Dynamics in Lead-Free Wave Soldering

The Performance Correlation to Machine Design and Configuration
A Flux Selection Study
A Performance Comparison of Lead-Free Alloys

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Abstract
The following report is fundamentally focused on how three popular lead-free alloys react in a wave solder application. The alloys were SAC305, SAC405 and a proprietary, low silver SAC alloy. In the process of attaining that goal, a flux selection methodology, and a study of top convection pre-heat were required. These three subjects are included in this report. Existing wave solder machines, materials, and methods were modified and tested over this study. The study used only Bellcore approved no-clean fluxes. Statistical analysis of the alloy study data was completed. The conclusions drawn suggest that except for one point, at least the defect of excess solder shows that there was no significant difference between those alloys. The main effect plots of the process defects used in the study would be very valuable in directing effective corrective action. In the flux selection methodology, a large test population was reduced to a few final candidates at low cost with little machine time or expensive test vehicles. A very detailed and extensive study on top-side convection pre-heat, by itself and used with infra-red panels, proved the system superior to alternatives. The minimal thermal stress and exceptional uniformity in the pre-heat of the machine have significant effect in providing uniform and efficient product preparation for solder. While not part of the study, a potential issue with minor flaws from bare board fabrication, or possibly a moisture sensitivity issue in the board was discovered. The issue causes large voids.

Introduction
The driving forces for the current attention to lead-free soldering are generally known. In regard to the development of lead-free soldering processes, it would seem that the general industry attention was initially focused on the SMT primary attach. The amount of published works for wave solder, mini-pot, hand solder, and hot gas was limited. Even during the development period, solder material price, as well as the annual amount of solder used, always had a part to play in material selection. The SMT processes use solder paste, and it is the technology of paste manufacture that significantly drives the cost of the product. The value of the alloy is of less consequence. While still in a state of some change, SMT processes migrated to the tin-silver-copper alloys, and remain there today. There have been some optimization studies in reflow, but there may be a perception that the SMT processes are far superior to lead-free wave solder, where advancement is often considered slow and not progressing anywhere near as well as SMT primary attach.

Early work in wave solder was affected by the same cost mentality, but in contrast to paste, wave solder bar cost is significantly affected by base metal price. Wave solder will use much more alloy per assembly than reflow, and alloy cost has become a critical selection criteria, even above performance. As an example, we might allow either SAC305 or SAC405 solder pastes to cost about $100 a pound, and very little of that paste is discarded. Almost every gram could be used to create a solder joint. At the wave solder, a pound of SAC 305 bar might cost $8, and the SAC405 will cost almost $10. This 25% cost increase is attributed to the higher percentage of silver. Next, the wave solder process will create solder dross, disregarding how many solder joints are made. That dross cost is variable, but a cost estimate is $30/hr., which could add $150,000 per year to the cost of making solder joints. Early work in lead-free wave solder was therefore primarily in a tin-copper (Sn-07Cu) alloy, with some testing of a tin-silver (Sn3.5Ag) alloy. The search for a world-standard lead-free wave alloy continues and solder bar cost has a strong influence.

As we consider the rapid improvements seen in SMT process and the perception that wave solder has not shown the same rate of improvement, there are some misconceptions but there are at least 3 considerations, as follow:

1. Resource focus was initially directed to SMT primary attach, not wave solder.
2. For numerous reasons, the wave solder is significantly more complicated and subject to more variability than reflow, complicating straight-forward, universal solutions
3. Beneficial design changes to wave solder process equipment lags the reflow process equipment

Logical and accurate studies of the wave solder process are now being pursued. One important point to emphasize is that the wave solder process has always been affected by numerous variables. When solutions address the complete process, rather than a single point, the corrective action can be most effective.

Goals

Summary

The primary goal of this work is to bring the lead-free wave solder process to a higher level of performance, to meet the demands of boards that are bigger, thicker, heavier, with more thermal challenge, with more density, and demanding a no-clean process.

Approach and Strategy

This work will focus on the wave solder challenges anticipated in heavier boards, looking at the process attributes of flux, pre-heat, and alloy. If the study focused on thinner product, existing materials and processes were seen as adequate.

The strategy applied was to begin with the confirmation of a flux. In parallel, because pre-heat was identified as a significant factor in soldering thicker, more thermally challenging boards, a test of pre-heat performance was planned. Alloy characteristics would then be studied, primarily by using designed experiment methods, followed by small confirmation runs. Current knowledge would be used to focus efforts and to optimize the design of experiments.

The above approach came from considering the following known conditions:

- While alloys may change, the fundamental rules of soldering do not change. To form a solder joint requires surfaces that are prepared for the solder process and meeting some time to temperature relationship.
- The wetting speeds and forces of the lead-free alloys are identified, and as compared to tin-lead, it takes longer to make the same solder joint.
- Considering the components used in the manufacture of a flux, there will be thermal degradation if their time-temperature balance is exceeded.
- Copper dissolution in the board is possible with extended contact times in SAC alloys.
- Considering the laminate and components on the soldered assemblies, there is also the potential for thermal degradation if a time-temperature balance is exceeded.
- The lead-free alloys have a smaller super-heat. (Super-heat is the difference between alloy melting point and process temperature and distinctly affects the time it takes to make any solder joint.) The typical superheat for a tin-lead process is in the range of 67C to 77C. In lead-free alloys, it does depend on which alloy is being used but it can be as low as 23C, and probably not too much more than 44C.

Put directly into the context of soldering the thermally challenging and thicker board assemblies:

- Flux spread and wetting is required.
- Flux performance and survival after longer solder contact times is required.
- Flux performance and survival in hotter and longer pre-heats is an advantage
- A full solder joint will not be formed if a minimum temperature to time point
- is not reached. If a lower pot temperature is used, a higher preheat is required. If a higher pot temperature is used, preheat can be lower. If contact time can be extended, lower pre-heat and lower pot temperature are possible.
- The laminate and components impose limitations on the above.
- There are characteristics of the alloy that affect process yield. -There are no independent variables.

Experiment Descriptions

Flux Testing

Outline / Goals:

Flux testing is required as a mandatory building block for all following work and has the following major parts:

1. Phase 1
   a. Test all flux candidates in a laboratory wetting capability test
   b. Thereby reducing the number of candidates to test more extensively in machine systems.
2. Phase 2
   a. Machine testing with Alloy A(SAC405), Machine A
      i. Flux application rate and pre-heat at vendor recommendation
      ii. Vary contact time to a maximum of 8 seconds
      iii. Vary pot temperature from 250C to a maximum of 275C
      iv. The population of flux candidates is expected to be reduced due to Phase 1 comparisons and elimination of weaker candidates
3. Phase 3
   a. Machine testing with Alloy B(SAC305), Machine B
   b. Flux application rate tested as before and at a lower rate
   c. Vary contact time and temperature as above
4. Phase 4
   a. Machine testing with Alloy B(SAC305), Configured to Machine B equivalent
   b. Same conditions as noted in Phase 3
5. Phase 5
   a. Visual / production scope inspection
   b. X-ray inspection to verify hole fill as required

Detailed Outline for Phase 1

Basically a solder alloy pellet is put onto a copper coupon, covered with 10 micro-liter of flux, then reflow in nitrogen atmosphere. The melting process is constantly monitored by a Video System that allows to see the profile of the alloy. The "contact angle" after 20 seconds from beginning of melting is considered. Initial and final situation are reported. Figure 1 shows the final wetting angle of one sample.

To approach a "standard surface" the coupons have been treated as follow: -degrease with Acetone (ACS grade). –treat in HCl solution 15 % for 15 – 20 seconds –rinse with DI water –dry under compressed nitrogen flow

Surface roughness and morphology can heavily affect the results so, the same type of copper clade laminate was used for all the fluxes. The treated copper surface of the copper clade laminate used in this work has been evaluated by AFM. Result is showed in Figure 2.

