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Wave Solder Process Optimization for Complex Electronic Assemblies: A Design of Experiments Approach

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Abstract
Numerous technical articles have dealt with machine parameters, and their effect on wave soldering of Printed Circuit Boards in the range of 40-93 mils and the typical 6 to 8 layers. This research concentrates on identifying the key process parameters that affect wave soldering with 63Sn/37Pb solder on a 15 layer (9 signals and 6 power and grounds) board that is 104 mils thick. A detailed Designed Experiment was developed and executed in multiple stages to identify the full impact of all the factors considered. Key response variables that would impact yield and reliability of the product were considered. The results were analyzed using the ANalysis Of VAriance or ANOVA approach. The aim of the research effort was to find a global solution that would work well for 60 to 200 mils thick boards. The study was also aimed at finding more specific solutions for other products based on board thickness. To date, this process had been successfully implemented on 135 mil thick 26 layer boards and 187 mil thick 16 layer boards.

Introduction
Wave soldering has typically been the last segment in the assembly process before the assemblies are electrically / optically tested for accuracy of placement and soldering (both reflow and wave). Wave soldering is generally used to solder through hole components to Printed Circuit Boards (PCBs). The general procedure used for wave soldering is as follows:

- Application of flux (either foam or spray) to clean the surface of oxides that may have developed before and during wave soldering.
- Preheating the PCB to help in the following ways;
  - It raises the flux to a temperature where it is chemically active to reduce the metal oxides.
  - It allows adequate temperature to be reached before contacting the solder, such that the solderable surfaces rises above the liquidus temperature while in the solder wave and allow soldering to occur.
  - It reduces the chance of thermal shock damage to the PCB and components.
- Soldering of through hole components is correctly done by capillary action. Hydraulic pressure is sometimes used to 'pump' the solder up the holes, though its use is both unnecessary and detrimental because 'hole-fill' can be achieved even without hydraulic pressure and it risks new defects such as 'bulbous solder', solder squeeze between the PCB and pallet, and PWB overflow with solder.

Equipment and Material Background
The machine / equipment used for the experimentation is an automated programmable wave soldering machine. The machine is equipped with a foam fluxer and has 3 distinct heating zones. Various attributes (viz. specific gravity, flow rate and size of the bubbles) of the flux are controlled within the machine. Preheat Zones 1 and 2 have both top InfraRed (IR) heaters and bottom forced convection heaters. Zone 3 consists of only the forced convection heater at the bottom. As for the solder waves, the machine has both the chip as well as the laminar waves. Individual motors control the flow of solder through the two waves. The laminar wave is "agitated" to create a small amount of turbulence on the surface of the wave. An oscillating metal plate at constant frequency and varying amplitude creates the turbulence. This amplitude can be manipulated to obtain varying degrees of turbulence (this turbulence is known to aid hole-fill, and will be demonstrated in a later section). The chip wave also uses a similar principle to create turbulence. The machine employs an air knife for de-bridging purposes. The assemblies are soldered in pallets that add to the thermal load on the wave soldering machine. The pallets are constructed from fiber reinforced high temperature polymer that withstands the temperatures seen during the preheat stages and the solder wave. Openings are provided at areas that require soldering, while other areas are shielded to prevent damage to bottom side

reflow SMT joints. Adequate pallet to PWB sealing is provided to prevent solder squeeze (molten solder flowing between the pallet and PWB), and thus risk causing a short.

Wave Soldering Principle

The principle behind wave soldering is simple: a PCB on a pallet rides on an inclined conveyor and skims the surface of flowing solder to allow capillary action to fill the Plated Through Holes (PTHs) with solder. The predominant force that aids wave soldering as mentioned above is capillary action, although in various instances, hydraulic pressure is used to compensate for poor preheat. Hydraulic pressure is created by "jacking-up" the wave height, thus allowing the solder to gush through the PTHs and filling them. This form of filling PTHs could lead to solder splash (as will be shown in a later section). An analytical model of capillary action hole-fill was developed and used to determine if 130 to 200 mil PWBs were inherently too thick to get good hole-fill. The physics of hole-fill by capillary action is shown in a free body diagram in Figure 1. In order to make the theoretical hole-fill sufficiently realistic, a sub- optimal wetting angle of 30° was assumed even though wetting angles are typically less than 15°. Figure 2 shows the maximum hole-fill without leads being present (worst case scenario) for various PCB real thicknesses under the assumption of having a constant wetting angle of 30^o (a wetting angle of 30^o is a conservative estimate). The calculations prove that hole-fill is immaterial and is not affected by the "thick PCB" scenario and thus provide the motivation for the process development effort. Hole-fill in the range of 796 and 907 mils are possible on PWBs having real thicknesses 65 and112 mils, respectively. If leads are present, maximum wetting height (possible PWB thickness) increases dramatically as lead diameter approaches PTH diameter as shown in Figure 3, which also conservatively uses a suboptimal wetting angle of 30º.

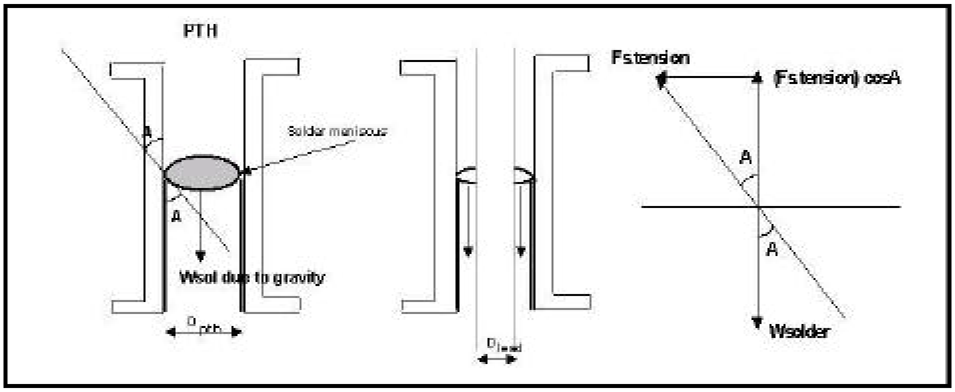
Product Specifications

All initial experiments were conducted on a 104 mil thick board. One consideration for the experiment was that the process developed would be developed in such a way as to facilitate process transfer to thicker boards that are up to 200 mils thick and comprising upwards of 26 Cu layers. Prior to experimentation, all the PTHs were inspected to avoid any unusual conditions. During the initial experimentation phase it was noticed that there was inconsistent hole-fill, especially on a pair of PTHs for an electrolytic capacitor. The pair of PTHs contained one with a circular land and one with square land to indicate capacitor insertion polarity. Only the lands were square and circular; both PTHs were circular and the same dimensions. Initial experiments and manufacturing data revealed that the PTH with the square land was much easier to fill with solder than the PTH with the circular land. Cross sections of the two holes revealed that the PTH with the round land was connected to 5 internal ground planes. Temperature measurements with the original soldering process indicated that the round land PTH did not reach the solder liquidus temperature (183^oC) while in contact with the solder wave. The ground planes are shown in Figure 4.

The specifications of the PCB under consideration are as follows:

- Thickness – 104 mils;
- Layers:
  - Signal – 9;
  - Power and Ground – 6.

All the experiments (and the results obtained) were based on the PTHs with round pads and the ability to consistently fill them. Several experiments were designed and multiple response variables were analyzed.



At equilibrium, (equilibrium prevails once the PWB leaves contact with the solder wave - i.e. hydraulic pressure is removed)

Vertical force due to solder wetting the Cu barrel $= W_{SOLDER}$

$$\gamma_{63Sn/37Pb}\ p\ D_{PTH}\ CosA = \rho_{SOLDER}(p/4(D_{PTH}^2 - D_{LEAD}^2))\ h\ g$$

$$h = \frac{[\rho_{SOLDER}\ (p\ (D_{PTH}^2 - D_{LEAD}^2))g]}{[4\ \gamma_{63Sn/37Pb}\ p\ D_{PTH}\ CosA]}$$

Figure 1 - Free Body Diagram of Hole-fill Mechanics

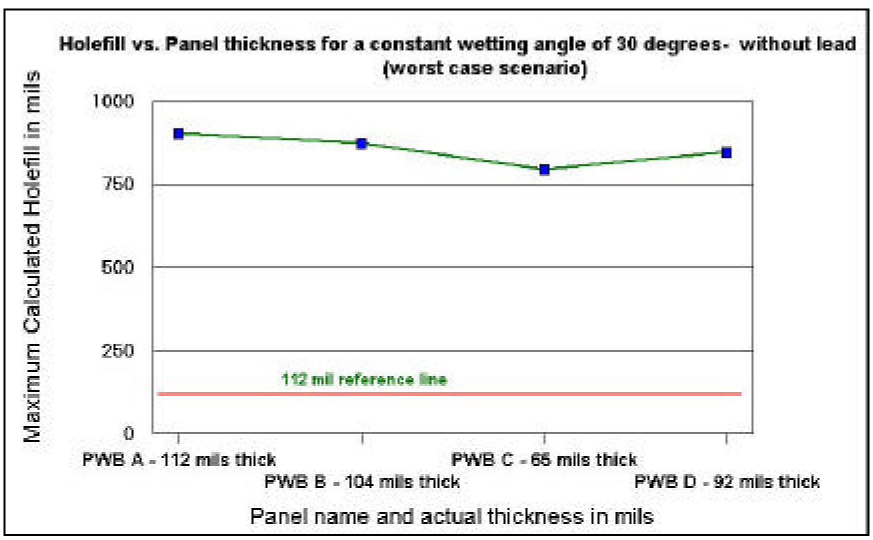


Figure 2 - Calculated Hole-fill with No Lead in PTH and a Constant Wetting Angle of 30°

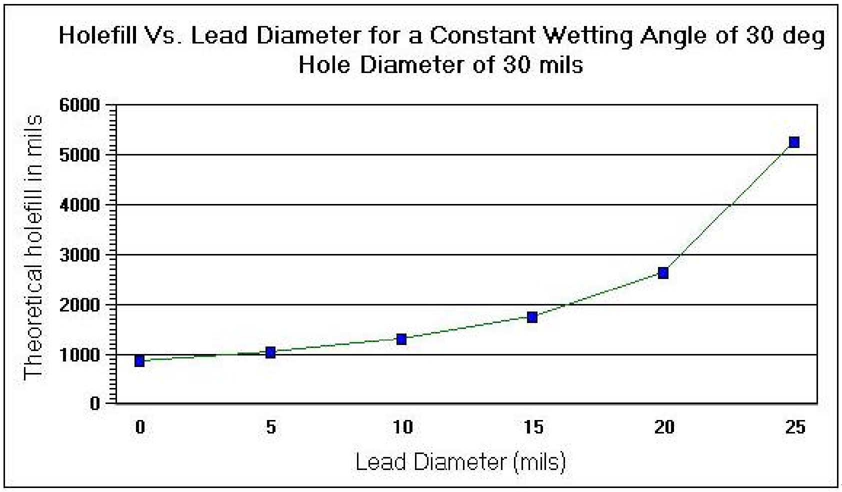


Figure 3 - Calculated Hole-fill with Lead in PTH and a Constant Wetting Angle of 30^o

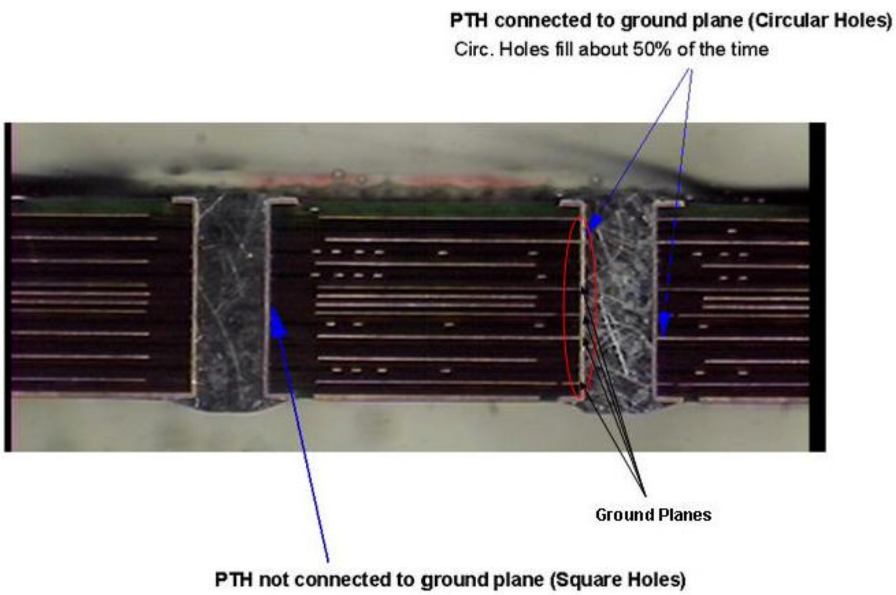


Figure 4 - PTH Connected to Multiple Ground Planes

Designed Experiments

Prior work was conducted to determine some of the critical factors that define the effectiveness of the wave soldering process. Some of these factors are:

- Surface temperatures of the PCB (both top and bottom side temperatures);
- Dwell time in the laminar wave;
- Effect of chip wave utilization;
- Effect of the laminar wave vibration.

With the above factors determined, the next stage was to develop experiments targeted at improving the above factors.

