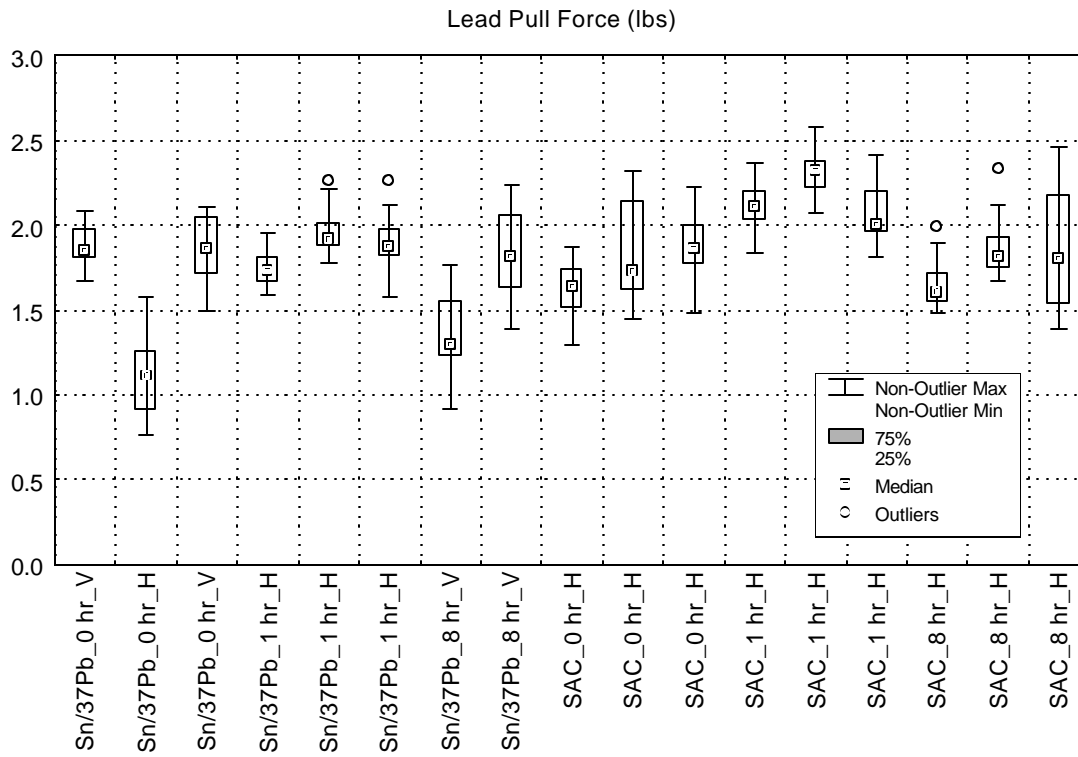
This project was completed at the Surface Mount Assembly Lab at Universal Instruments Corporation. The authors would like to extend gratitude to Mark Dunlap for assembly expertise, sample preparation, and Instron setup. Dr. Anthony Primavera is also recognized for his invaluable input.

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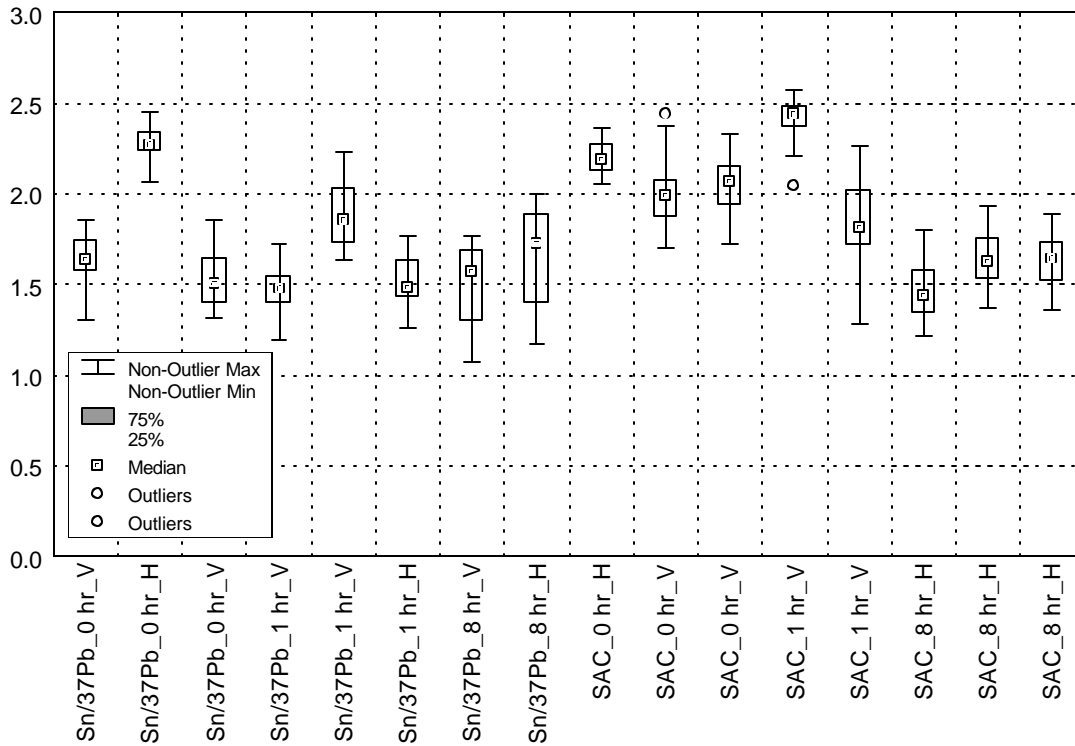
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**Fig. 1: Test matrix**