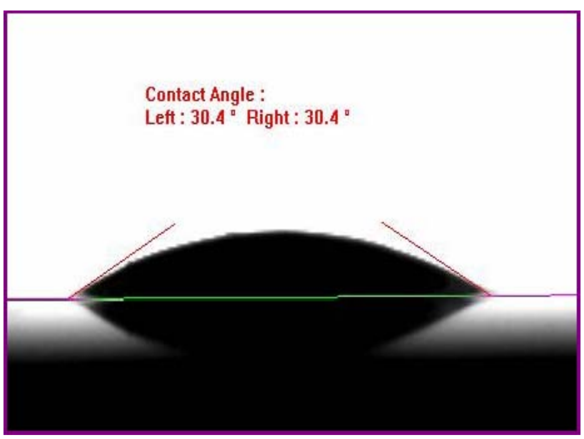

Figure 1 – Final Wetting Angle

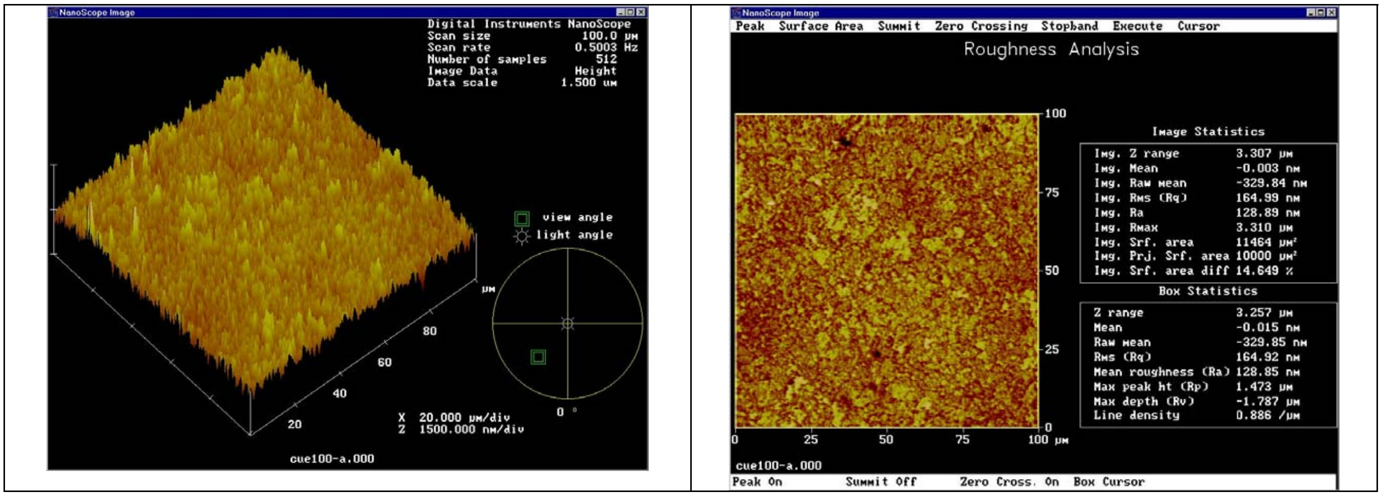

Figure 2 - Wetting index

The wetting capability of flux is reported with a number, scale 0-100, that I defined as “wetting index”. It is simply the cosine of “contact angle” - - (multiply by 100).

e.g.: Contact angle = 44 ° → “wetting Index “: cos 44 ° (=0.72) x 100 = 72.

Wetting index 100 → ideal perfect wetting (.= 0)

The higher the wetting index the better the wettability.
Using the “Cos “ makes more sense then consider the. itself, since the “Work of adhesion - Wa - ” is function of cos according to the following equation :

Wa = $_{l}$ (1+ cos).

Surface Tension or InterFacial Tension (IFT)
IFT of liquid flux can play an important role in soldering process. The IFT of alcohol based flux is mainly dictated by alcohol ; The IFT of IPA is around 22 mN/m. The IFT of water is significantly higher : 72 mN/m. This high IFT would not allow the flux to work properly. “Surfactants” are usually added to the VOC-free flux formulation in order to lower the IFT.

The lower the flux IFT the higher its capability to spread through the holes. Conversely, low IFT could favorite the dilution of activator along the board surface.

The IFT of VOCs fluxes has been measured by Pendand drop.

Detailed Outline for Phase 2, Phase 3, Phase 4:
In the machine testing of fluxes, the experiments are similar, in that they are searching for both flux performance and flux survival. They differ by machine description and alloy. This is explained by the fact that the general customer base may chose either a SAC305 or a SAC405 alloy. Within the company, the two different machines comprise the defined base for lead-free work.

Some indications of the difference in performance due to the specific alloy are addressed in the next part of the experiment., which looks specifically at the solder alloys.

In Phase 2, 3 and 4, it is noted that the machine set-up was always optimized and confirmed as good. In all cases, it was a double wave process. Any parameter outside the DOE was made as uniform and controlled as possible. These phases of testing are designed to take the limited population of flux candidates and rank their performance.

The specific structure of Phase 2 Design of Experiment (DOE) is as follows: (See Table 1.)

Table 1 – Phase 2

Run #	Qty of Samples	Var. 1 – Pot Temp.	Var.2 – Contact Time
1	3	275C	3 seconds
2	3	275C	7.5 seconds
3	3	255C	3 seconds
4	3	255C	7.5 seconds
5	3	265C	3 seconds
6	3	275C	7.5 seconds

Phase 2 testing was done with a SAC305 alloy, and a standard lead-free solder module configuration.
For Phase 3 the testing continues to look at flux performance and survival, but the amount of flux applied is significantly reduced, to further stress the material.

The specific structure of Phase 3 Design of Experiment is as follows: Phase 3 testing was done with a SAC305 alloy, and an enhanced lead-free solder module configuration. (See Table 2.)

Table 2 – Phase 3

Run #	Qty of Samples	Var. 1 – Pot Temp.	Var.2 – Contact Time	Var.3-Flux Qty
1	3	255C	3 seconds	Hi
2	3	265C	3 seconds	Hi
3	3	275C	3 seconds	Hi
4	3	255C	7.5 seconds	Hi
5	3	265C	7.5 seconds	Hi
6	3	275C	7.5 seconds	Hi
7	3	255C	3 seconds	Lo
8	3	265C	3 seconds	Lo
9	3	275C	3 seconds	Lo
10	3	255C	7.5 seconds	Lo
11	3	265C	7.5 seconds	Lo
12	3	275C	7.5 seconds	Lo

For Phase 4 the testing continues to look at flux performance and survival. The amount of flux applied is significantly reduced, to further stress the material. The wave forms are changed to duplicate the machine in Phase 2.

The specific structure of Phase 4 Design of Experiment is shown in Table 4.

Table 4 – Phase 4

Run #	Qty of Samples	Var. 1 – Pot Temp.	Var.2 – Contact Time	Var.3-Flux Qty
1	3	255C	3 seconds	Hi
2	3	265C	3 seconds	Hi
3	3	275C	3 seconds	Hi
4	3	255C	7.5 seconds	Hi
5	3	265C	7.5 seconds	Hi
6	3	275C	7.5 seconds	Hi
7	3	255C	3 seconds	Lo
8	3	265C	3 seconds	Lo
9	3	275C	3 seconds	Lo
10	3	255C	7.5 seconds	Lo
11	3	265C	7.5 seconds	Lo
12	3	275C	7.5 seconds	Lo

Phase 4 testing was done with a SAC305 alloy, and the standard lead-free solder module configuration.

Detailed Outline for Phase 5
In the given project, the question of alloy acceptability is not a subject of investigation or discussion. Previous works address that subject. Consequently, micro-structure analysis has minimal value in this paper. Previous works also addressed voiding, and that has minimal value to this paper.

Given these situations, the majority of analysis is visual inspection and inspection under production scopes. Hole-fill, solder balls, solder-bridges, excess solder, cosmetics and joint shape per IPC 610D are applied. Cosmetics are a secondary issue, compared to first pass yield, given approximately the same visual appearance.

Solder Machine Pre-Heat Testing
Outline / Goals
For the purpose of lead-free wave soldering, equipment features that could serve to reduce the insufficient hole-fill defect category were identified for evaluation.

The value of improved pre-heat is one of those features. Specifically, in the wave solder process, less effective board preheat creates a greater thermal challenge for the molten metal moving up a PTH to make a top fillet. In lead-free wave solder, the process superheat (Super heat is the difference between alloy melt temperature and process set-point.) is about 50% of that in tin-lead process. All of the chemical and thermal requirements to make a full solder joint, in a limited amount of time, cannot be met unless pre-heating of the sample board is done more effectively.

This study will review both I.R and Convection heat units, in top and bottom locations, for contribution to improved machine yield. This study was extended to include cumulative impact of heaters in mixed configurations.

Equipment
1 Wave solder machine, Date of Manufacture 05/2005.
2 Solder module configuration was an “A” wave form.
3 Flux module was a traversing head spray unit.
4 Conveyor module was a variable speed finger conveyor
5 Pre-heater type and configuration in Table 5.