DOE 1
In order to provide uniform PWB temperature, a substantial amount of heat was supplied in the first two heat zones with an asymptotic thermal soak during the third and final preheat zone. This was effective at providing uniform PWB temperature and was adopted for thermal profiling in all experiments. The factors, levels and the response variables for DOE 1 are listed below:

- Dwell time in the wave (only laminar wave)
  - 9 seconds;
  - 5 seconds.
- Preheat temperature
  - 135-145^{o}C (140^{o}C nominal);
  - 115-125^{o}C (115^{o}C nominal).
- Laminar wave oscillation (% of maximum amplitude)
  - 50%;
  - 100%.
- Chip Wave
  - Off;
  - On (with the chip wave motor [height control] running at 750 rpm and the rotary motor [turbulence producer] at 300 rpm).

The PCB selected for experimentation contains 52 PTHs (26 circular pad PTHs and 26 square pad PTHs as shown in Figure 5). The response variables monitored were as follows.

Response Variables
RP 1 – Number of incompletely soldered lands (*the total number of PTHs that failed to have 100% solder coverage of the Cu lands)*.
RP 2 – Number of incompletely filled holes (*the total number of square and circular holes/PTHs that were partially filled – as shown in Figure 6*).
RP 3 – Solder squeeze (*solder getting squeezed between the PCB and the pallet and likely to cause a short- as shown in Figure 7*).
RP 4 – Bulbous solder (*gushing of solder paste through vias and PTHs and forming attached solder balls in the topside of the PCB* holes– as shown in *Figure 8*).
The "Likert" or "Summative" scale was used to measure the extent of solder squeeze and bulbous solder. This method is used in cases where the response being assessed cannot be easily quantified. In such cases, the measured quantity is rated on a response scale after verification of all the possible outcomes. In the case of solder squeeze and bulbous solder a scale of 0 - 2 was used with the following interpretation:
0 – No solder squeeze or bulbous solder on the PCB;
1 – Intermediate "damage" between the two extremities; and
2 – Extensive solder squeeze or bulbous solder on the PCB.
RP 5 – Ionic contamination (*ionic residue left on the PCB*). (Note: This last response variable was considered only for DOE 2).

Thermal profiling was undertaken in order to determine the critical process parameters. The 4-factor 2-level experiment translated into 16 runs / replicate. Two replications were conducted for DOE 1, and the results were analyzed using the ANOVA approach. For all experiments, the wave height was set to rise up the pallet and 50% of the PCB thickness.

Results – DOE 1
Although all the five response variables RP1-RP4 were analyzed, the results of the first two are discussed in detail as part of DOE 1. As for response variables RP3 and RP4, only a summary has been provided as part of DOE 1. The main and interaction effects of the response variable RP1 (RP1 – incompletely soldered lands) are shown in Figure 9 and Figure 10, respectively.

The main effect plot illustrates very clearly that the factors preheat temperature and dwell time in the wave affect the total number of soldered lands (maximum – 52 holes / PTHs), while the other main effects (laminar wave vibration and chip wave – on vs. off) do not significantly affect the response variables under consideration.
The interaction effect plot shows that the interaction between preheat temperature and dwell time in the wave and the interaction between laminar wave vibration and chip wave are significant. The ANOVA table is shown in Table 1. shows that the aforementioned factors are significant at an a – value of 0.05.

Figure 11 and Figure 12 are the main and interaction plots for the response variable RP2 (RP2 – incompletely filled holes), while the ANOVA results are shown in Table 2. Figure 11 shows preheat temperature and dwell time in the wave as being significant main effects, while Figure 12 and Table 2 shows the interaction effects of preheat temperature + dwell time in the wave and dwell time in the wave + omega vibration as being significant interaction factors, all at an a – value of .117. As for the response variable RP3 (RP3 – Solder squeeze), the factors that impact this variable are dwell time in the wave and laminar wave vibration in addition to the following interaction effects of preheat temperature*dwell time in the wave, preheat temperature*dwell time in the wave*chip wave. As laminar wave vibration amplitude increases, the tendency for solder squeeze increases. For the response variable RP4 (RP4 – Bulbous solder), the factors that impact this variable are dwell time in the wave and laminar wave vibration and the interaction effects of dwell time in the wave*laminar wave vibration. As laminar wave vibration amplitude increases, the tendency for bulbous solder protruding from vias increases.

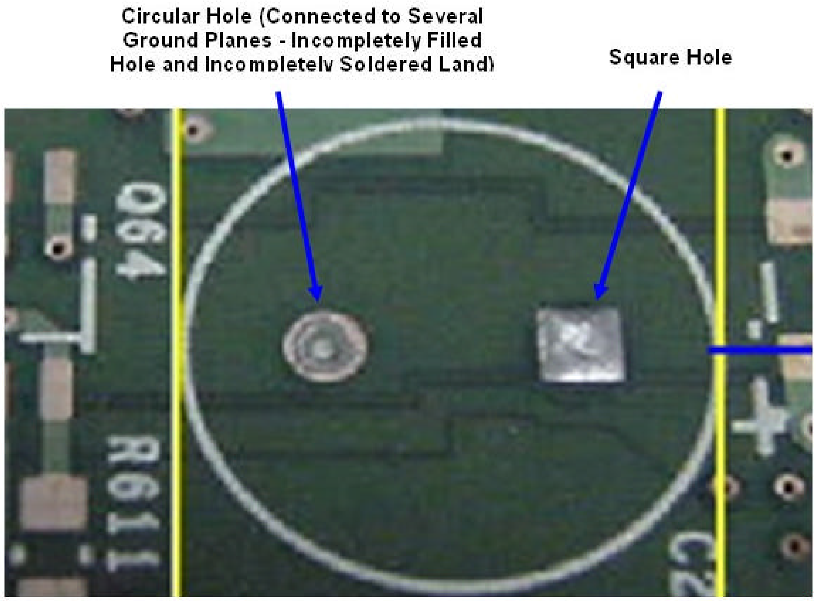


Figure 5 - Circular Pad (Connected to Several Internal Ground Planes) and Square Pad PTH of Electrolytic Capacitor Site

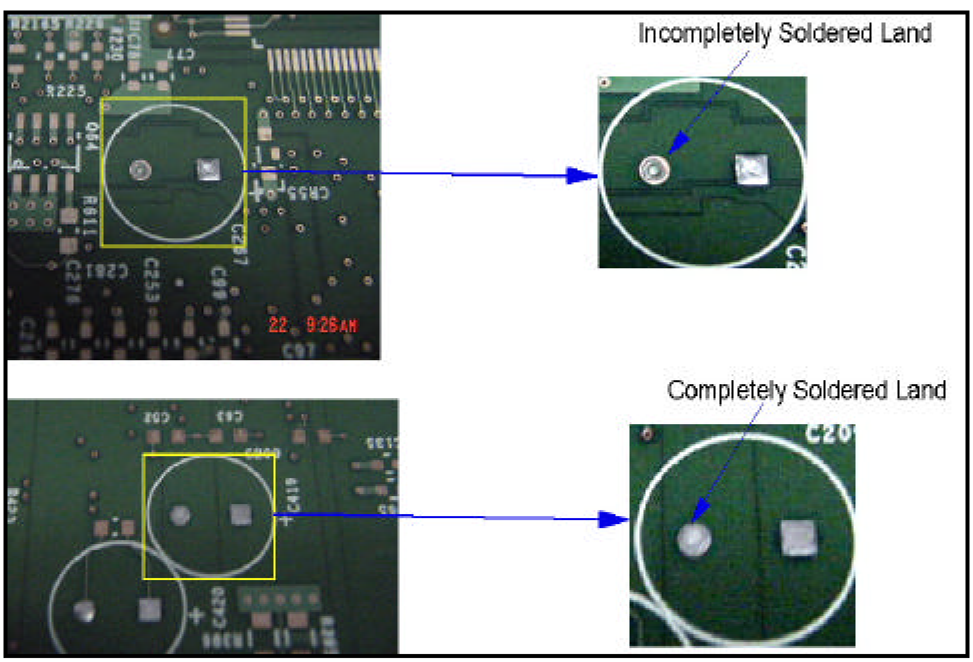


Figure 6 - Response Variable 1 – Incompletely Soldered Lands (Exposed Cu on Pad Annular Ring)

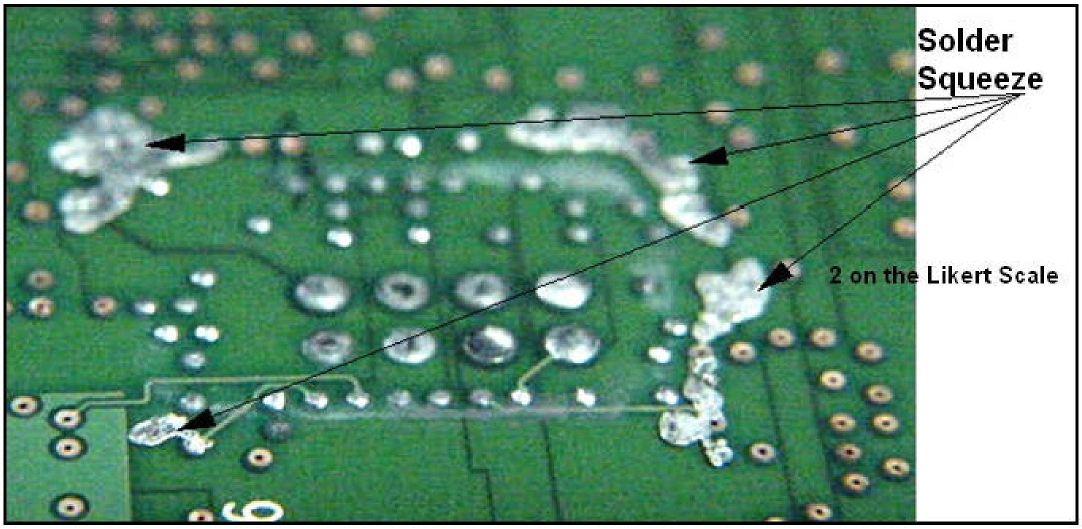


Figure 7 - Response Variable 3 – Solder Squeeze on Bottom of PWB (Solder Flows between the Pallet and PWB)

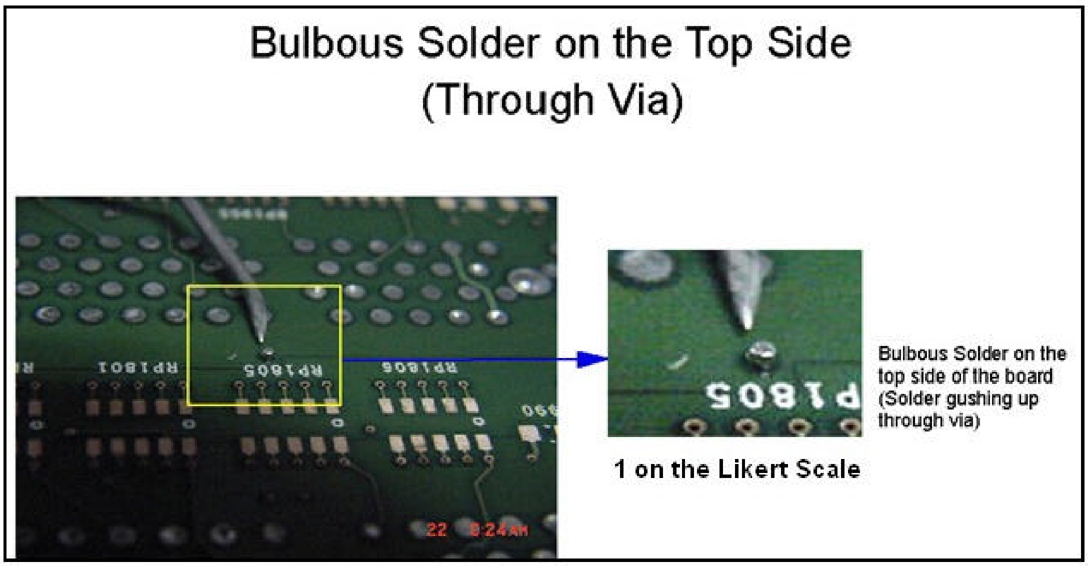


Figure 8: Bulbous Solder

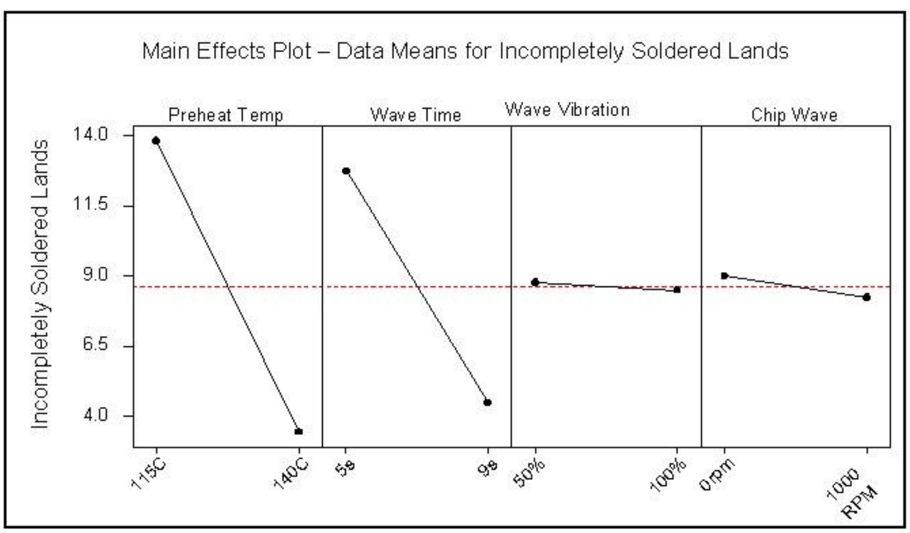


Figure 9 - Main Effects Plot for Incompletely Soldered Lands (RP 1)

