Observations on the Influences of Various Parameters on Pb-free Solder Joint Appearance and Strength

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Abstract
A designed experiment evaluated the influence of several variables on visual appearance and strength of Pb-free solder joints. Components, with leads finished with nickel-palladium-gold (NiPdAu), were used from Texas Instruments (TI) and two other integrated circuit suppliers. Pb-free solder paste used was tin-silver-copper (SnAgCu) alloy. Variables were printed wiring board (PWB) pad size/stencil aperture (the pad finish was consistent; electroless Ni/immersion Au), reflow atmosphere, reflow temperature, Pd thickness in the NiPdAu finish, and thermal aging. Height of solder wetting to component lead sides was measured for both ceramic plate and PWB soldering. A third response was solder joint strength; a "lead pull" test determined the maximum force needed to pull the component lead from the PWB.

This paper presents a statistical analysis of the designed experiment. Reflow atmosphere and pad size/stencil aperture have the greatest contribution to the heights of lead side wetting. Reflow temperature, palladium thickness, and preconditioning had very little impact on side wetting height. For lead pull, variance in the data was relatively small and the factors tested had little impact on lead pull results.

Introduction
The "ceramic plate test", CPT, (Surface Mount Process Simulation Test, Test S in IPC/EIA/JEDEC J-STD-002) has been used in the industry since the early 1990's. The CPT method simulates the environment which surface mount devices encounter during solder reflow. In this method, solder paste is screened onto a ceramic substrate, the devices to be tested are placed on the printed solder paste, the ceramic substrate is processed through a reflow cycle and allowed to cool. After reflow, the units are easily removed from the ceramic for inspection. The beauty of this test is that the IC devices are subjected to the same solder paste and reflow environment seen in printed wiring board (PWB) processing and use of a ceramic substrate allows for inspection of the soldered lead surface (underside of lead foot) . However, use of a CPT in place of PWB soldering introduces a variable: the ceramic is by design a non-solderable surface while a PWB pad is a solderable surface. This non-wettability of the ceramic substrate can introduce artifacts into the appearance or geometry of the solder wetted to the lead.

As the industry moves into Pb-free processing with reflow environments and materials different from tin-lead (SnPb) soldering, it is imperative to understand the impact of these variables on solderability testing when using CPT and PWB methods.

Experiment
A designed experiment (DOE) evaluated the effect of several variables, summarized in table 1, on component lead side wetting and lead pull performance.

Table 1 - DOE Input Variables

I.D.	Variable	# Levels	L1	L2	L3
Pad	Pad Size/Stencil Aperture	3	CUST	IPC	TID
RA	Reflow Atmosphere	2	Air	N2	
RT	Reflow Temperature	2	230C	240C	
PDT	Palladium Thickness	2	0.01µ (0.4u")	>/=0.02µ (0.8u")	
AG	Precondition	2	None	16hr 155°C	

Three levels were evaluated for the PWB pad size/stencil aperture opening. “CUST” is a customer design, “TID” is a TI design and IPC is from the IPC guidelines. All were included on one board. The pad dimension correlated 1:1 with the stencil aperture. Dimensions and areas of the 3 levels evaluated are shown in table 2.

Table 2 - PWB Pad and Stencil Aperture Size

Pad / Aperture Opening	Length (mm)	Width (mm)	Area (mm2)
Cust	1.2	0.6	0.72
IPC	1.9	0.55	1.045
TID	1.52	0.76	1.155

RA was either air or nitrogen (N_2) purge. A Pb-free SnAgCu solder paste was used. RT of 230C and 240C were used. Pb-free, NiPdAu finished components were used. Components from 3 different suppliers were used with different Pd thicknesses, as shown in table 3.

Table 3 - Different Palladium Thicknesses

Component	Pd thickness um (u”)
TI	0.01 (0.4)
Comp 1	0.05 (1.97)
Comp 2	0.04 (1.57)

Pre-conditioning (thermal aging) was another variable. The two levels were no preconditioning and 16 hours/155°C

The designed experiment layout is shown in table 4.