Table 5 – Pre-heater Type and Configuration

Heater Type	***Location***	***Description***	***Comments***
Lower Convection	Slot 3 – Bottom Slot 2 – Bottom	Existing design for lower convection module	In the associated machine, Slot #1 is closest to the solder module
Top Convection	Slot 2 – Top	Unique convection design unit for upper location in a wave solder.	Not interchangeable with lower unit.
I.R.	Slot 1 - Bottom Slot 1 - Top		The common machine configuration is for an I.R. heater to be over a convection unit in SLOT #1

Test / Analysis Materials and Equipment
1 ECD Super Mole Gold
2 30 AWG, type K thermocouples (t/c)
3 24 AWG, type K thermocouples (t/c)
4 Aluminum, Kapton and hi-temp solder for t/c attachment
5 Test Vehicle A (TVA)
   a. 0.130” thick, large panel, un-populated
   b. (5) t/c space uniformly across diagonal
   c. The t/c tips are trapped under torque-set flat washers/screw/nut hardware
   d. Design goal is to measure area uniformity and heat transfer
   e. Modeled after BTU Oven Calibration Control Sample
   f. See photograph in Attachments Section

6 Test Vehicle B (TVB)
   a. 0.062” thick, sample product, populated and previously soldered
   b. To demonstrate reaction to shadowing and physical size differences
   c. T/C attachment method was hi-temp solder on legs and pads
   d. See photograph in Attachments Section
7. Test Vehicle C (TVC)
   a. 0.062” thick, sample product, populated and previously soldered
   b. To demonstrate reaction to shadowing and physical size differences
   c. T/C attachment method was hi-temp solder on legs and pads
   d. See photograph in Attachments Section

Test Outline

The evaluation outline, with description of test and abbreviated results are as follow:
1. Opposing element thermal control limits
   a. While the temperature set point of one of the paired heaters is not varied, the temperature set point of the opposite heater is changed in 20 degree increments.
   b. The temperature set points are run, with a conveyor speed of 3 fpm, for a minimum of 20 minutes, as a stabilization allowance.
   c. The temperatures are recorded after 20 minutes, or until the actual temperature of either heating element exceeds the factory set tolerance range.
   d. After running the tests with the bottom unit as the constant, the top unit is set as the constant. The bottom unit becomes the variable, and the above outline is repeated.
   e. In summary, the I.R. pair operates with a 500 C maximum limit, and the convection units work with a 200 C limit.
2. Single pair of heaters and thermal performance on TVA
   a. Conveyor speed is constant at 3 fpm
   b. Three combinations of temperatures are used in the paired heaters
   c. The convection heater combinations are:
      i. Bottom at 120 C versus Top at 120 C
      ii. Bottom at 120 C versus Top at 140 C
      iii. Bottom at 140 C versus Top at 120 C
   d. The I.R. heater combinations are:
      i. Bottom at 250 C versus Top at 250 C
      ii. Bottom at 250 C versus Top at 350 C
      iii. Bottom at 350 C versus Top at 250 C
   e. The temperate seen on the board, the rising slope of temperature, and the temperature difference between the (5) thermocouples are the points of evaluation
3. Combined thermal performance on TVA of paired convection and paired I.R.
   a. The same temperatures as noted above were used
4. Paired convection heater performance on a test board (TVB)
   a. This test applied the same temperatures as previously noted, but the test vehicle presented variations in color, size, thermal mass and air flow to the test panel.
5. Paired convection heater performance on a test board (TVC)
   a. Same as above.
   b. A second “production similar” test board was used to confirm the first set of results, and search for performance inconsistencies.
6. Paired I.R. heater performance on a test board (TVB)
   a. This test applied the same temperatures as previously noted, but the test vehicle presented variations in color, size, thermal mass and air flow to the test panel.
7. Paired I.R. heater performance on a test board (TVC)
   a. This test applied the same temperatures as previously noted, but the test vehicle presented variations in color, size, thermal mass and air flow to the test panel.
   b. This is a second “production similar” test board, and it was used to confirm the first set of results, and search for performance inconsistencies.
8. Combined convection and I.R. performance on a test board (TVB)
   a. This test applied the same temperatures as previously identified, but in the combined configuration.
9. Combined convection and I.R. performance on a test board (TVC)
   a. Same as above.
   b. This is a second “production similar” test board, and it was used to confirm the first set of results, and search for performance inconsistencies.

10. Thermal recovery and capacity in a 5-panel test
    a. The purpose of the test is to show that when a production load is put on the machine, there is enough capacity and recovery in the heaters to give the same profile to each panel along the length of the conveyor. (That is, a loaded machine is not prone to “cold spots” because it is filled with product.)
        i. Basically, a series of boards are profiled as a group. A significant profile differences between the individual boards is cause for review.
        ii. Each panel will have 3 t/c sites
        iii. For this test, long T/C wires are required
    b. There are a minimum of (3) t/c per board
        i. Lower left corner, 1” along diagonal from the corner
        ii. Center of diagonal line drawn across panel
        iii. Top right corner, 1” along diagonal from the corner
        iv. All t/c are attached by the aluminum foil method
        v. All t/c are the same AWG
        vi. All t/c are 30 AWG, unless otherwise specified.
    c. The test will use a minimum of (2) conveyor speeds and the three temperature range settings noted above.
    d. With the machine stabilized for 20 minutes prior to the test, the five panels are loaded onto the conveyor at approx 12” to 15” spacing
    e. A single profile run shows the temperature of a given on each panel along the length of the conveyor, satisfying the following Table 6.

Table 6 – Sample Chart that Outlines the Pre-Heater Matrix Testing

	Profile #1	***Profile #2***	***Profile #xxx***
Conveyor fpm			
P.H. #2-Top			
P.H. #2-Bottom			
P.H. #1-Top			
P.H. #1-Bottom			
TV #1, t/c #1			
TV #2, t/c #1			
TV #3, t/c #1			
TV #4, t/c #1			
TV #5, t/c #1			

Alloy Impact on Process

Purpose of Study / Goals

As the general electronic industry considers different lead-free alloys for lead-free wave soldering, the question of how the alloy impacts the process develops. In a similar vein, as production moves from alloy A to alloy B, it would be valuable to know how much process knowledge is transferable between these alloys. These are the points that drive this experiment section.

The goals in this section will be to standardize everything in a wave solder process, and manipulate only pot temperature and preheat, across 3 current lead-free alloys. The alloys studied were SAC405, SAC305, and a proprietary low-silver SAC alloy. After measuring the defect rates from the different DOE steps, a limited confirmation study would be run. The DOE work and the Confirmation work data would be compared

Equipment

1. Wave solder machine, Date of Manufacture 02/2005.
2. Solder module configuration included turbulent and smooth wave forms.
3. Solder module was a “roll-out” assembly allowing for easier alloy changes, and it was the only change that occurred between alloy tests.
4. The solder nozzle assemblies were the same in all cases. They were moved to the alloy pots and re-installed to exact parameters by use of hard tooling.
5. Flux module was a traversing head spray unit.

6. Conveyor module was a variable speed finger conveyor

Test / Analysis Materials and Equipment:

1. ECD Super Mole Gold
2. 30 AWG, type K thermocouples (t/c)
3. Aluminum, Kapton and hi-temp solder for t/c attachment
4. Test Vehicle A
    a. 0.062" thick x 6 in. x 8 in. with (4) test components
        i. (2) DIMM connectors at C3, C2
        ii. 0.100" grid at C1, with leg-stick-out under 0.050"
        iii. 0.100" grid at C4, with leg-stick-out near 0.125"
    b. (3) t/c space uniformly across diagonal for profile
    c. Two internal layers of 3 oz. Cu, with ½ oz. Surfaces.
    d. See photograph in Attachments Section

Test Outline

1. The test matrix is a simple, 3 variable design of experiment format, shown in Table 7.
2. The correlation of conveyor speed to contact time is as follows:
    a. 1.75 fpm = 7.5 seconds of contact time
    b. 4.5 fpm = 3 seconds of contact time
3 The confirmation run is done at the setting of best yield, based upon field inspection of the collection of DOE samples.
    a. Confirmation runs include OSP and L-F HASL boards

Table 7 - 3 Variable Design of Experiment Format

Step	Qty	Var. 1- conveyor	Var.2- Pre-heat	Var.3- Pot Temp
1	2	1.75 fpm	130 C	265 C
2	2	1.75 fpm	130 C	250 C
3	2	1.75 fpm	90 C	265 C
4	2	1.75 fpm	90 C	250 C
5	2	4.5 fpm	130 C	265 C
6	2	4.5 fpm	130 C	250 C
7	2	4.5 fpm	90 C	265 C
8	2	4.5 fpm	90 C	250 C

Analysis of Samples

1 Visual inspection will record solder shorts, excess solder, insufficient solder and hole-fill by component type.
2 Solder balls are reported for the entire board.
3 Cosmetics are noted for the assembly
4 Nicolet Imaging System, NXR-1400I used for hole fill confirmation
    a. Reference settings are:
    i. Power at 30
    ii. KVA at 80-110
    iii. Board held at a constant 45 degree angle.
5 Interpretation of results to utilize:
    a. IPC 610C and D
    b. X-ray
    c. Main effect plots of DOE and confirmation runs
    d. Box plots as above
    e. One Way ANOM as above
    f. Interaction plots as above

Results

Flux Evaluations

A VOC-no-clean formula with 6% rosin was the clear cut winner with fewest solder defects, and moderate flux residue. There was no discernable difference when used in either SAC305 or SAC405 alloy. (The flux selection work was done with only two alloys.) Performance was uniform across all temperatures and contact times. The enhanced lead-free wave solder

configuration gave results measurably better than the standard configuration, and flux residues were less obvious.
In the VOC-free-no-clean flux formulas, the resistance to bridges was slightly less than the VOC category leader, but cosmetics were generally better.