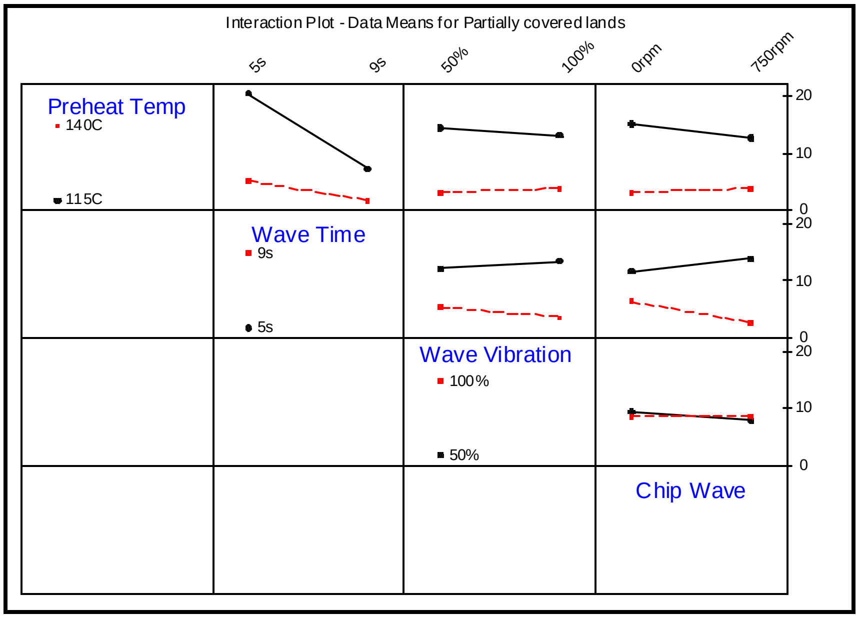


Figure 10 - Interaction Effects plot for Incompletely Soldered Lands (RP 1)

Table 1 - DOE 1 -ANOVA Results for Incompletely Soldered Lands (RP 1)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Preheat Temp	1	861.13	861.13	861.13	79.18	**0.000**
Wave Time	1	544.5	544.5	544.5	50.07	**0.000**
Wave Vibration	1	0.5	0.5	0.5	0.05	0.833
Chip Wave	1	4.5	4.5	4.5	0.41	0.529
Preheat Temp*Wave Time	1	190.13	190.13	190.13	17.48	**0.001**
Preheat Temp*Wave Vibration	1	10.12	10.13	10.13	0.93	0.349
Preheat Temp*Chip Wave	1	21.12	21.12	21.12	1.94	0.182
Wave Time*Wave Vibration	1	18	18	18	1.66	0.217
Wave Time*Chip Wave	1	72	72	72	6.62	**0.020**
Wave Vibration*Chip Wave	1	4.5	4.5	4.5	0.41	0.529
Preheat Temp*Wave Time*Wave Vibration	1	0.13	0.13	0.13	0.01	0.916
Preheat Temp*Wave Time* Chip Wave	1	21.13	21.13	21.13	1.94	0.182
Preheat Temp*Wave Vibration*Chip Wave	1	6.13	6.13	6.13	0.56	0.464
Wave Time*Wave Vibration*Chip Wave	1	0.5	0.5	0.5	0.05	0.833
Preheat Temp*Wave Time * Wave Vibration*Chip Wave	1	3.12	3.12	3.12	0.29	0.599
Error	16	174	174	10.87		
Total	31	1931.5				

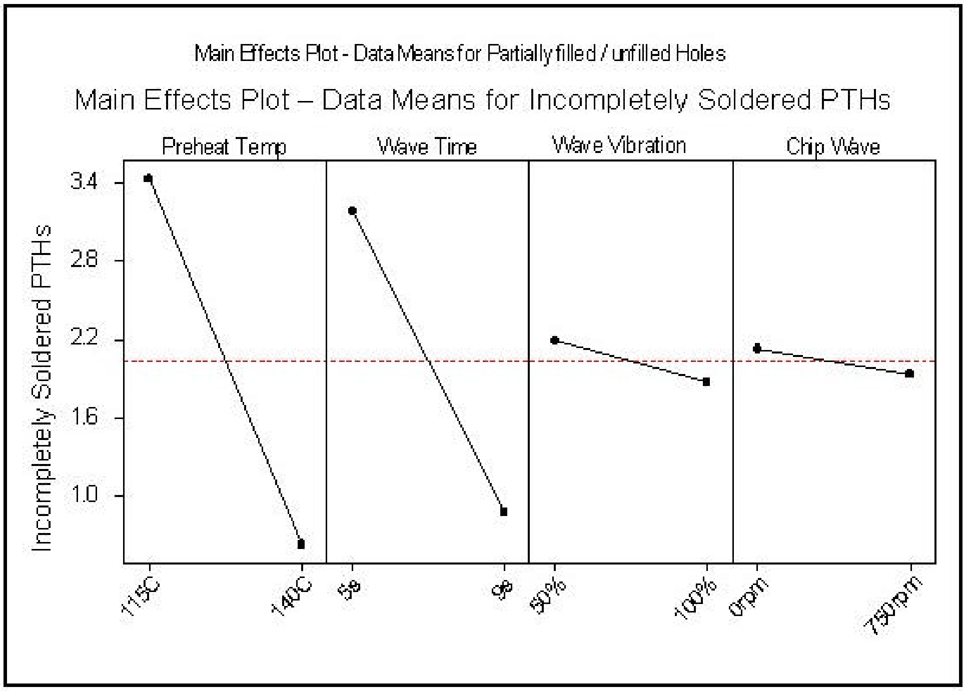


Figure11 - DOE 1 - Main Effects plot for Incompletely Soldered PTHs (RP 2)

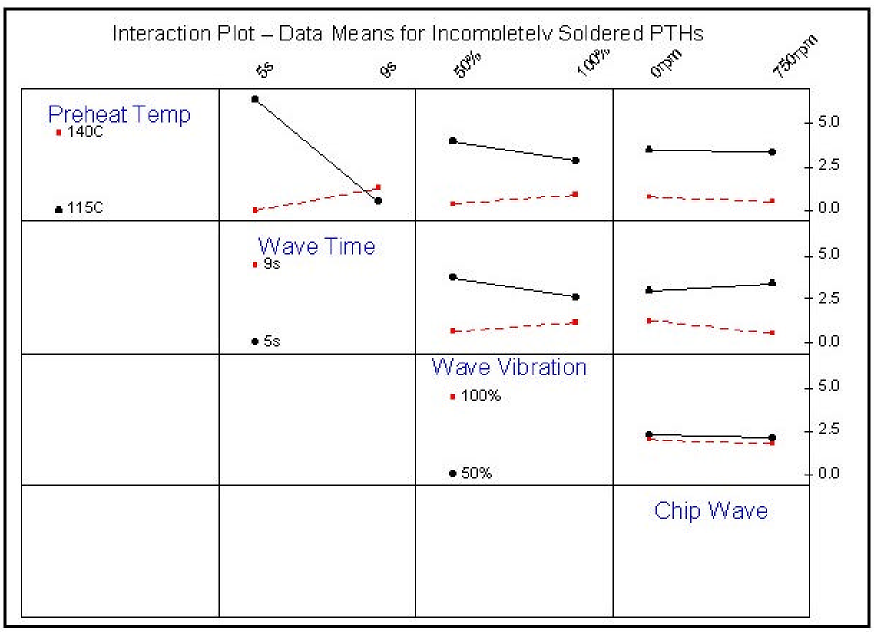


Figure12 - DOE 1 - Interaction Effects plot for Incompletely Soldered PTHs (RP 2)

Table 2 - DOE 1 - ANOVA Results for Incompletely Soldered PTHs (RP 2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Preheat Temp	1	63.28	63.28	63.28	4.06	**0.061**
Wave Time	1	42.78	42.78	42.78	2.74	**0.117**
Wave Vibration	1	0.78	0.78	0.78	0.05	0.826
Chip Wave	1	0.28	0.28	0.28	0.02	0.895
Preheat Temp*Wave Time	1	101.53	101.53	101.53	6.51	**0.021**
Preheat Temp*Wave Vibration	1	5.28	5.28	5.28	0.34	0.569
Preheat Temp*Chip Wave	1	0.03	0.03	0.03	0	0.965
Wave Time* Wave Vibration	1	5.28	5.28	5.28	0.34	0.569
Wave Time*Chip Wave	1	2.53	2.53	2.53	0.16	0.692
Wave Vibration*Chip Wave	1	0.03	0.03	0.03	0	0.965
Preheat Temp*Wave Time* Wave Vibration	1	0.78	0.78	0.78	0.05	0.826
Preheat Temp*Wave Time* Chip Wave	1	0.78	0.78	0.78	0.05	0.826
Preheat Temp*Wave Vibration *Chip Wave	1	0.03	0.03	0.03	0	0.965
Wave Time*Wave Vibration*Chip Wave	1	0.03	0.03	0.03	0	0.965
Preheat Temp*Wave Time* Wave Vibration*Chip Wave	1	0.03	0.03	0.03	0	0.965
Error	16	249.5	249.5	15.59		
Total	31	472.97				

DOE 2

A second DOE (DOE 2) was planned to provide finer details on the impact of varying the laminar wave vibration in smaller increments. A new response variable was also included in DOE 2 – ionic contamination. An automated, high resolution, Solvent Extract Conductivity (SEC) tester was used to determine the amount of ionic residue on the PCBs after soldering and standard deionized water wash. For DOE 2, the long dwell time in the laminar wave was reduced from 9 seconds to 7 seconds. DOE 1 revealed wave vibration as being a significant factor when considering the response variables solder squeeze and bulbous solder (the factor chip wave – being on – also proved to be a significant factor). Based in the above results, the factors for DOE 2 were reduced from 4 factors to 2 factors and are as follows:

- Dwell time in the wave
  - 5 seconds;
  - 7 seconds.
- Wave Vibration (% of maximum amplitude)
  - 62%;
  - 75%;
  - 88%;
  - 100%.

A two replicate full - factorial experiment was conducted, resulting in 16 runs. The detailed results for solder squeeze, bulbous solder and ionic contamination are presented as part of DOE 2, while only the summary of response variables – incompletely soldered lands and incompletely filled holes is provided in this section.

Results – DOE 2

Figure 13 and Figure 14 represent the main and interaction effects plot for the response variable – solder squeeze. As the vibration increases, so does solder squeeze. Table 3 shows the ANOVA results for the response variable – solder squeeze. While Figure 13 and Figure 14 suggest trends in factor significance, the ANOVA in Table 3 shows no statistically significant factors as an a – value less than .26. However, the p-value for laminar wave vibration is significantly smaller than the main effect of dwell time in the wave as well as the interaction between the two factors. The lack of statistical significance is likely due to the combined limited number of factors, levels and replicates. Although statistical significance is lacking, the general trend is that as the Wave Vibration increases the incidence of solder squeeze also increases.

Figure 15 and Figure 16 show the main and interaction effect plots for the response variable - bulbous solder. The main effect plot shows that the 7 second dwell time in the wave results in fewer instances of bulbous solder and the ANOVA (in Table 4) shows statistical significance at an a – value of .081. There is no interaction between the two main factors as shown by the two parallel lines of the interaction plot in Figure 16.

Figure 17 and Figure 18 represent the main and interaction effects as pertaining to the response variable ionic contamination. No main or interaction effect was significant for the response variable, RP5 – ionic contamination as indicated in the ANOVA results as shown in Table 5.