Solder Paste	Component Lead Finish	Steam Age Precondition	QFP Sites	Reflow
Sn/37Pb	SnPb	0 hour	3	215°C (Air)
		1 hour	3	
		8 hour	3	
	Sn	0 hour	3	
		1 hour	3	
		8 hour	3	
	SnCu	0 hour	3	
		1 hour	3	
		8 hour	3	
SAC	SnPb	0 hour	3	245°C (Air)
		1 hour	3	
		8 hour	3	
	Sn	0 hour	3	
		1 hour	3	
		8 hour	3	
	SnCu	0 hour	3	
		1 hour	3	
		8 hour	3	



**Fig. 15: Lead pull results for SnCu lead finish**



**Fig. 16: Lead pull results for Sn lead finish**

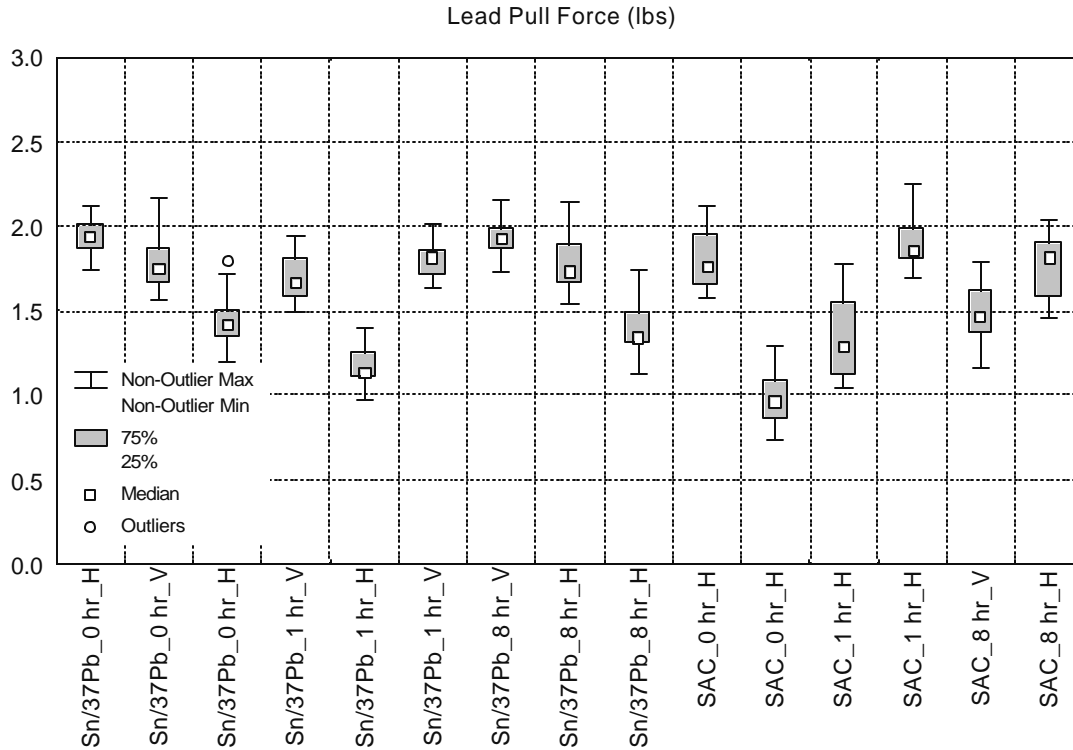


Fig. 17: Lead pull results for SnPb lead finish

Table 3: Summary of microscopic examination

Lead Finish	Solder Paste	Steam Precondition	Voiding Level	% Pad Peel Offs	% No-Wets
Sn	Sn/37Pb	0 hour	1/3/3	19%	-
		1 hour	3/3/3	2%	-
		8 hours	1/2/3	-	52%
	SAC	0 hour	2/2/2	14%	-
		1 hour	1/2	11%	-
		8 hours	2/2/3	-	-
SnCu	Sn/37Pb	0 hour	2/2/2	16%	-
		1 hour	2/2/2	14%	-
		8 hours	1/2	3%	19%
	SAC	0 hour	1/2/3	32%	-
		1 hour	2/2/2	25%	-
		8 hours	2/2/2	3%	-
SnPb	Sn/37Pb	0 hour	3/3/3	-	-
		1 hour	3/3/3	5%	23%
		8 hours	1/3/3	-	16%
	SAC	0 hour	1/1	11%	-
		1 hour	1/1	-	-
		8 hours	1/1	-	6%

Voiding Level: 1 - Minimal, 2 - Moderate, 3 - Numerous