Pre-heater Study

Summary

This preliminary study shows that paired convection pre-heaters perform better than an I.R./ convection pair. Paired ("Paired" is a term used to identify a top-side pre-heater being located directly above a similar bottom-side heater.) convection pre-heaters operated with good predictability and with excellent efficiency. The individual top convection heater was superior to the individual top I.R. heater. When used prior to a paired set of I.R. pre-heaters, the net effect is superior to a single top-side I.R. pre-heater.

Pre-Heater Study of I.R. Bottom with I.R. Top

The Table 8 shows the influence of a top-side heater vs. the opposite bottom-side heater in achieving and holding set-points. (Temperatures in Celcius)

Table 8 – Top-Side v s. Opposite Bottom-Side Heater

S.P. Bottom	***S.P. Top***	***ACTUAL – BOTTOM***	***ACTUAL – TOP***
200	100	201	128
200	120	200	120
200	140	200	138
200	160	200	161
200	180	200	180
200	200	200	200
200	220	200	217
200	240	201	238
200	260	200	260
200	280	199	281
200	300	201	303
200	320	200	320
500	340	223	340
480	400	502	400
460	400	480	399
300	400	459	401
300	100	307	151
300	120	Skip	Skip
300	140	301	164
300	160	300	175
300	180	300	188
300	200	300	200

Table 9 shows the influence of top heater vs. bottom heater in achieving and holding set-points. (Temperatures in Celcius)

Table 9 - Pre-Heater Study of Convection Bottom with Convection Top

S.P. Bottom	***S.P. Top***	***ACTUAL – BOTTOM***	***ACTUAL – TOP***
120	60	119	
120	80	120	
120	100	120	
120	120	120	
120	140	120	
120	160	120	
120	180	121	
120	200	124	
120	220	Not a valid setting	Not a valid setting
100	200	127	200
120	200	127	201
140	200	140	200
160	200	160	200
180	200	179	201
200	200	201	199

Representative Profile of top Convection Pre-heater

Figure 3 shows a rapid and uniform affect on the board, with a minimal temperature difference across the panel. Set point temperatures were approx 50% of I.R.

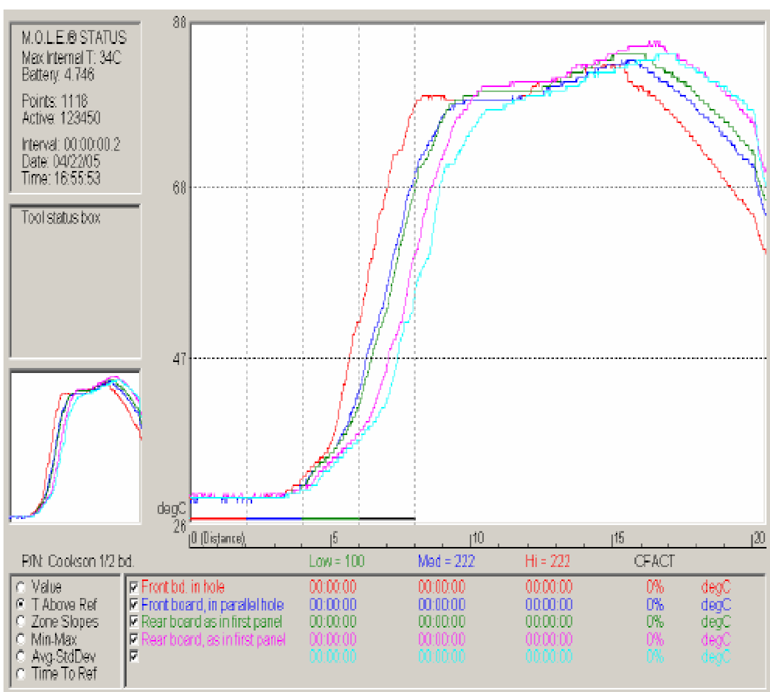

Figure 3 – Rapid and Uniform Affect on the board with Minimal Temperature Difference across the Panel

Representative Profile of top I.R. Pre-heater
Figure 4 shows a slower and non-uniform affect on the board, with a wide temperature difference across the panel. Set point temperatures were approx double convection system.

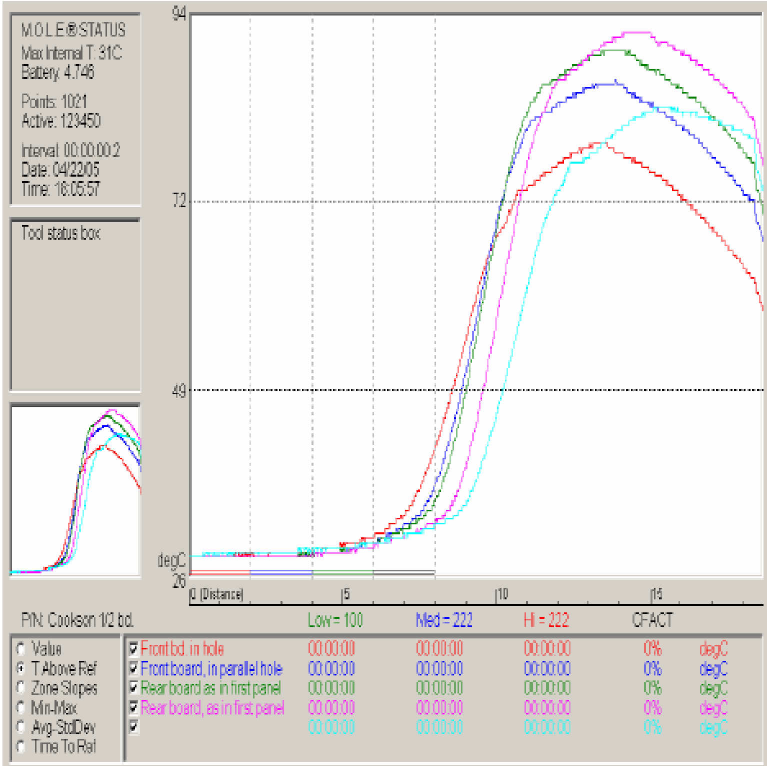

Figure 4 - Non-Uniform Affect on the Board, with a Wide Temperature Difference across the Panel

Alloy Study
Special Comment on Un-Anticipated Solder Joint Defect: In the course of this study, there was a re-occurring situation with large voids, especially in a single drilled hole size. It was explored, and the following is presented as a point for future study for both bare board quality standards, MSL of bare boards, and process parameters.

In summary, a minor imperfection in a PTH, in conjunction with a hydroscopic laminate, and a solder contact time over 3 seconds, at a 265 C pot temperature, resulted in large voids. (See Figures 5-7 and Tables 10-11.)

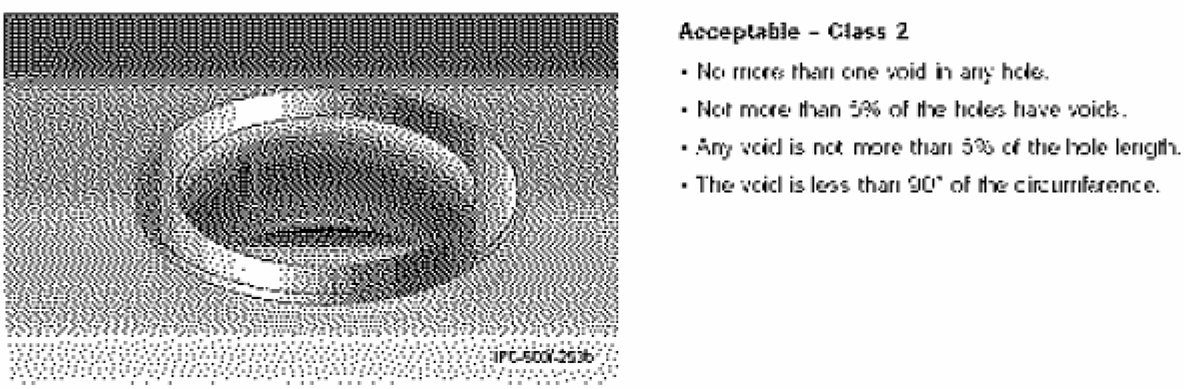

Figure 5 – Reference to Existing Standard

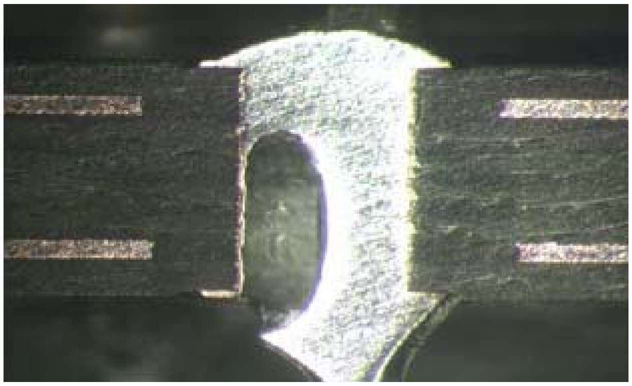

Figure 6 – Micro-Section view of the Subject Void

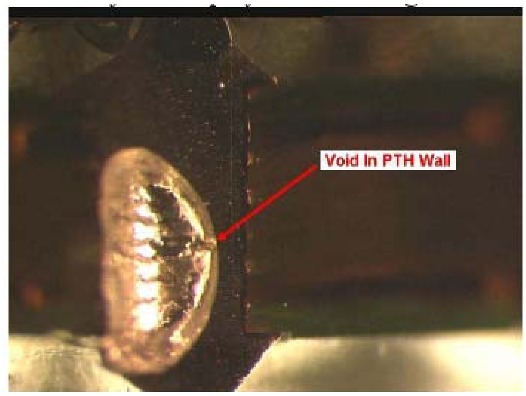

Figure 7 – Exploded View of Wall Imperfection causing the above Void

Statistical Representation of Alloy Interaction Study as follow (See Figures 8-24)