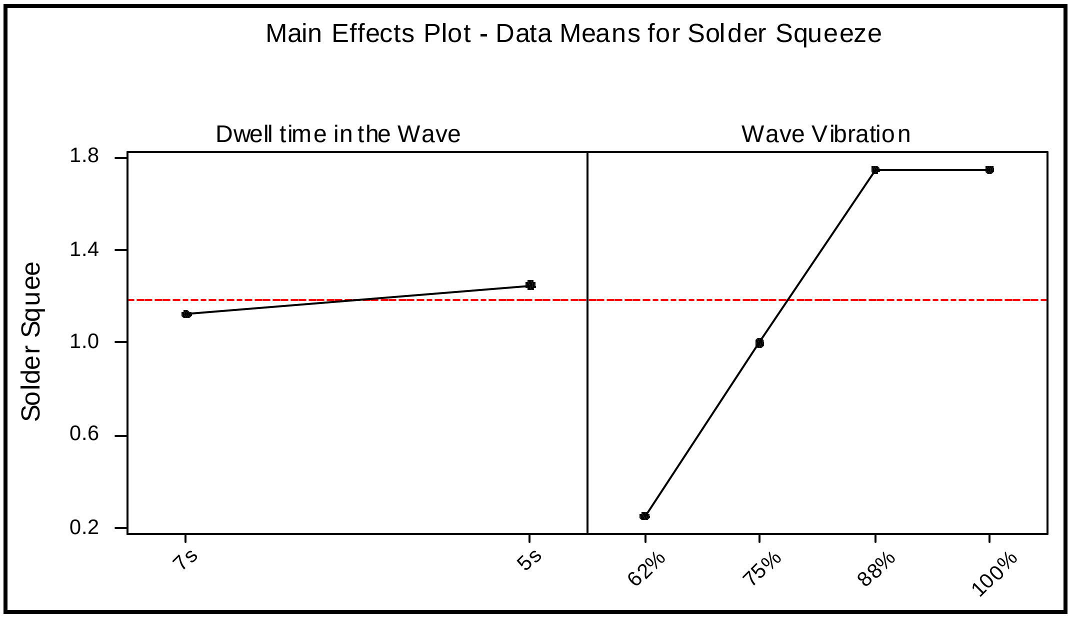


Figure13 - DOE2 -Main Effects plot for Solder Squeeze (RP 3)

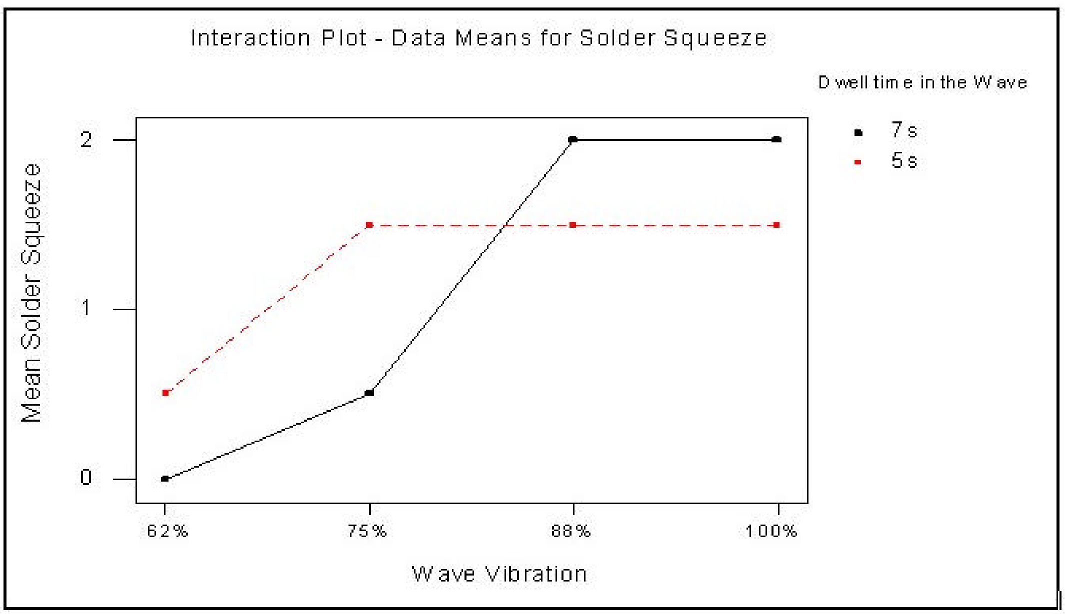


Figure14 - DOE 2 - Interaction Effects plot for Solder Squeeze (RP 3)

Table 3 - DOE 2 - ANOVA Results for Solder Squeeze (RP 3)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wave Time	1	0.063	0.063	0.063	0.05	0.833
Wave Vibration	3	6.187	6.187	2.062	1.57	0.27
Wave Time*Wave Vibration	3	1.687	1.687	0.562	0.43	0.738
Error	8	10.5	10.5	1.312		
Total	15	18.437				

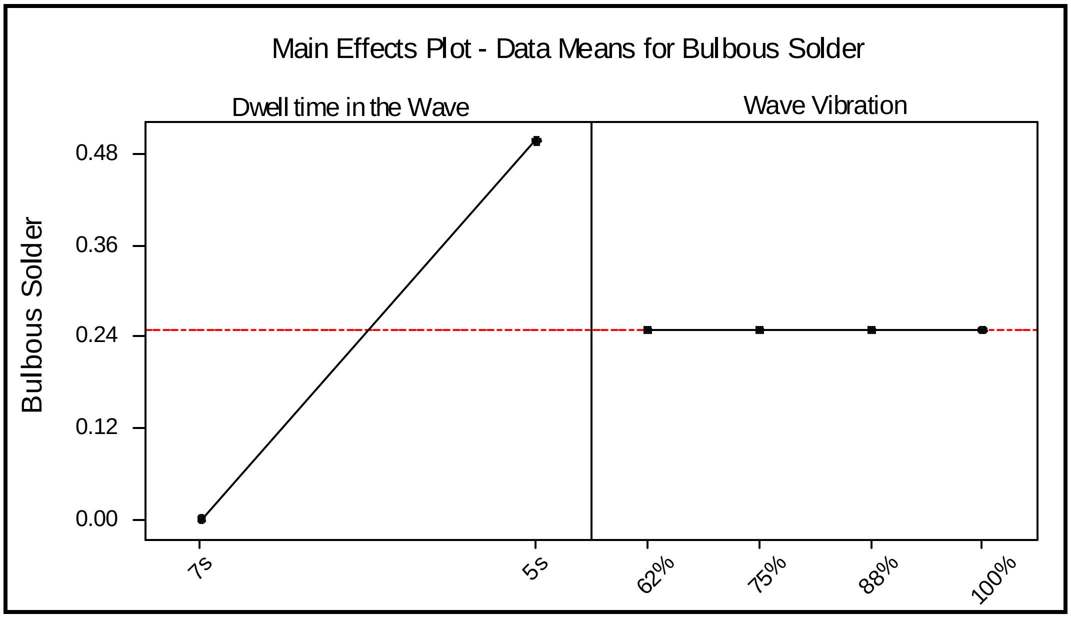


Figure15 - Main Effects plot for Bulbous Solder (RP 4)

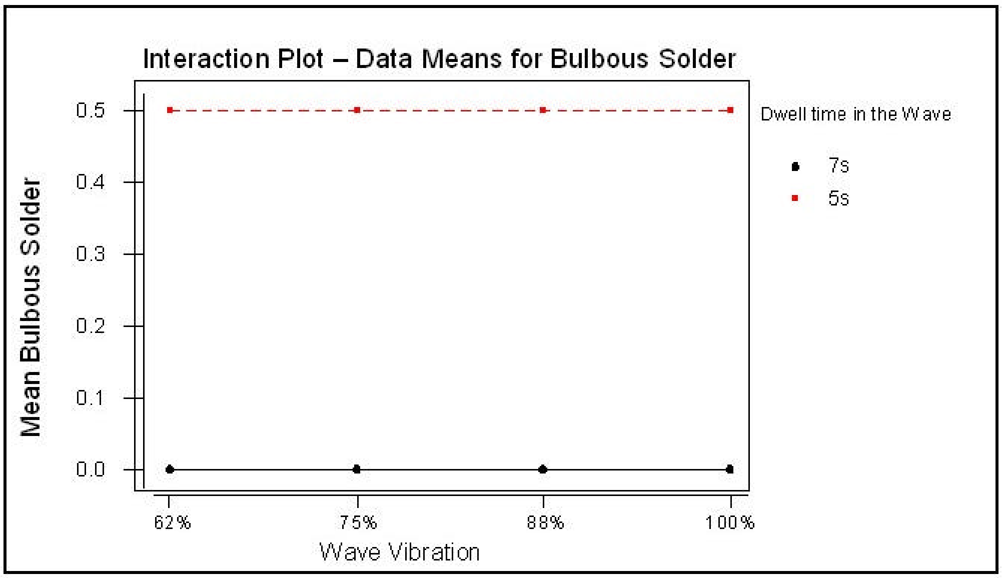


Figure16 - Interaction Effects plot for Bulbous Solder (RP 4)

Table 4 - ANOVA Results for Bulbous Solder (RP 4)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wave Time	1	1	1	1	4	0.081
Wave Vibration	3	0	0	0	0	1
Wave Time*Wave Vibration	3	0	0	0	0	1
Error	8	2	2	0.25		
Total	15	3				

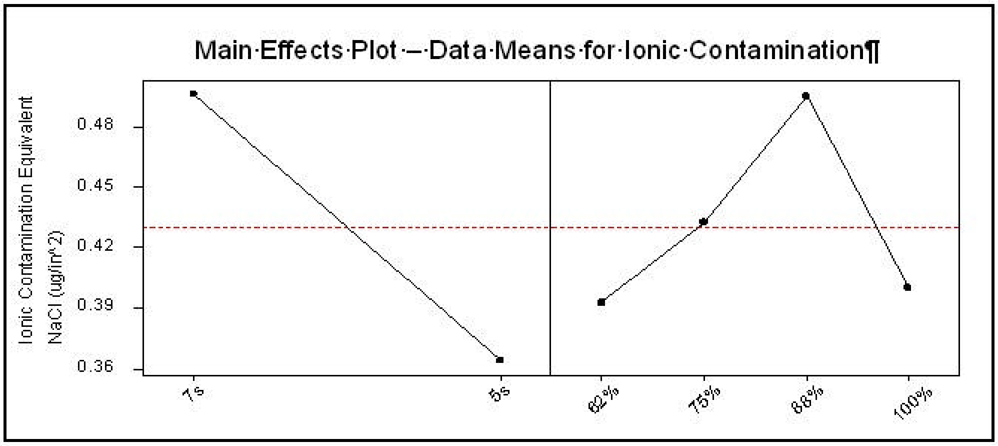


Figure17 - DOE 2 - Main Effects plot for Ionic Contamination (RP 5)

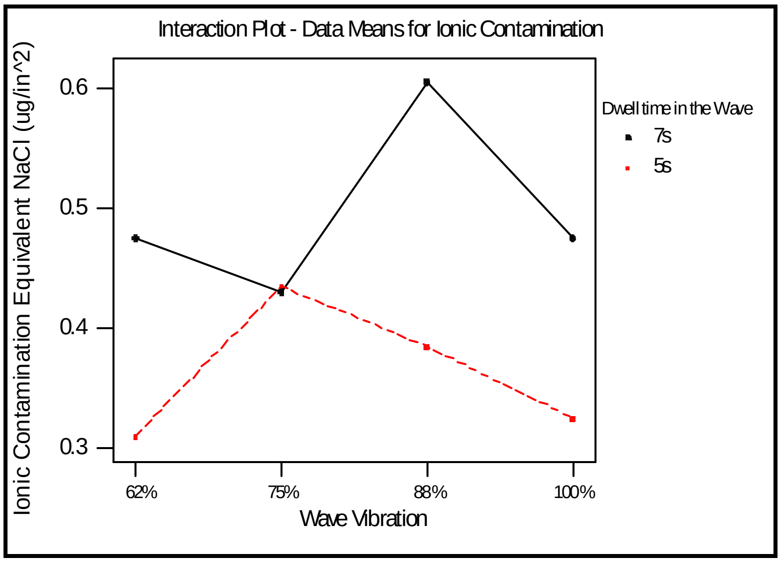


Figure18 - DOE 2 -Interaction Effects plot Ionic Contamination (RP 5)

Table 5 - DOE 2 - ANOVA Results for Ionic Contamination (RP 5)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wave Time	1	0.07023	0.07023	0.07023	1.55	0.248
Wave Vibration	3	0.02615	0.02615	0.00872	0.19	0.898
Wave Time*Wave Vibration	3	0.02792	0.02792	0.00931	0.21	0.890
Error	8	0.36190	0.36190	0.04524		
Total	15	0.48620				

Summary

A summary of main effects is shown in Table 6. A summary of interaction effects is shown in Table 7. No third or fourth order interactions were statistically significant at an a – value less than 0.182.

Inferences

This paper has focused on some of the key defects that have plagued the wave soldering process, and has attempted to address these issues. The paper also focuses on the effective use of Design of Experiments approach, and its advantages The crux of the experimentation has hinged upon factors that can easily controlled and in doing so be able to achieve the necessary benefits. Factors such as preheat temperature and dwell - time in the wave are product parameters (PCB related) and can be easily controlled by making adjustments to the preheaters and the conveyor speed. The supposition that 'thick boards have some inherent hole-fill problems' has been disproved, since all of wave heights were set at 50% up the PWB thickness. If flux and heat are properly supplied with correct dwell time in the wave, good hole-fill can be obtained. Consistent hole-fill can be obtained without raising the solder wave height to utilize hydraulic pressure to pump solder into the PTHs of thick PWBs.

Table 6 - Summary of Main Effects Impact on Response Variables (* indicates result is taken from DOE 1 and not quantified in detail)

	RP1 Number of Incompletely Soldered Lands	RP2 – Number of Incompletely Filled Holes	RP3 – Solder Squeeze on a Likert Scale	RP4 – Bulbous Solder on a Likert Scale	RP5 - Ionic Contamination
Increasing preheat temperature	Beneficial at a = 0.000	Beneficial at a = 0.061	Not Significant *	Not Signficant *	Not Significant *
Increasing dwell time in wave	Beneficial at a = 0.000	Beneficial at a = 0.117	Not Significant, P-value =0.833	Beneficial at a = 0.081	Not Significant, P-value =0.248
Increasing laminar wave vibration amplitude	Not Signficant, P-value =0.833	Not significant, P-value =0.826	Not Significant, P-value =0.270	No Effect, P-value =1.000	Not Significant, P-value =0.898
Chip wave on	Not Signficant, P-value =0.529	Not significant, P-value =0.895	Not Significant *	Not Significant *	Not Significant *

Table 7 - Summary of Interaction Effects Impact on Response Variables

	RP1 Number of Incompletely Soldered Lands	RP2 – Number of Incompletely Filled Holes	RP3 – Solder Squeeze on a Likert Scale	RP4 – Bulbous Solder on a Likert Scale	RP5 - Ionic Contamination
Preheat Temp*Wave Time	**Significant, a = .001**	**Significant, a = .021**	Not Significant	Not Significant	Not Significant
Preheat Temp*Wave Vibration	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Preheat Temp*Chip Wave	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Wave Time*Wave Vibration	Not Significant	Not Significant	Not Significant	**No Effect**	Not Significant
Wave Time*Chip Wave	**Significant, a = .020**	Not Significant	Not Significant	Not Significant	Not Significant
Wave Vibration*Chip Wave	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Preheat Temp*Wave Time*Wave Vibration	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Preheat Temp*Wave Time*Chip Wave	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Preheat Temp*Wave Vibration*Chip Wave	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Wave Time*Wave Vibration*Chip Wave	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant
Preheat Temp*Wave Time*Wave Vibration*Chip Wave	Not Significant	Not Significant	Not Significant	Not Significant	Not Significant

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Wave Solder Process Optimization for Complex Electronic Assemblies: A Design of Experiments Approach

Session: Mixed Technology
Wed. 2/25/04 9:30-11:00 AM

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All research was conducted at Endicott Interconnect Technologies, Inc.