Table 4 - Layout of Designed Experiment

Run	Pad	RA	RT	PDT	AG
1	Customer	Air	230	0.01	16 hr
2	Customer	Air	230	>0.02	0
3	Customer	Air	240	0.01	0
4	Customer	Air	240	>0.02	16 hr
5	Customer	N2	230	0.01	0
6	Customer	N2	230	>0.02	16 hr
7	Customer	N2	240	0.01	16 hr
8	Customer	N2	240	>0.02	0
9	IPC	Air	230	0.01	16 hr
10	IPC	Air	230	>0.02	0
11	IPC	Air	240	0.01	0
12	IPC	Air	240	>0.02	16 hr
13	IPC	N2	230	0.01	0
14	IPC	N2	230	>0.02	16 hr
15	IPC	N2	240	0.01	16 hr
16	IPC	N2	240	>0.02	0
17	TID	Air	230	0.01	16 hr
18	TID	Air	230	>0.02	0
19	TID	Air	240	0.01	0
20	TID	Air	240	>0.02	16 hr
21	TID	N2	230	0.01	0
22	TID	N2	230	>0.02	16 hr
23	TID	N2	240	0.01	16 hr
24	TID	N2	240	>0.02	0

Pad = pad dimension; RA = reflow atmosphere; RT = reflow temperature
PDT = Pd thickness; AG = preconditioning

Responses were component lead side wetting height in the CPT and PWB mount, and lead pull measurements after PWB mount. For lead side wetting height, the degree of wetting was judged on a scale of 0 – 1, with '0' being no solder wetting the side of the lead and '1' showing solder to the top edge of the lead, i.e 100% of the lead side was covered with solder. Statistical analysis of the output was performed using a common statistical analysis software package and output data was summarized in an Analysis of Variance (ANOVA) table and Effects Table.

The results will be presented below as TI components versus Comp 1 components and TI Components versus Comp 2 components – looking at CPT, PWB mount and lead pull results in that order.

Results: TI versus Comp 1

Lead Side Wetting Height in CPT Test Method

Analysis of Variance (ANOVA) results for CPT lead side wetting height of TI versus Comp 1 are shown in Table 5.

Table 5 - ANOVA Results for CPT Side Wetting, TI versus Comp 1

Rank	Source	df	SS	F Ratio	Prob>F	%Contribution
1	RA	1	7.287526	206.286	<0.0001	44.92
2	Pad (IPC&CUST-TID)	1	4.245326	120.171	<0.0001	26.17
3	PDT	1	1.438151	40.709	<0.0001	8.86
4	Pad (IPC&CUST-TID)*RA	1	1.325013	37.507	<0.0001	8.17
	Pad (IPC&CUST-TID)*PDT	1	0.7190755	20.355	<0.0001	4.43
	Pad(IPC-CUST)	1	0.2691016	7.617	0.0061	1.66
	Pad(IPC-CUST)*RT	1	0.2197266	6.220	0.0131	1.35
	AGE	1	0.206276	5.839	0.0162	1.27
	Pad(IPC-CUST)*RA	1	0.175352	4.964	0.0265	1.08
	RA*PDT	1	0.170859	4.847	<0.0001	1.05
	RA*AGE	1	0.162526	4.601	0.0326	1.00
	RT	1	0.005859	0.166	0.6841	0.04
	Total		16.224792			100.00

RA and Pad have the strongest contribution to side wetting height in the CPT method. Other factors (PDT, RT, and AG) all have lesser or no contribution.

The average effects table for individual factors is shown in Table 6.

Table 6 - Average Effects Table for CPT Side Wetting, TI versus Comp 1

Level	RA		Pad		PDT		AG		RT	
1	AIR	0.648	IPC	0.679	0.01	0.847	0	0.809	230	0.790
2	N2	0.923	Cust	0.744	0.05	0.724	16	0.763	240	0.782
3			TID	0.934						

The effects table clearly shows that RA and Pad have a strong effect. N2 provides higher side wetting performance. For factor of Pad, the wider the pad opening the higher the side wetting (see table 2). Thinner Pd showed higher side wetting. The effects of AG and RT are very minor.

Lead Side Wetting Height in PWB Soldering

ANOVA results for PWB lead side wetting height of TI versus Comp 1 are shown in Table 7.

Table 7 - ANOVA Results for PWB Lead Side Wetting, TI versus Comp 1

Rank	Source	df	SS	F Ratio	Prob>F	%Contribution
1	Pad (IPC&CUST-TID)	1	1.8116	131.448	<0.0001	53.85
2	RA	1	0.735	53.332	<0.0001	21.85
3	RT	1	0.2301	16.696	<0.0001	6.84
4	Pad (IPC-CUST)*AG	1	0.18598	13.495	0.0003	5.53
	Pad (IPC&CUST-TID)*RA	1	0.17824	12.933	0.0004	5.30
	Pad(IPC-CUST)*RT	1	0.10973	7.962	0.0050	3.26
	RA*RT	1	0.065104	4.724	0.0304	1.94
	AGE	1	0.04167	3.023	0.0829	1.24
	Pad(IPC-CUST)	1	0.0066	0.479	0.4893	0.20
	PDT	1	0			0.00
	Total		3.364024			100.00

Pad and RA have the strongest contribution to side wetting height in PWB mount. Other factors (PDT, RT, and AG) all have lesser or no contribution.