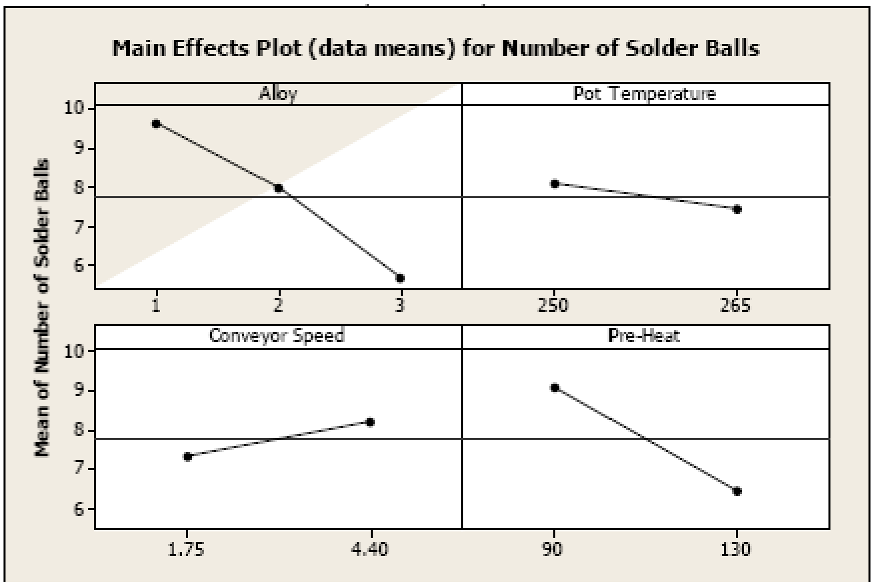

Figure 8 - DOE Main Effect Plots (data means) for Solder Balls

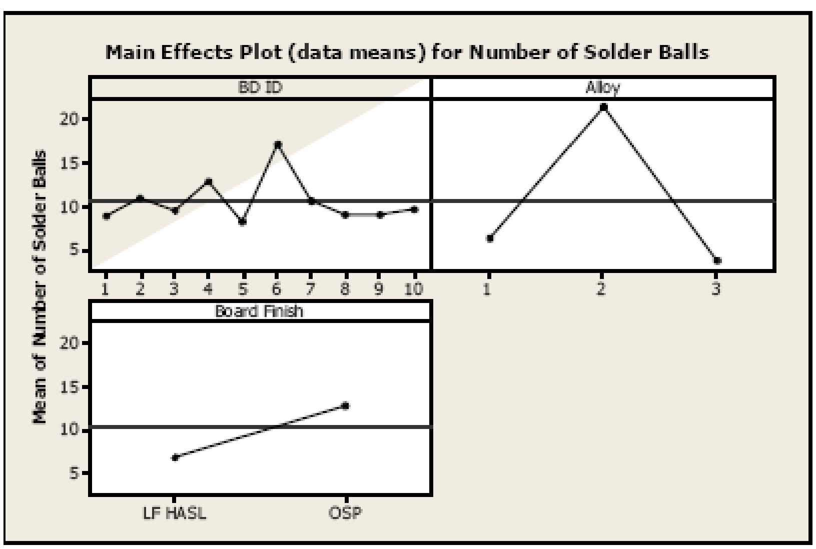

Figure 9 - Confirmation Run Main Effect Plot

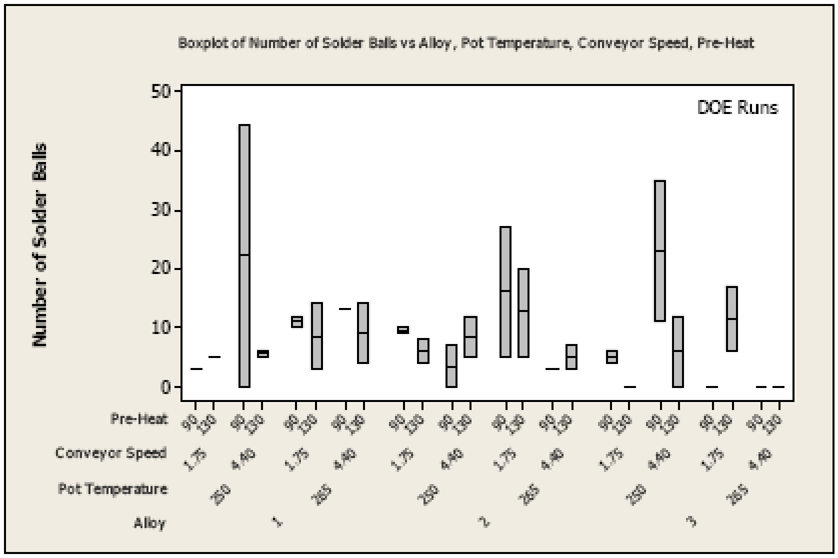

Figure 10 – DOE Box for Solder Balls

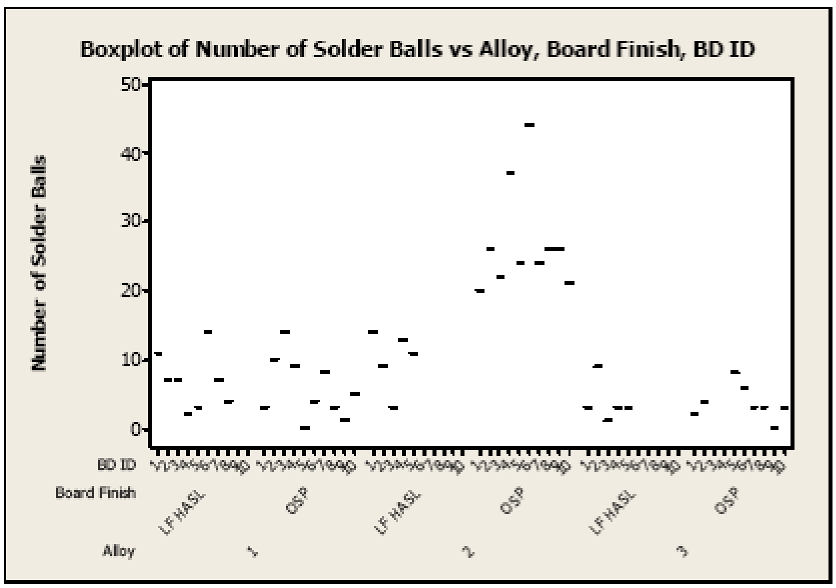

Figure 11 - Confirmation Run Box Plot for Solder Balls

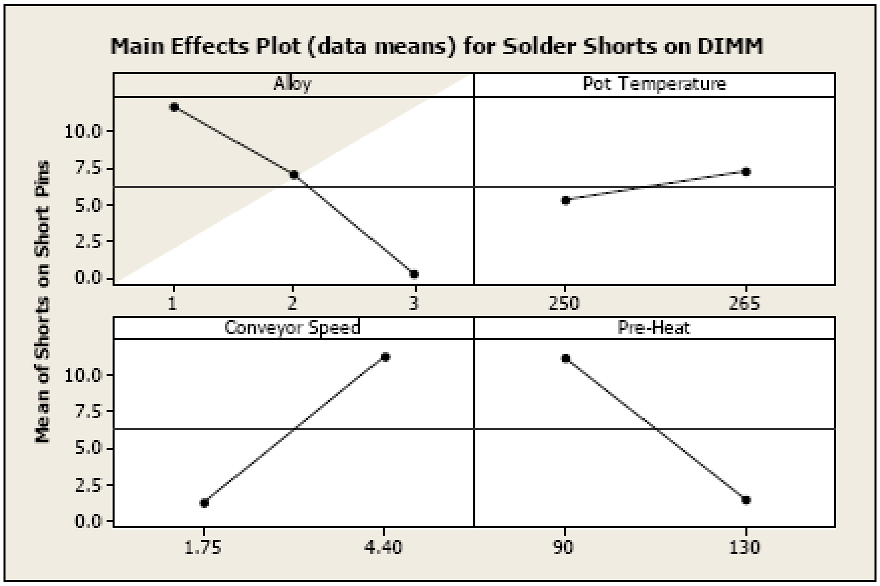

Figure 12 - DOE Main Effect Plots (data means) for Solder Shorts

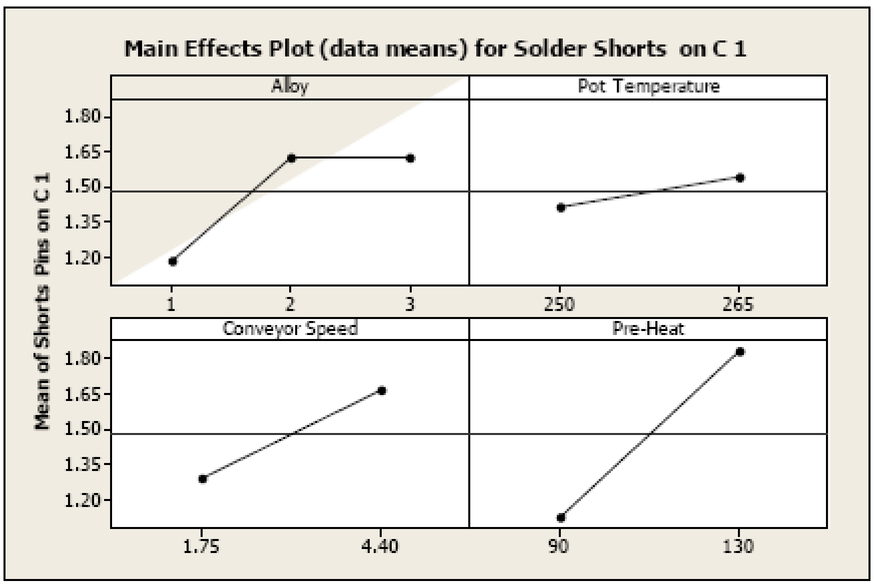

Figure 13 - DOE Main Effect Plots (data means) for Solder Shorts