Overview

- Complex assembly challenges
- Physics of wetting PTH analysis
- DOE 1 Experiment Plan
- DOE 1 Results
- DOE 2 Experiment Plan
- DOE 2 Results
- Analysis
- Conclusion

Complex Assemblies

- Unique challenges
- High reliability, high I/O and high complexity.
- PWBs thicknesses up to 200 mils
- Very high layer counts are common–

  For example:

  26 Cu layers, 135 mils
  16 Cu layers, 187 mils
- PWAs are large and double sided SMT, thus large wave solder fixtures with selective openings are needed – large heat shield and heat sink

Experience

- Solder hole fill met customer specs but often needed x-ray inspection (to insure hole fill under connectors) – resulted in extra labor from manufacturing and engineering.

- Historical position – ‘it is not possible to consistently obtain 100 percent hole fill on **<u>thick</u>** PWAs – we are fighting physics”.

Physics of Wetting PTH

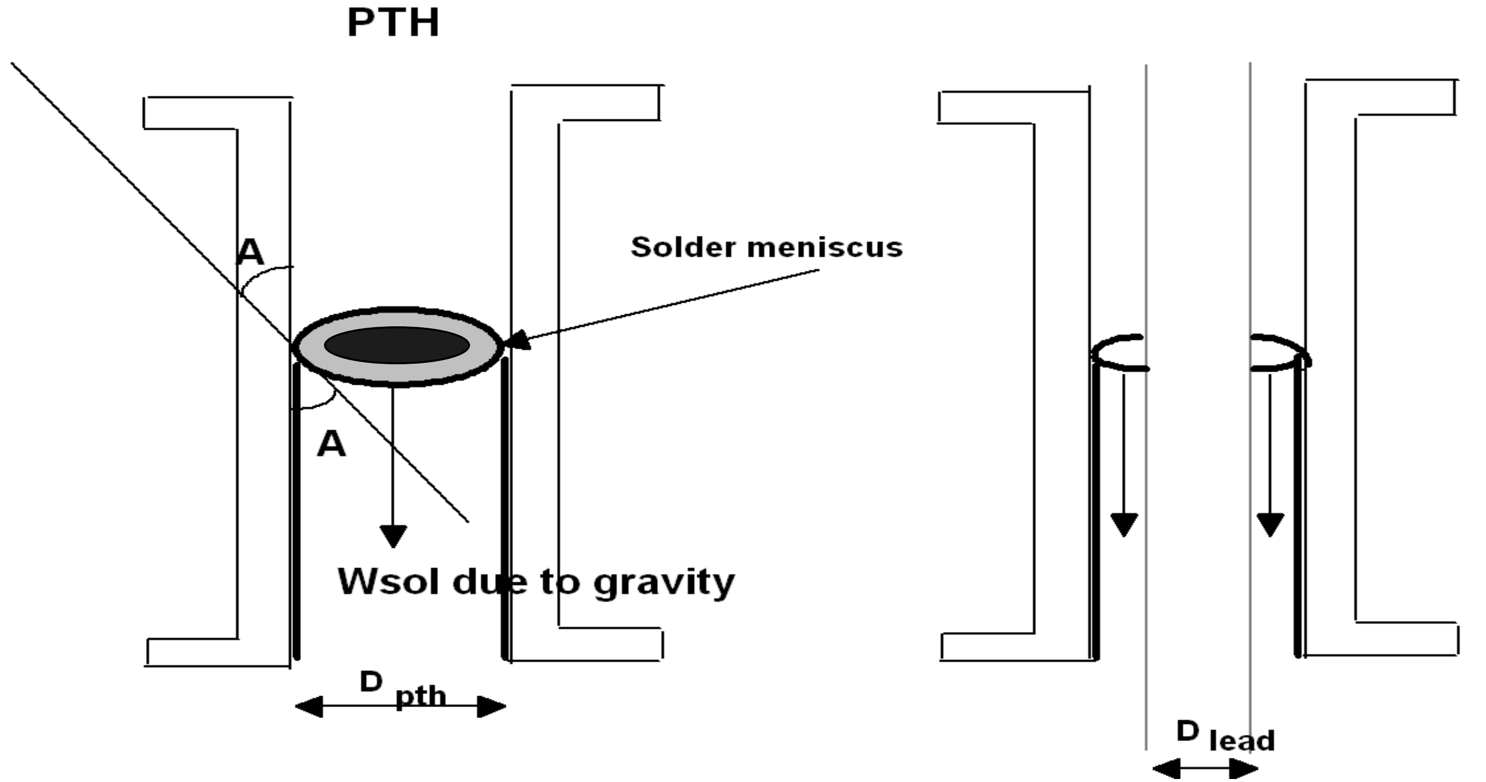
Wetting of PTHs occurs by capillary action/rise.

From the free body diagram, the forces were analyzed to find an expression for the hole fill height (h).

Sensitivity analysis was performed to determine if the hole fill should be consistent over the likely range of input variables.

Physics of Wetting PTH

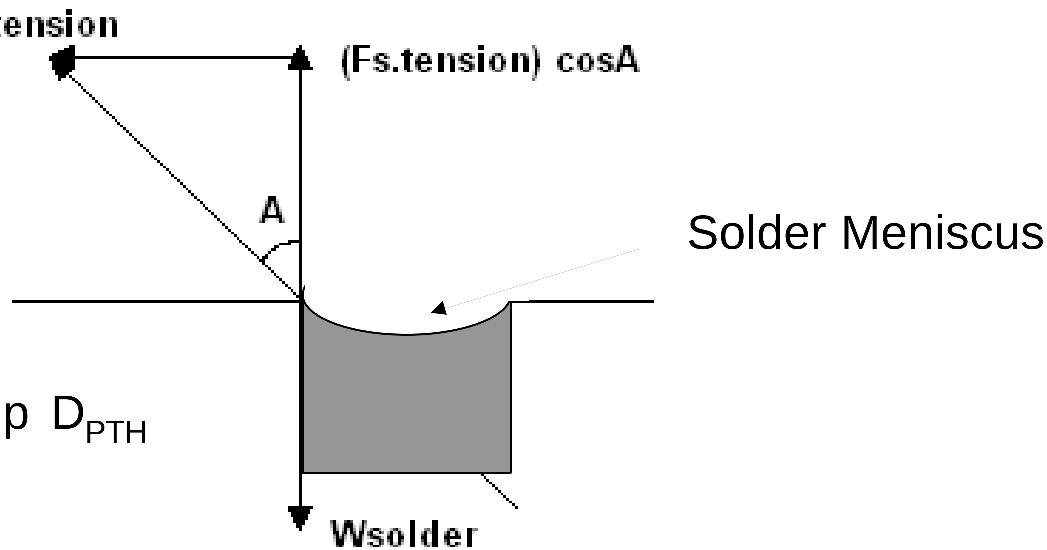
Freebody Vector diagram of solder in PTH - Interaction of surfaces i.e. PTH copper (solid), solder(liquid) and flux vapors and air (gas).



Without Lead in PTH –
Worse case than with the lead, due to less surface to wet

With Lead in PTH –
Capillary rise is enhanced since there is the PTH and lead to wet

Physics of Wetting PTH



$F_{SURFACE\ TENSION} = \gamma_{63Sn/37Pb}\, p\ D_{PTH}$

At equilibrium:

Vertical force due to solder wetting the Cu barrel = W_{SOLDER}

$$\gamma_{63Sn/37Pb}\ p\ D_{PTH}\ \mathrm{Cos}A = \rho_{SOLDER}((p/4)(D_{PTH}^2 - D_{LEAD}^2))\ h\ g$$

$$h = \frac{[\rho_{SOLDER}\ (p\ (D_{PTH}^2 - D_{LEAD}^2))g]}{[4\ \gamma_{63Sn/37Pb}\ p\ D_{PTH}\ \mathrm{Cos}A]}$$

Physics of Wetting PTH

Material Properties:

Solder Density @ 260 °C: $\rho_{63Sn/37Pb}$= 8.16 g/cc*

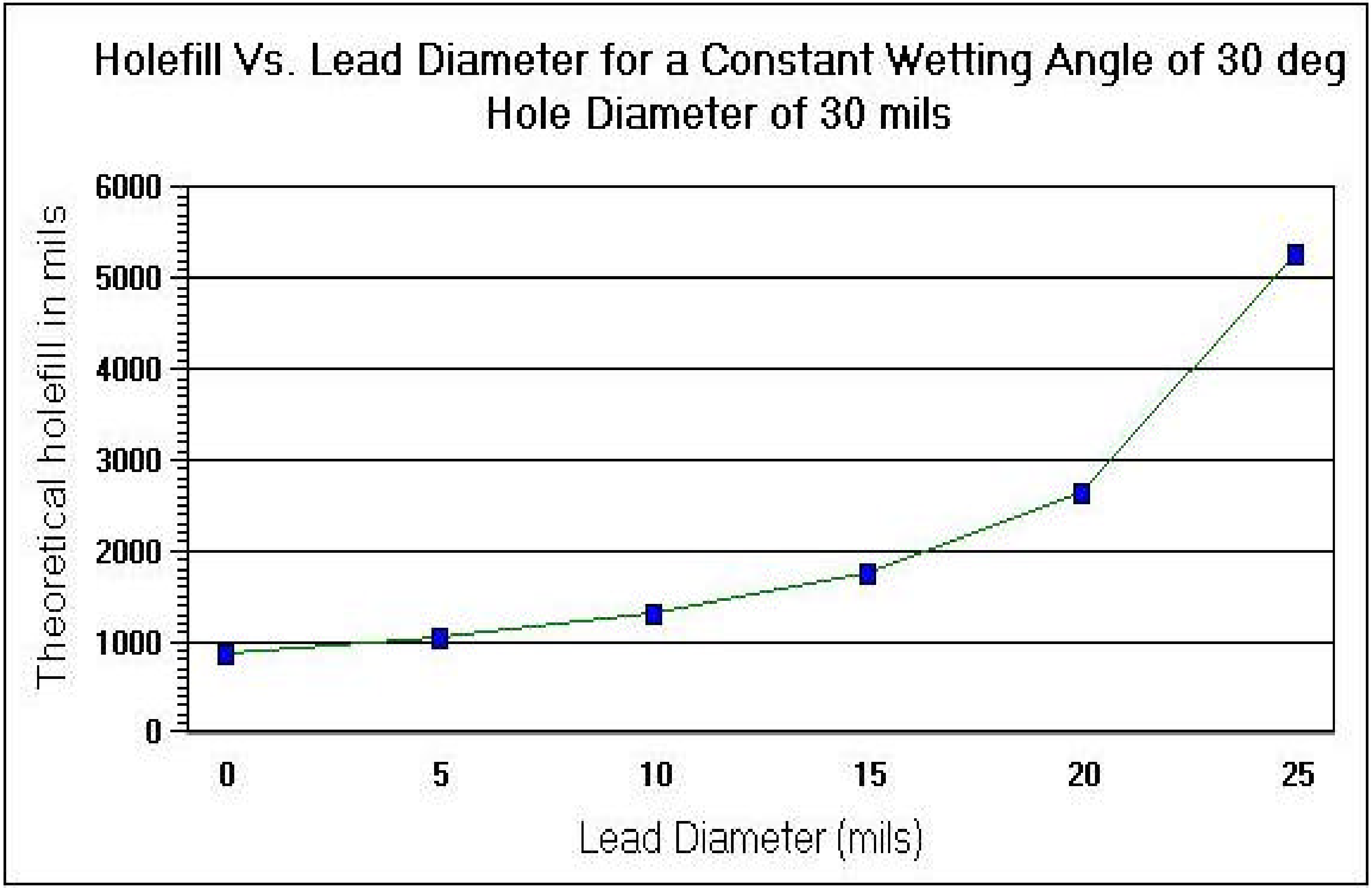
Surface Tension of 63Sn/37Pb: γ=400 μN/mm ideally*

IPC component solderability tests use 200 μN/mm as a minimum for a component of acceptable solderability

This following analysis is based on the de-rated 200 μN/mm value for conservativeness

*Soldering in Electronics: A Comprehensive Treatise on Soldering Technology for Surface Mounting and Through-Hole Techniques, Wassink, R. J. Klein, 2nd edition, Electrochemical Publications Ltd., Ayr, Scotland, 1989.

Physics of Wetting PTH



Analysis Results

100% holefill is possible for PWBs with no leads inserted, even when the surface tension is de-rated and the wetting angle is de-rated.