The average effects table for individual factors is shown in Table 8.

Table 8 - Average Effects Table for PWB Lead Side Wetting, TI versus Comp 1

Level	Pad		RA		RT		AG		PDT	
1	IPC	0.836	Air	0.846	230	0.865	0	0.879	0.01	0.890
2	Cust	0.846	N2	0.933	240	0.914	16	0.9	0.05	0.889
3	TID	0.987								

The effects table shows that Pad and RA have a strong effect. Once again for the Pad factor, the wider pad opening yields higher lead side wetting. For RA, N_2 provides higher lead side wetting. The effects of RT, AG and PDT are very minor.

Lead Pull Variation in PWB Soldering

ANOVA results for component lead pull after PWB soldering of TI versus Comp 1 are shown in Table 9.

Table 9 - ANOVA Results for Lead Pull after PWB Soldering, TI versus Comp 1

Rank	Source	df	SS	F Ratio	Prob>F	%Contribution
1	RT	1	2.5438	21.264	<0.0001	48.44
2	Pad (CUST&IPC-TID)	1	2.1901	18.307	<0.0001	41.70
3	Pad (IPC-CUST)*RT	1	0.405	3.386	0.0674	7.71
4	Pad (IPC-CUST)	1	0.1128	0.943	0.3328	2.15
	Total		5.2517			100.00

RT and Pad contribute strongly to lead pull variation after PWB mount. Other factors (RA, PDT, and AG) have no contribution.

The average effects table for individual factors is shown in Table 10.

Table 10 - Average Effects Table for Lead Pull after PWB Soldering, TI versus Comp 1

Level	Pad		RA		RT		AG		PDT	
1	IPC	2.033	Air	2.042	230	1.964	0	2.083	0.01	2.1
2	Cust	1.973	N2	2.116	240	2.194	16	2.074	0.05	2.057
3	TID	2.230								

The effects table for lead pull shows extremely little contribution from any variable in this experiment. Basically, all lead pull data is in the same range.

Summary / Conclusions for TI versus Comp 1

In both CPT and PWB soldering, RA and Pad contribute strongest to component lead side wetting height. The other factors had negligible or no contribution. N_2 provided the highest side wetting of leads and for Pad, the wider the pad/stencil aperture opening, the higher the lead side wetting. For lead pull after PWB mount, RT and Pad had the greatest contribution to variance. However, the effects table shows there is very little variation in the lead pull data across all groups.

Results: TI versus Comp 2

Lead Side Wetting Height after CPT Testing

Analysis of Variance (ANOVA) results for CPT lead side wetting height of TI versus Comp 1 are shown in Table 11.

Table 11 - ANOVA Results for CPT Side Wetting, TI versus Comp 2

Rank	Source	df	SS	F Ratio	Prob>F	%Contribution
1	RA	1	4.6376042	146.650	<0.0001	61.53
2	Pad (IPC&CUST-TID)	1	1.622513	51.307	<0.0001	21.53
3	Pad (IPC&CUST-TID)*RA	1	0.5365755	16.968	<0.0001	7.12
	Pad(IPC-CUST)*RT	1	0.2691016	8.510	0.0037	3.57
	Pad(IPC-CUST)	1	0.2562891	8.104	0.0047	3.40
	PDT	1	0.1426042	4.509	0.034	1.89
	Pad(IPC-CUST)*PDT	1	0.0722266	2.284	0.1316	0.96
	Total		7.5369142			100.00

RA and Pad have the strongest contribution to lead side wetting height in the CPT. Other factors (PDT, RT, and AG) all have lesser or no contribution. The average effects table for the individual factors is shown in Table 12.

Table 12 - Average Effects Table for CPT Side Wetting, TI versus Comp 2

Level	RA		Pad		PDT		AG		RT	
1	AIR	0.718	IPC	0.750	0.01	0.847	0	0.829	230	0.829
2	N_2	0.938	Cust	0.813	0.04	0.808	16	0.826	240	0.826
3			TID	0.920						

The effects table shows that RA and Pad have a strong effect. N_2 provides higher lead side wetting. For the factor of Pad, the wider the pad opening the higher the lead side wetting. Thinner Pd showed slightly higher side wetting. AG and RT had no effect.