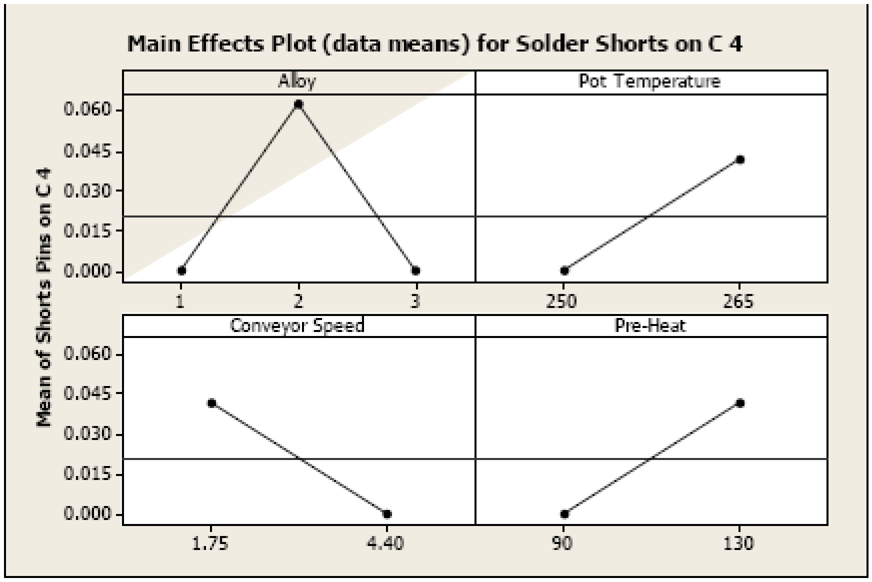

Figure 14 - DOE Main Effect Plots (data means) for Solder Shorts

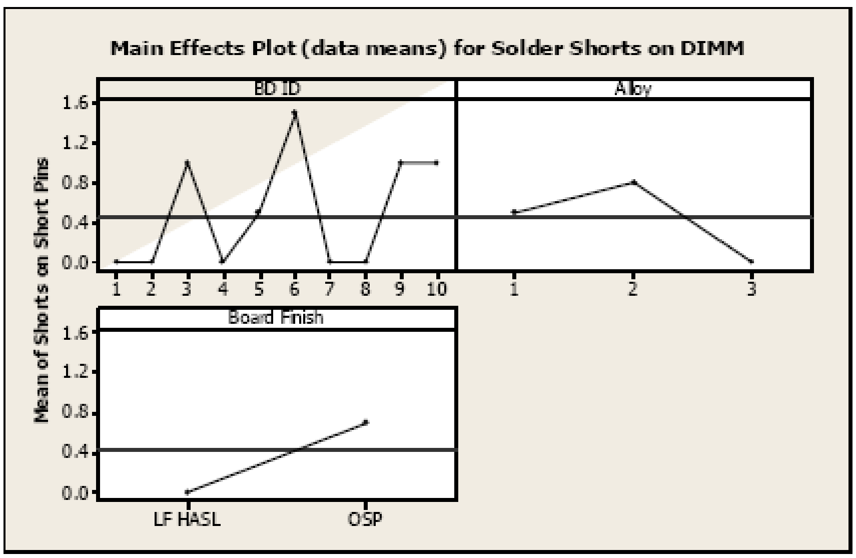

Figure 15 - Confirmation Run Main Effect Plots for Solder Shorts

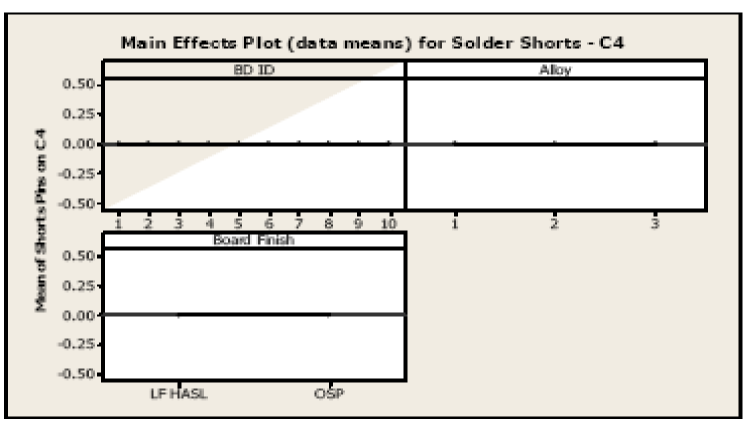

Figure 16 - Confirmation Run Main Effect Plots for Solder Shorts

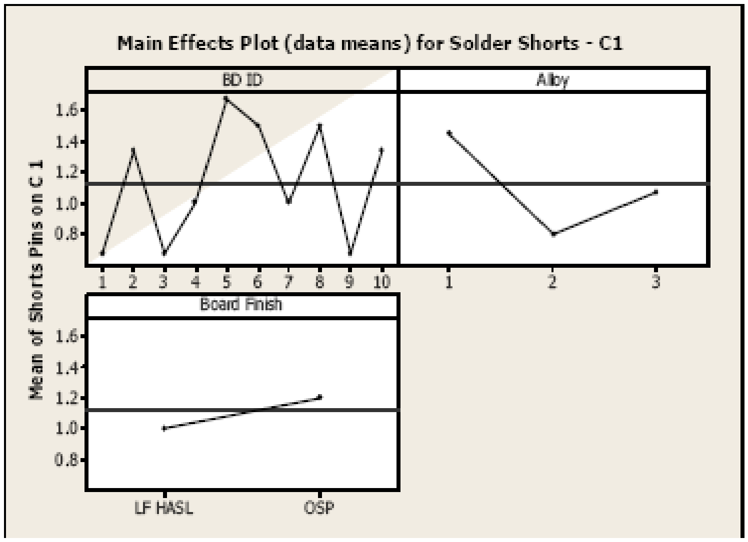

Figure 17 - Confirmation Run Main Effect Plots for Solder Shorts

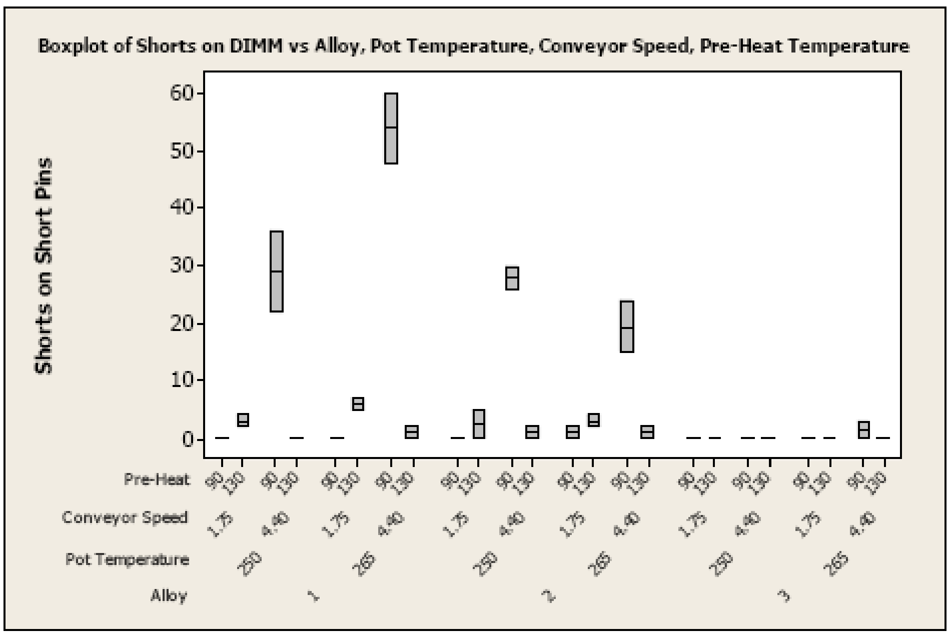

Figure 18 - DOE Box Plot of Solder Shorts on DIMM Connectors (Short Pins)