Therefore, the historical position ‘it is not possible to consistently obtain 100 percent hole fill on **thick** PWAs – we are fighting physics” is not valid

“The will to do, springs from the knowledge that we can do.”

James Allen, “As a Man Thinketh”, 1902

Building the mathematical model and analyzing it over the likely range of input variables provided motivation to conduct experimentation.

Failure Mode Effects Analysis

Possible root causes for insufficient hole fill:

Inadequate quantity of flux supplied

Insufficient activation of flux.

Over drying of flux before the PWA contacts the solder wave.

Too low of a preheat temperature.

Too little time in the solder wave.

Failure Mode Effects Analysis

Inadequate quantity of flux supplied – eliminated this possibility with thermal fax paper testing – paper is taped to the topside of the PWB and the PWB is then fluxed and quickly run up the preheats without solder contact – any part of the paper touched by flux turns black and leaves a flux ‘witness mark’.

The other four failure modes are all thermally related.

A product was chosen for extensive thermal profiling and experimentation using Design of Experiments (DOE).

Experiment Plan

Test Vehicle Chosen:
Thickness – 104 mils;
Layers:

- Signal – 9;
- Power and Ground – 6

This assembly was know to have historical hole fill challenges especially on one lead of a capacitor.

It is common for one lead of a capacitor to go to a internal ground plan – thus thermal root cause suspicion is supported

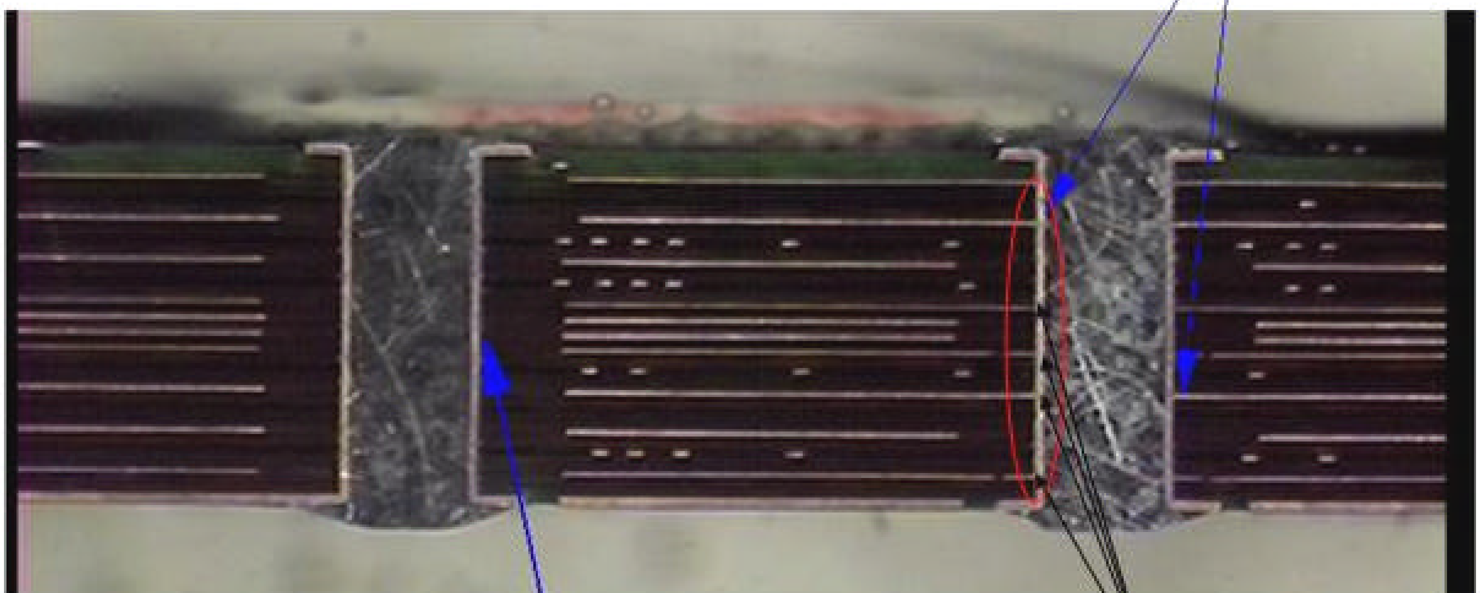
There were 26 capacitors (52 PTHs) on the PWB.

Although this PWB is not at the maximum PWB thickness, the process was developed such that it would be transferable to thicker assemblies.

Experiment Plan

PTH connected to ground plane

Circular Pad – hole fills completely about 50% of the time



Ground Planes

PTH not connected to ground plane Square Pad

Experiment Plan

Preliminary Experimentation:

Extensive work was done in thermal profiling to minimize the range of preheat temperatures seen on the product.

In order to provide uniform PWB temperature, a substantial amount of heat was supplied in the first two heat zones with an asymptotic thermal soak during the final preheat zone.

This technique was effective at providing uniform PWB temperature and was adopted for thermal profiling in all experiments.

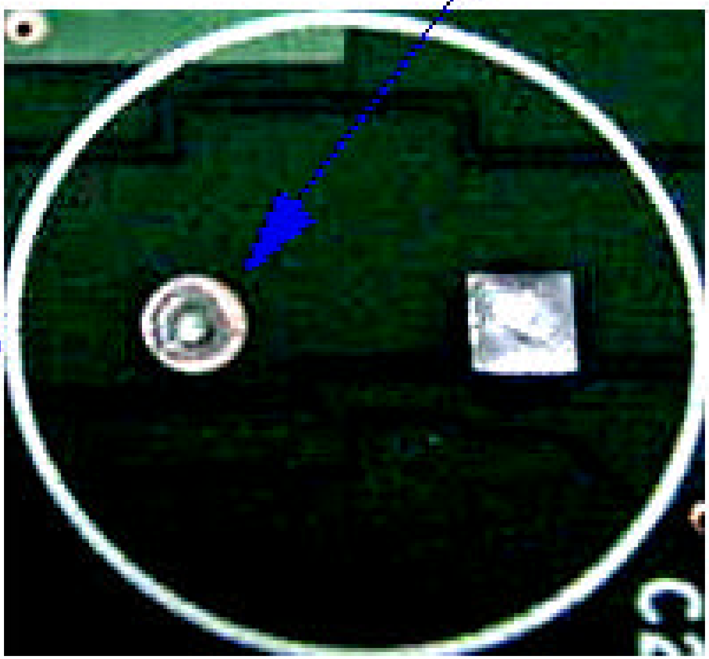
DOE 1 Plan

DOE 1				
Factors	**Dwell Time the in Solder Wave (s)**	**Preheat Temperature (ºC)**	**Laminar Wave Oscillation (% of maximum amplitude)**	**Chip Wave**
	9	135-145 (140 nominal)	50	On (height pump at 750 RPM, turbulence pump at 300 RPM)
	5	115-125 (115 nominal)	100	Off
Levels	**2**	**2**	**2**	**2**
Response Variables	RP1: – Number of incompletely soldered lands (*the total number of PTHs that failed to have 100% solder coverage of the Cu lands).* RP2: Number of incompletely filled holes (*the total number of square and circular holes/PTHs that were partially filled*).			
Replicates	2			
# Runs	2 * 2 *2 * 2 * 2 = 16			

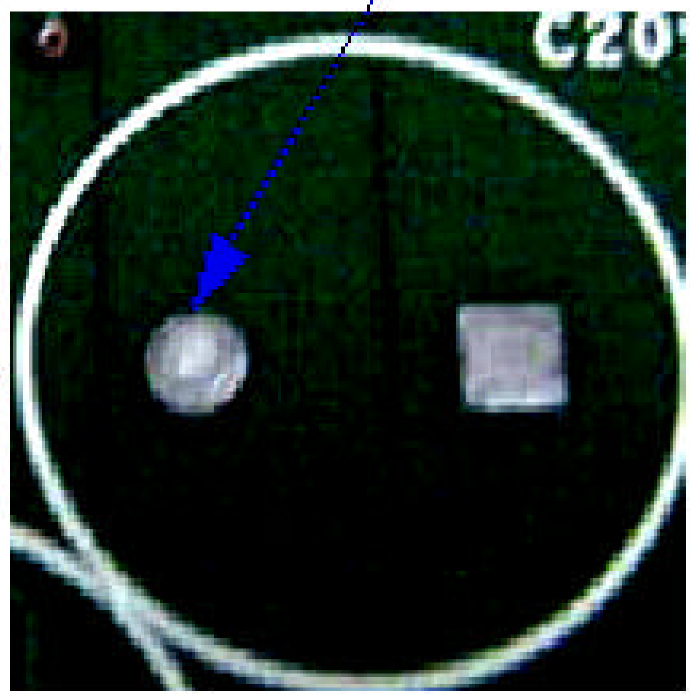
This DOE is full factorial.