PWB Lead Side Wetting Height

ANOVA results for PWB lead side wetting height of TI versus Comp 2 are shown in Table 13.

Table 13 - ANOVA Results for PWB Lead Side Wetting, TI versus Comp 2

Rank	Source	df	SS	F Ratio	Prob>F	%Contribution
1	Pad (IPC&CUST-TID)	1	1.3167187	83.324	<0.0001	48.16
2	RA	1	0.8251042	52.214	<0.0001	30.18
3	RT	1	0.2604167	16.480	<0.0001	9.52
4	Pad (IPC&CUST-TID)*RA	1	0.2200521	13.925	0.0002	8.05
	PDT	1	0.0816667	5.168	0.0236	2.99
	RT*PDT	1	0.0301042	1.905	0.1683	1.10
	Total		2.7340626			100.00

Again, Pad and RA have the strongest contribution to lead side wetting height in board mount. Other factors (PDT, RT, and AG) show less or no contribution.

The average effects table for the individual factors is shown in Table 14.

Table 14 - Average Effects Table for Lead Side Wetting after PWB Soldering, TI versus Comp 2

Level	Pad		RA		RT		AG		PDT	
1	IPC	0.859	Air	0.858	230	0.879	0	0.898	0.01	0.890
2	Cust	0.867	N_2	0.951	240	0.931	16	0.912	0.05	0.919
3	TID	0.988								

The effects table shows that Pad and RA have minor effect. Once again for the Pad factor, the wider pad opening provides higher side wetting. For RA, N_2 provides higher side wetting. For RT effect is minor and 240°C provides higher wetting. AG and PDT have virtually no effect on side wetting height in PWB soldering.

Lead Pull Variation in PWB Soldering

ANOVA results for component lead pull after PWB soldering of TI versus Comp 2 are shown in Table 15.

Table 15 - ANOVA Results for Lead Pull after PWB Soldering, TI versus Comp 2

Rank	Source	df	SS	F Ratio	Prob>F	%Contribution
1	RT	1	1.6875	12.676	0.0005	28.27
2	PDT	1	1.4352	10.781	0.0012	24.04
3	Pad (CUST&IPC-TID)*RA	1	1.0732	8.061	0.0050	17.98
4	Pad (CUST&IPC-TID)	1	0.7975	5.991	0.0153	13.36
	RA*PDT	1	0.6075	4.563	0.0340	10.18
	RA	1	0.3008	2.260	0.1345	5.04
	RT*PDT	1	0.0675	0.507	0.4773	1.13
	Total		5.9692			100.00

The variation seen in lead pull after PWB mount is spread across the main factors of RT, PDT, and RA. The other factors (Pad and AG) show no contribution to variation.

The average effects table for the factors is shown in Table 16.

Table 16 - Average Effects Table for Lead Pull after PWB Soldering, TI versus Comp 2

Level	RT		PDT		Pad		RA		AG	
1	230	1.920	0.01	2.1	IPC	1.995	Air	2.053	0	1.994
2	240	2.107	0.04	1.927	Cust	1.941	N2	1.974	16	2.033
3					TID	2.105				

The effect of the main factors is very small for lead pull response. RT has a slight effect with 240°C being best case. PDT has a slight effect with 0.01 being best case setting. Pad also has a slight effect with TID being best case. RA and AG have no effect. In general for lead pull after PWB soldering the variation in the data is very small confirming that the effect of these variables is also small.

Summary / Conclusions for TI versus Comp 2

In both CPT and PWB soldering, RA and Pad contribute strongest to component lead side wetting height. The other factors had negligible or no contribution. N_2 provided the highest side wetting of leads and for Pad, the wider the pad/stencil aperture opening, the higher the lead side wetting. For lead pull after PWB mount, RT and Pad had the greatest contribution to variance. However, the effects table shows there is very little variation in the lead pull data across all groups.

Summary / Conclusions

In both CPT and PWB soldering, RA and Pad gave the strongest contribution to component lead side wetting height. Other factors have little or no contribution. N_2 provided the highest side wetting and for Pad, the widest pad/stencil aperture opening showed the highest side wetting. For lead pull after PWB mount, the variance in the data was spread across RT, PDT, and RA, however, the effects table shows very little variation in the lead pull data across all groups.

Conclusions

- Of the factors tested, reflow atmosphere and pad/aperture size have the greatest contribution to component lead side wetting height.
- Reflow temperature, palladium thickness, and precondition had very little impact on lead side wetting height performance.
- For lead pull, variance in the data was relatively small. Factors tested had little impact on lead pull results.