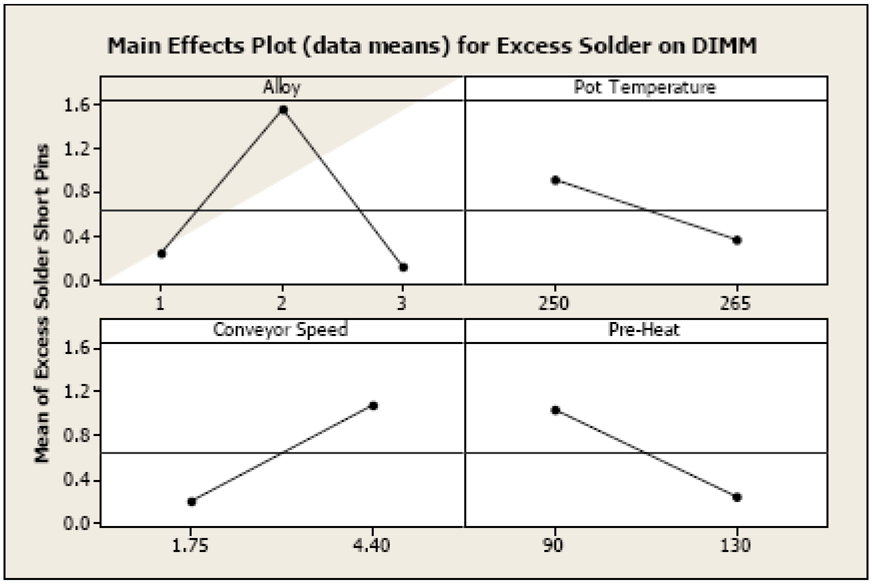

Figure 19 – DOE Main Effect Plots (data means) for Excess Solder

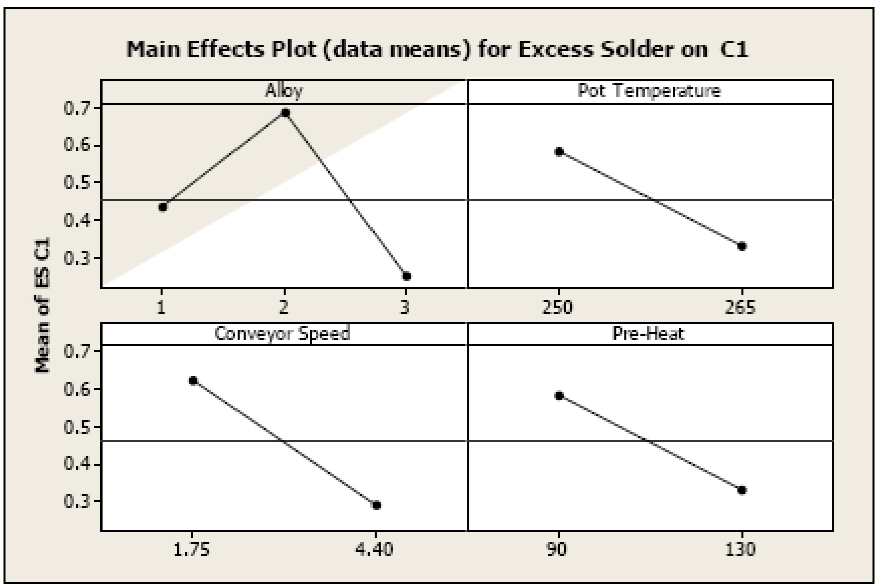

Figure 20 - DOE Main Effect Plots (data means) for Excess Solder

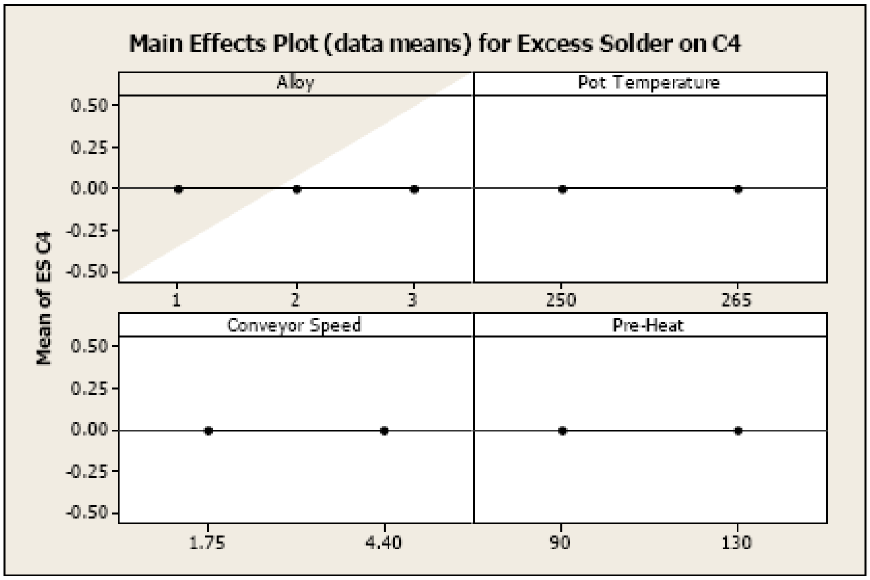

Figure 21 - DOE Main Effect Plots (data means) for Excess Solder (Note: C4 has a thru-board length of 0.175")