DOE 1 Plan

Incompletely Soldered Land

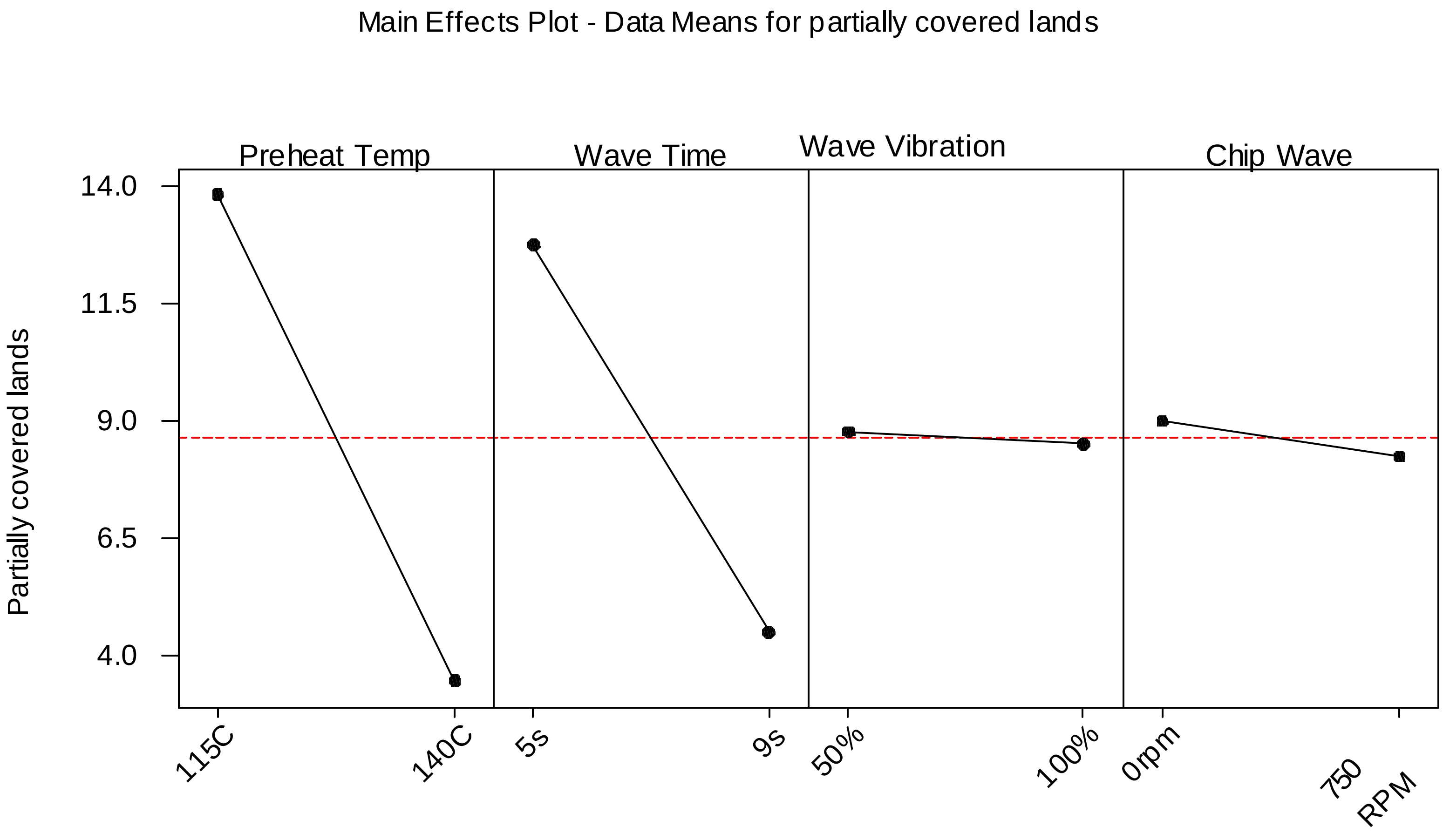


Completely Soldered Land



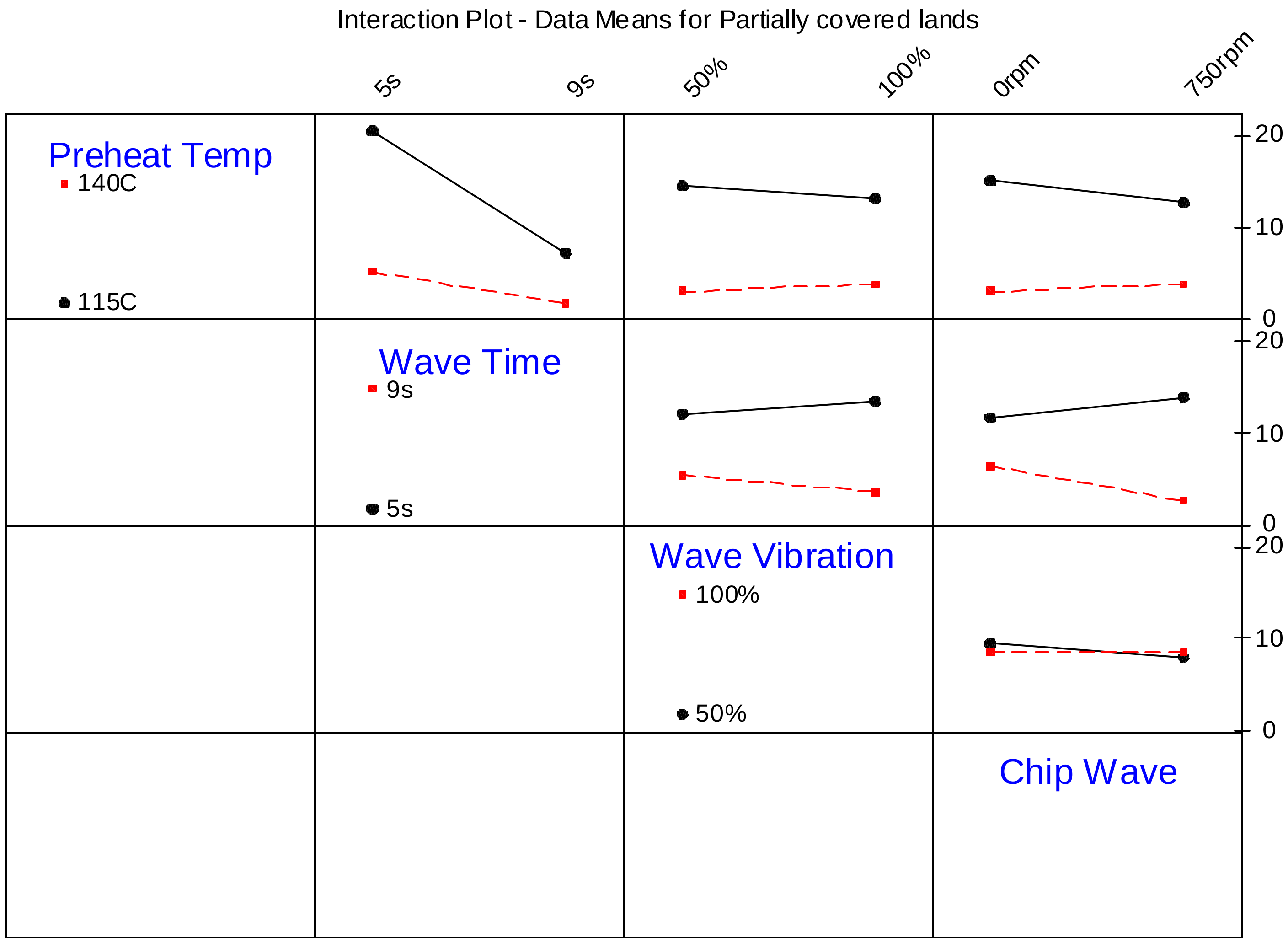
DOE 1 Results

Response Variable: Incompletely Covered Lands



DOE 1 Results

Response Variable: Incompletely Covered Lands



DOE 1 Results - ANOVA

Response Variable: Incompletely Covered Lands

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Preheat Temp	1	861.13	861.13	861.13	79.18	**0.000**
Wave Time	1	544.5	544.5	544.5	50.07	**0.000**
Wave Vibration	1	0.5	0.5	0.5	0.05	0.833
Chip Wave	1	4.5	4.5	4.5	0.41	0.529
Preheat Temp*Wave Time	1	190.13	190.13	190.13	17.48	**0.001**
Preheat Temp*Wave Vibration	1	10.12	10.13	10.13	0.93	0.349
Preheat Temp*Chip Wave	1	21.12	21.12	21.12	1.94	0.182
Wave Time*Wave Vibration	1	18	18	18	1.66	0.217
Wave Time*Chip Wave	1	72	72	72	6.62	**0.020**
Wave Vibration*Chip Wave	1	4.5	4.5	4.5	0.41	0.529
Preheat Temp*Wave Time*Wave Vibration	1	0.13	0.13	0.13	0.01	0.916
Preheat Temp*Wave Time* Chip Wave	1	21.13	21.13	21.13	1.94	0.182
Preheat Temp*Wave Vibration*Chip Wave	1	6.13	6.13	6.13	0.56	0.464
Wave Time*Wave Vibration*Chip Wave	1	0.5	0.5	0.5	0.05	0.833
Preheat Temp*Wave Time * Wave Vibration*Chip Wave	1	3.12	3.12	3.12	0.29	0.599
Error	16	174	174	10.87		
Total	31	1931.5				

DOE 1 Results - ANOVA

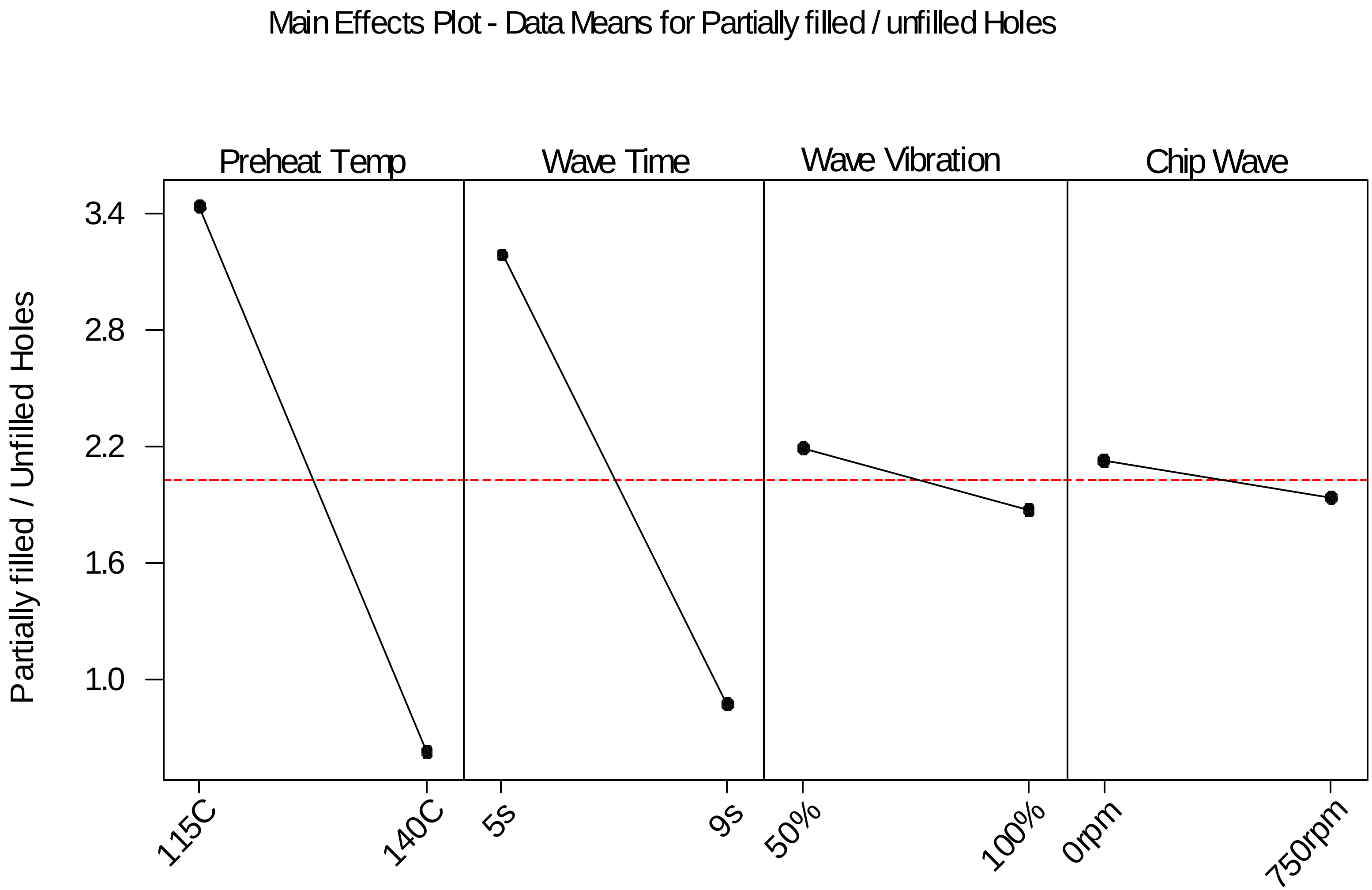
Response Variable: Incompletely Filled Holes

Main effects **Preheat Temp, Wave Time** were statistically significant at $\alpha = .05$.

Interaction effects **Preheat Temp * Wave Time**, and **Wave Time * Chip Wave** were statistically significant at $\alpha = .05$.

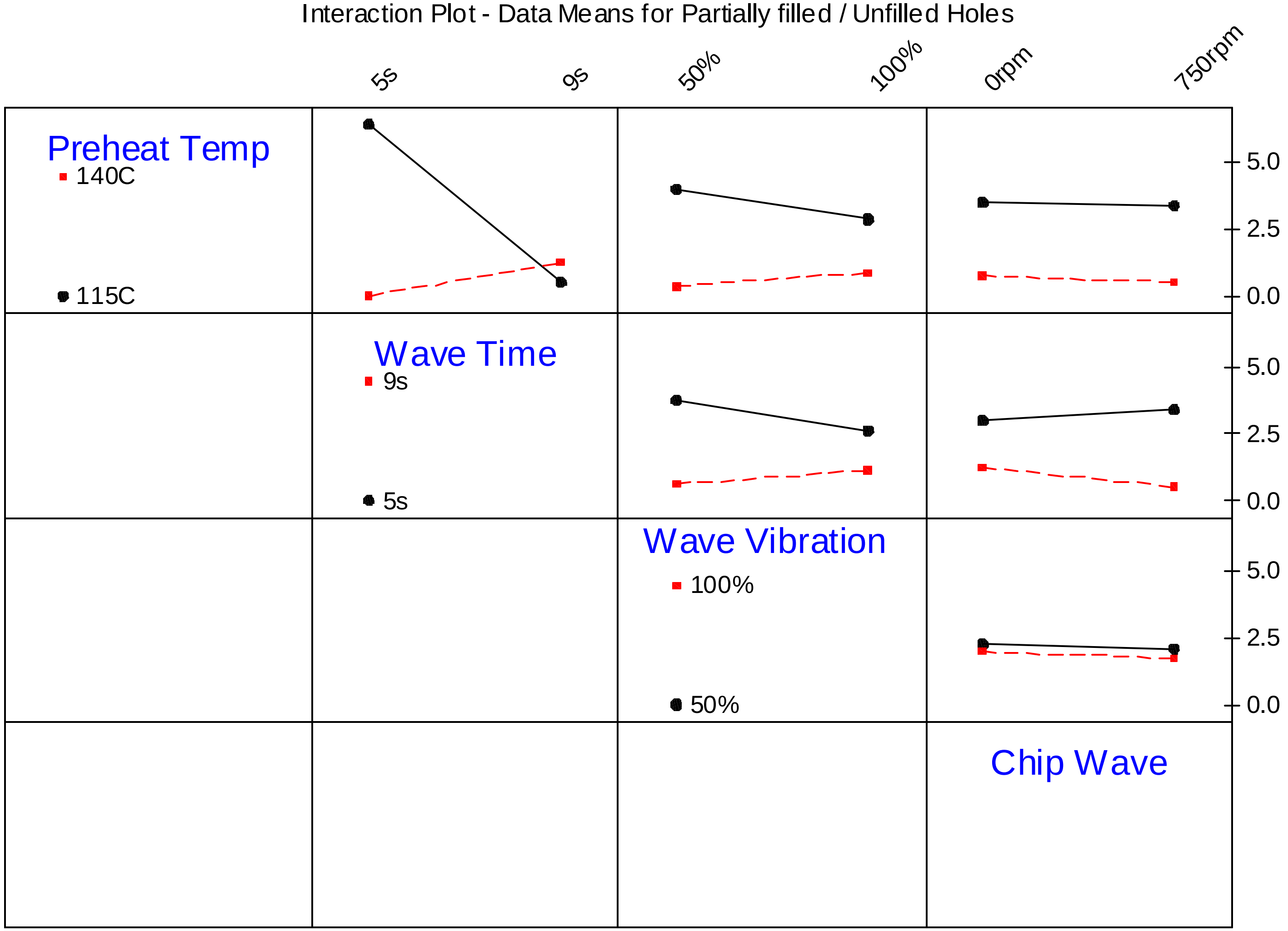
DOE 1 Results

Response Variable: Incompletely Filled Holes



DOE 1 Results

Response Variable: Incompletely Filled Holes



DOE 1 Results - ANOVA

Response Variable: Incompletely Filled Holes

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Preheat Temp	1	63.28	63.28	63.28	4.06	**0.061 ***
Wave Time	1	42.78	42.78	42.78	2.74	0.117
Wave Vibration	1	0.78	0.78	0.78	0.05	0.826
Chip Wave	1	0.28	0.28	0.28	0.02	0.895
Preheat Temp*Wave Time	1	101.53	101.53	101.53	6.51	**0.021 ***
Preheat Temp*Wave Vibration	1	5.28	5.28	5.28	0.34	0.569
Preheat Temp*Chip Wave	1	0.03	0.03	0.03	0	0.965
Wave Time* Wave Vibration	1	5.28	5.28	5.28	0.34	0.569
Wave Time*Chip Wave	1	2.53	2.53	2.53	0.16	0.692
Wave Vibration*Chip Wave	1	0.03	0.03	0.03	0	0.965
Preheat Temp*Wave Time* Wave Vibration	1	0.78	0.78	0.78	0.05	0.826
Preheat Temp*Wave Time* Chip Wave	1	0.78	0.78	0.78	0.05	0.826
Preheat Temp*Wave Vibration *Chip Wave	1	0.03	0.03	0.03	0	0.965
Wave Time*Wave Vibration*Chip Wave	1	0.03	0.03	0.03	0	0.965
Preheat Temp*Wave Time* Wave Vibration*Chip Wave	1	0.03	0.03	0.03	0	0.965
Error	16	249.5	249.5	15.59		
Total	31	472.97				