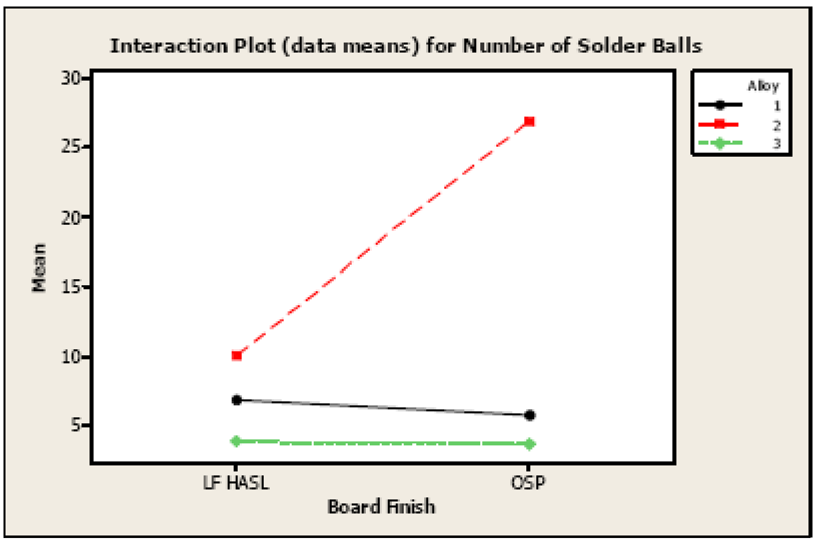

Figure 22 – Confirmation Run Data for Solder Balls by Surface Finish

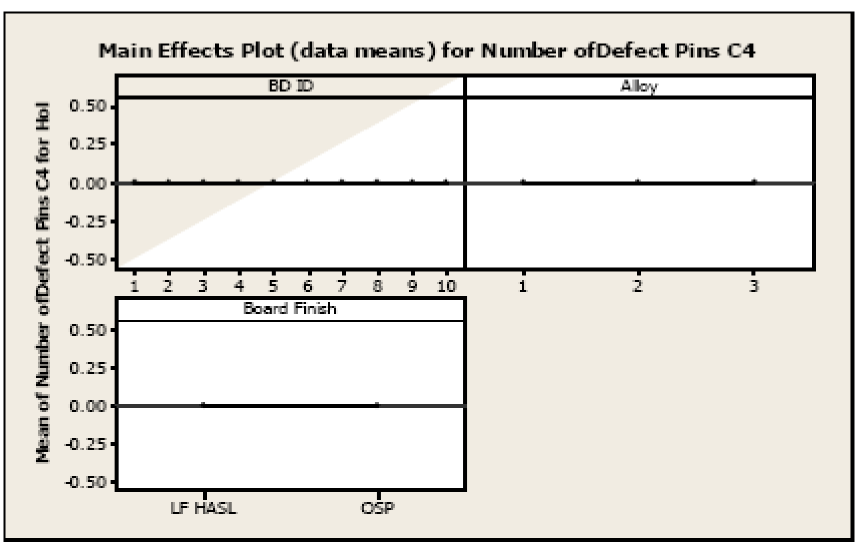

Figure 23 – Confirmation Run Data for Hole Fill

Table 10 -Confirmation Run – Non-Solder Ball Defects

Data	Alloy 1	2	3	Grand Total
Sum of Shorts Pins on C3 DIMM	0	3	0	3
Sum of Shorts Pins on C2 DIMM	9	9	0	18
Sum of Shorts Pins on C 1	26	12	16	54
Sum of Shorts Pins on C 4	0	0	0	0
Sub total Shorts	36	26	19	75
Sum of ES C3 DIMM	0	2	0	2
Sum of ES C2 DIMM	1	1	0	2
Sum of ES C1	7	10	8	25
Sum of ES C4	0	1	0	1
Sub Total Excess Solder	8	14	8	30
Sum of Number of Defect Pins C3 for Hole Fill	0	0	0	0
Sum of Number of Defect Pins C2 for Hole Fill	0	0	0	0
Sum of Number of Defect Pins C1 for Hole Fill	0	0	0	0
Sum of Number ofDefect Pins C4 for Hole Fill	0	0	0	0
Sub Total Defect Pins	0	0	0	0

Table 11 - Confirmation Run – All Defects

	Alloy			
Data	1	2	3	Grand Total
Sum of Number of Solder Balls Sum of Shorts Pins on C3 DIMM Sum of Shorts Pins on C2 DIMM Sum of Shorts Pins on C 1 Sum of Shorts Pins on C 4 Sum of ES C3 DIMM Sum of ES C2 DIMM Sum of ES C1 Sum of ES C4 Sum of Number of Defect Pins C3 for Hole Fill Sum of Number of Defect Pins C2 for Hole Fill Sum of Number of Defect Pins C1 for Hole Fill Sum of Number ofDefect Pins C4 for Hole Fill	112 0 9 26 0 0 1 7 0 0 0 0 0	320 3 9 12 0 2 1 10 1 0 0 0 0	48 0 0 16 0 0 0 8 0 0 0 0 0	480 3 18 54 0 2 2 25 1 0 0 0 0
Totals	155	358	72	585

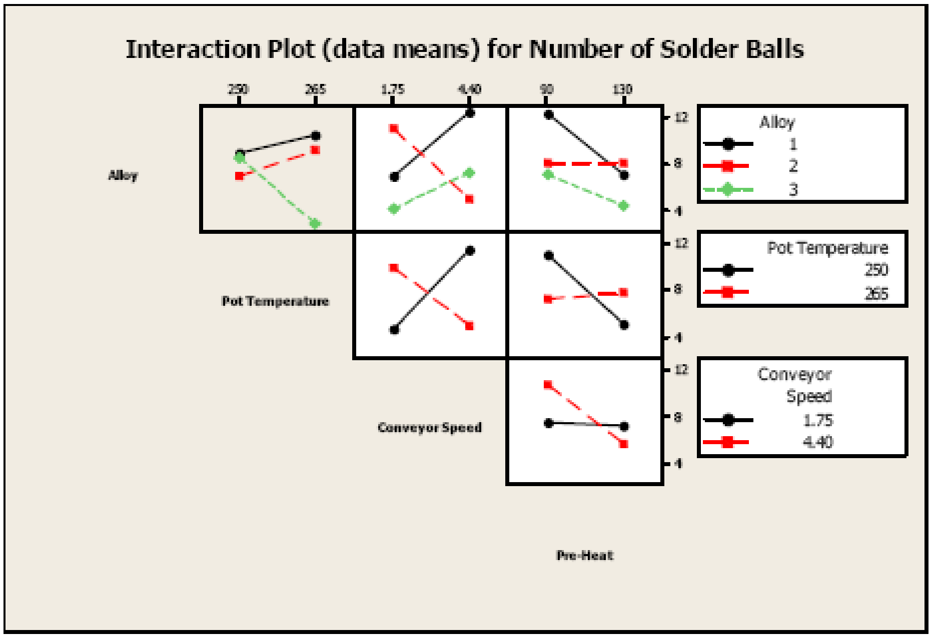

Figure 24 - Interaction Plot from DOE Data (data means) for Solder Balls

Conclusions

FLUX

1 The flux evaluation methodology was successful for the conditions applied.

2. The points to emphasize in this work were as follow:
   a. A very large field of candidates was put under evaluation, increasing the opportunity to find the most appropriate candidate for the given business.
   b. The laboratory test process reduced the field of candidates very quickly, with very low costs, and was both impartial and repeatable.
   c. A minimum number of test vehicles was required for actual machine work.
   d. The machine time used for the testing was very short
   e. The program can be modified to suit business needs.

PRE-HEAT

1 Given the rules of solder joint formation that demand a time-temperature thresh-hold to be met, the performance improvements seen in the pre-heat test are desirable.

2. Points to emphasize include the following:
   a. As compared to other pre-heaters, the set-points on the convection unit are generally lower.
   b. From the profiles, three attributes in convection heaters are noted:
      i. The assembly reacts to the thermal energy more quickly
      ii. In a shorter period of time, the assembly has a lower delta t than the alternative methods
      iii. The convection heaters are less sensitive to color or thermal mass.

c Given the study detail and results, top convection heaters are identified as a process advantage.

<u>ALLOY</u>

1. The alloys tested are identified as follow:
   a Alloy 1 was SAC405
   b Alloy 2 was SAC305
   c Alloy 3 was a proprietary, low silver SAC

2. The response variables measured were:
   a Solder bridges
   b Insufficient hole fill
   c Excess solder
   d Solder ball

3. By doing the study on a single machine, using the roll-out solder pot option, numerous sources of statistical noise were

either reduced or eliminated.

   a. The confidence in the results from planned interactions is improved
   b. The process parameters varied were pre-heat, solder pot temperature, and conveyor speed.

4 The following are ANOM charts of the excess solder data, and except for one point, they show the study results to generally be within the anticipated range of statistical error. In effect, this chart supports the statement that there is not a significant difference in the process characteristics of each alloy.

5 In the DIMM ANOM chart, the response in OSP is the single point that does not follow the trend. For those test conditions, it cannot presently be explained. All samples were the same lot, and the same OSP. An extended study is suggested. Presently, a single, small study cannot be considered a process standard.

6. While one ANOM chart supports no statistical difference between alloys, the analysis of main effects and interactions for solder balls and hole-fill are of interest.
   a. The low-silver SAC alloy generally had the best performance.
   b. When the main effect plots are reviewed, the line slopes clearly suggest the stronger process set-points.
   c. As an example, for any given alloy, the confirmation run set points were determined by the best DOE set-points.
   d. All alloy confirmation runs were the same set-points for pre-heat, conveyor speed, and pot temperature.
   e. For hole-fill, there were no defects in any confirmation run.
7. The large voids that we un-expectedly found in this study may be associated with bare board specifications that are not adequate for lead-free wave solder.
   a. The voids could be eliminated by holding contact time under 3 seconds.
   b. That situation is commonly violated in current tin-lead work.
   c. An industry effort will be the required corrective action on this problem.
8. As un-expected as the voids were, another un-expected finding was the total lack of defects on C4.
   a. C4 was a 0.100” grid pin header. The thru-board stick-out was purposely made very long, to 0.175”, to encourage solder bridges.
   b. There was never a bridge on this connector, while there was often a bridge on the exact same part that had a stick-out of about 0.050”.
   c. In another study, the leg stick-out was about 0.090”, and bridges will occur.
9. In discussion, there are other ways to interpret this study, and one of them is to look at all test conditions, and make an alloy selection based on the alloy with the largest number of test runs that have few defects.
   a. This logic suggests that the lead-free HASL surface finishes may have a place in lead-free wave soldering.

Future Work:

1. A study of defects by alloy and surface finish, with larger sample sizes.
2. The explanation of the large voids formed after exceeding a minimum contact time and solder pot temperature.
3. Process characterization in board thicknesses over 0.135”, with mixed component loading and variations in thermal mass.
4. A comparison of selective soldering machines, with lead-free alloys, to the optimized lead-free wave solders.

Appendix
Pre-heater Test Board for Product Robustness
Pre-heater Test Board for Uniformity Basic Test Vehicle
Product Sample:

Pre-Heater Uniforminty Test Board:

Basic Test Vehicle:

Sourced in High Temperature OSP and L-F HASL