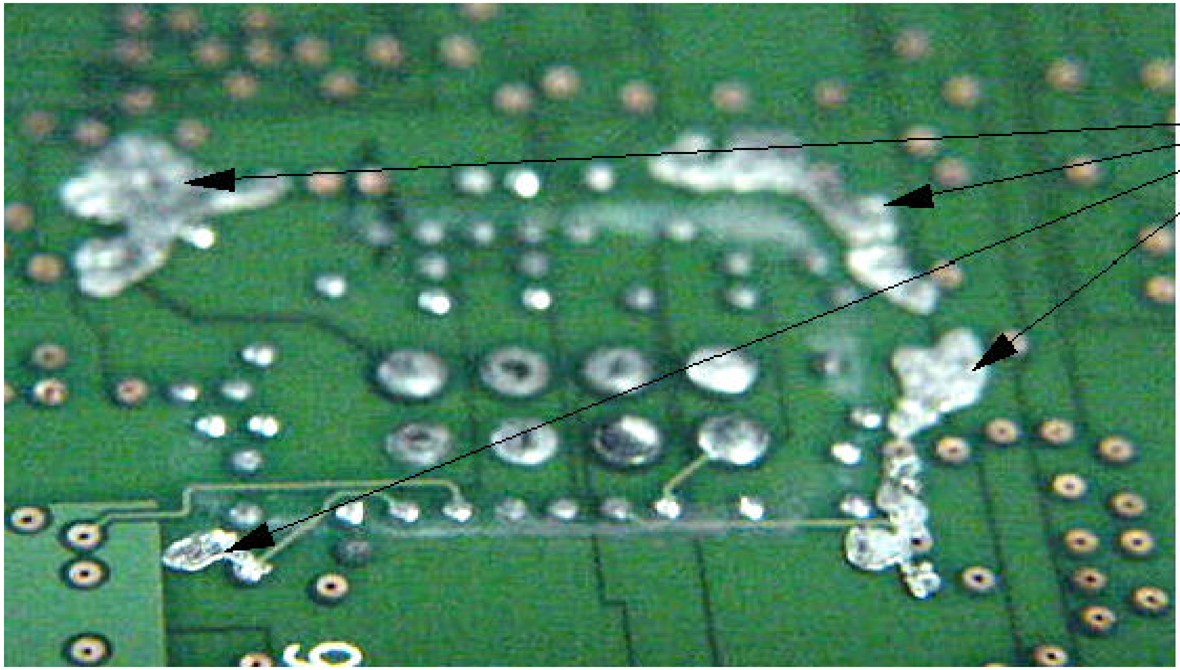
DOE 1 Results - ANOVA

Response Variable: Incompletely Filled Holes

Main effect **Preheat Temp** and interaction effect **Preheat Effect*Wave Time** were statistically significant at $\alpha = .1$.

DOE 1 Observations

A correlation was observed (no ANOVA) between Laminar Wave Oscilation (%) and solder becoming squeezed between the pallet and PWB (on the bottom side of the PWB). This defect was labeled “solder squeeze”.



Solder Squeeze

This sample is a 2 on the Likert Scale

Since quantitative measurements of ‘solder squeeze’ were not possible, images were ranked as 0 (no solder squeeze), 1 (slight solder squeeze) or 2 (extensive solder squeeze) on a Likert/summative scale.

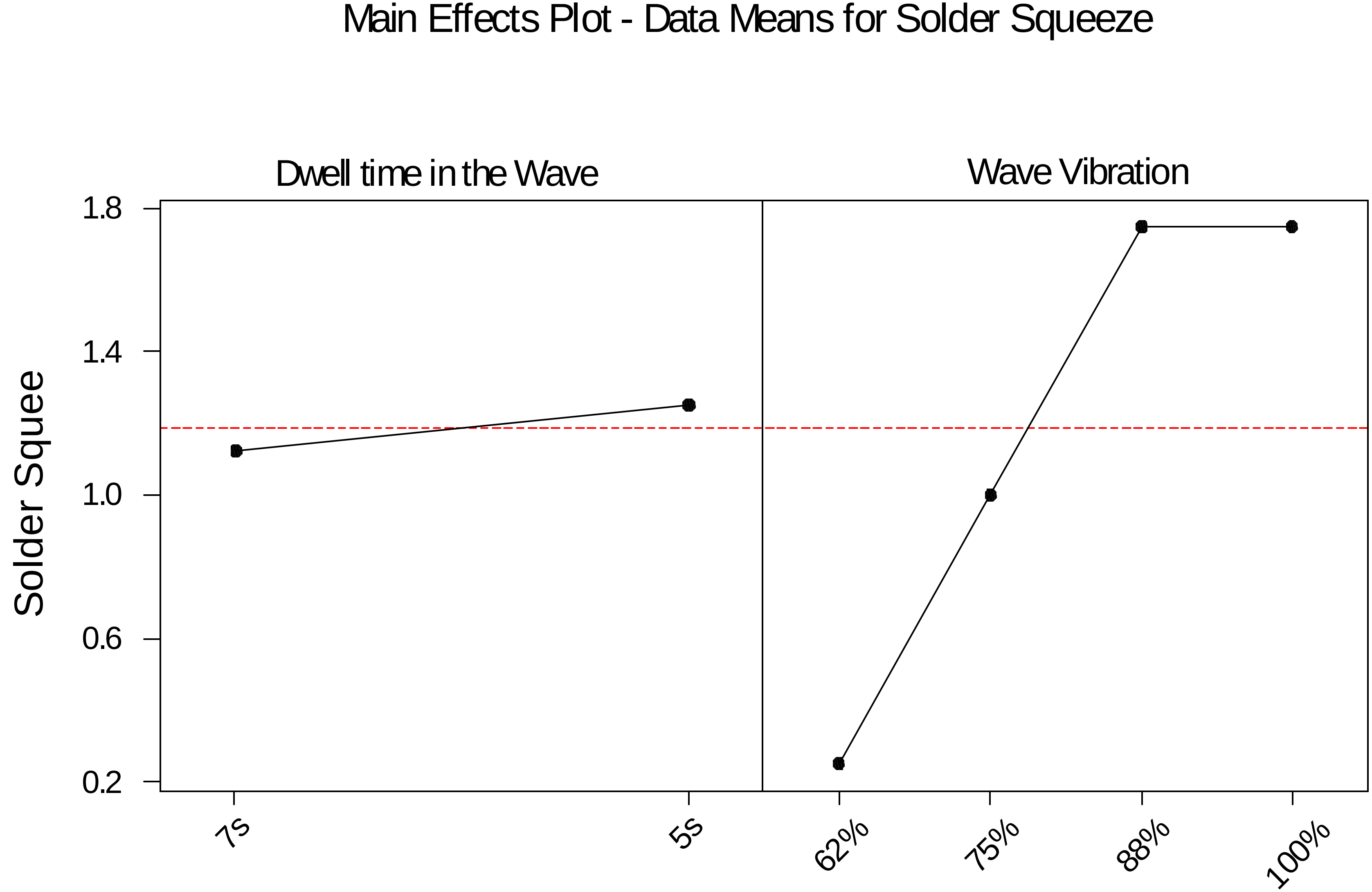
DOE 2 Plan

DOE 1		
Factors	**Dwell Time the in Solder Wave (s)**	**Laminar Wave Oscillation (% of maximum amplitude)**
	5	62
	7	75
		88
		100
Levels	**2**	**4**
Response Variables	RP3: – Solder Squeeze Measured on the Likert scale 0=none, 1=small amount, 2=large amount	
Replicates	2	
# Runs	2 * 4 *2 * 1 * 1 = 16	

This DOE is full factorial. Preheat was at 140 C and Chip Wave was on (height pump at 750 PRM, turbulence pump at 300 RPM)

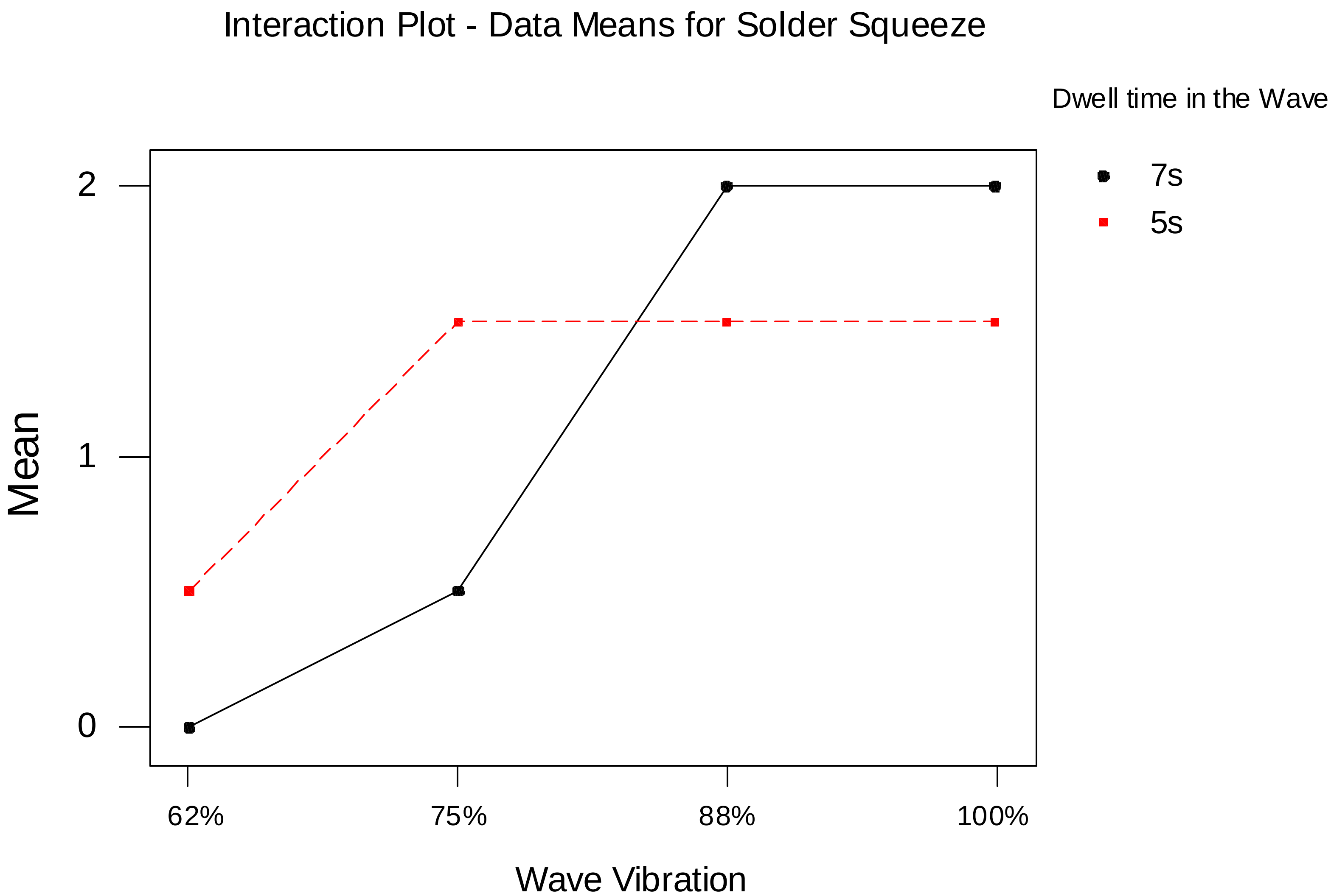
DOE 2 Results

Response Variable: “Solder Squeeze”



DOE 2 Results

Response Variable: “Solder Squeeze”



DOE 2 Results - ANOVA

Response Variable: “Solder Squeeze”

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wave Time	1	0.063	0.063	0.063	0.05	0.833
Wave Vibration	3	6.187	6.187	2.062	1.57	0.270
Wave Time*Wave Vibration	3	1.687	1.687	0.562	0.43	0.738
Error	8	10.500	10.500	1.312		
Total	15	18.437				

No main or interaction effects were statistically significant at any $\alpha < .27$.

However, the general trend was for less “Solder Squeeze” defects at 7 seconds dwell time and laminar wave oscillation amplitudes of 62% and 75%

Conclusion

Holefill and topside land soldering have improved markedly.

This process had been successfully implemented on 135 mil thick 26 layer boards and 187 mil thick 16 layer boards.

The postulate that ‘it is not possible to consistently obtain 100 percent hole fill on **thick** PWAs – we are fighting physics” has been disproven.

Acknowledgements:

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Questions?