Design for Manufacturability in the Lead Free Wave Solder Process

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ABSTRACT
The recent use of lead free alloys has made the wave solder process more challenging in terms of achieving acceptable solder joints for both SMT and PTH components. It has been found that the Design for Manufacturability (DFM) guidelines, which were established for tin lead processes, in many cases do not result in the same level of quality joints when soldering with lead free alloy. Therefore, in order to improve the process yields and reduce manufacturing costs when converting to lead free, it is essential to establish DFM guidelines specifically for lead free soldering. The effect of pin to hole ratio, quantity of large copper planes connected to a pin through hole barrel, connection types for PTH and land patterns for glue and wave chip components are some of the main features which require further investigation for design optimization.

As there are a variety of lead free alloys available on the market today, each with differing properties, it is also important to determine if a set of DFM guidelines result in similar results among these various alloys.

This paper will discuss the outcome of a project which studied several DFM features incorporated on an internally designed wave test vehicle, which was created to evaluate alternative lead free alloys. The DFM features included in this study were: land pattern design and varying component spacing for chip components, pin to hole ratio and its interaction with the quantity of large copper planes connected to a PTH, quantity of large copper planes connected to a PTH and its interaction with the type of connection either solid or four spokes. The test vehicle was assembled with four Pb-free alloys: Sn-Cu-Ni, Sn-Ag-Cu-Bi, Sn-Cu-X & SAC405 as the baseline. The quality level of each of the described DFM features will be discussed. In addition to this, a detailed barrel fill analysis for the PTH components will be shown.

Keywords: DFM, Wave Solder, Lead Free Alloy, Process Yield

INTRODUCTION
By the time a new product has been designed, a little part of the budget for the product launch has been already spent; however most of the total cost of the product has been set by the design (Figure 1). Conceptual design, development and detailed design are steps in the design stage of the product life cycle that will contribute to the cost setting. These steps include everything in the life cycle to define fit, form and function prior to launch for production. DFM becomes an important tool to gain competitiveness in the cost competitive electronic industry. Once the cost is fixed by the design, it will be very difficult to remove at manufacturing. The design defines the manufacturability of the product, which determines a significant part of the introduction and production costs. The use of DFM principles early in the product design stage, gives the opportunity to optimize the use of materials and processes when change is easier and less expensive. This concept also applies to printed wiring board (PWB) design, and referencing DFM principles in this area is critical in the cost definition for electronic products.

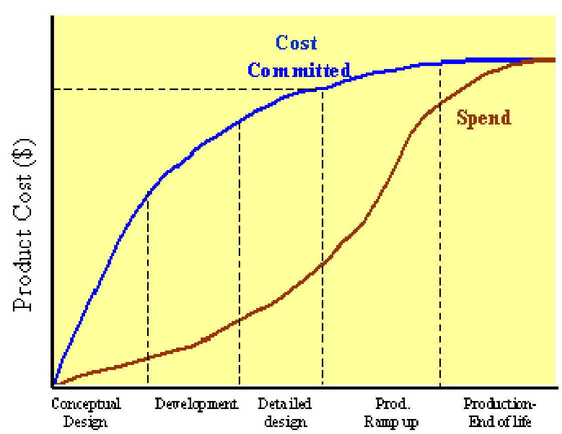


Figure 1: Product development phases vs product cost

The interactions of selected design features that are important for through hole and SMT assembly for wave soldering are reviewed in this paper. There are a number of guidelines used for many years in the industry to support and optimize the use of tin lead solders for various design features. Some of those guidelines have been found through experimentation and experience, and different companies and consortia have defined small variations to central design specifications to help accommodate specific needs. However, most of them are "flavors" of the widely accepted general guideline. For lead free alloys, there is little information to support the validity of the current Sn-Pb guidelines defined and moreover, there is the question of whether the same guidelines would apply to all of the various types of alternative Pb-free alloys on the market today. The process window that a new set of guidelines can provide becomes more important where there are multiple choices for lead free alloys competing in the market for cost, reliability and ease of operation.

This paper describes the experimental procedure and findings in the performance of four lead free wave solder alloys that were used to test the current Sn-Pb DFM guidelines. The paper also examines the limits of the selected design features in order to validate the applicability of the current guidelines, as well as the impact based on the performance of the four Pb-free alloys tested. The four Pb-free alloys tested are listed in Table 1, along with their respective melting points. The SAC405 (Sn-4.0%Ag-0.5%Cu) alloy was considered the baseline performer, given its broader acceptance and use as a result of the greater availability of reliability information. The other three proprietary alloys used are based on high Sn content with 2 or 3 additional alloying elements and different levels of additives. We will refer in this paper to them as alloys A, B and C.

Table 1: Melting temperatures

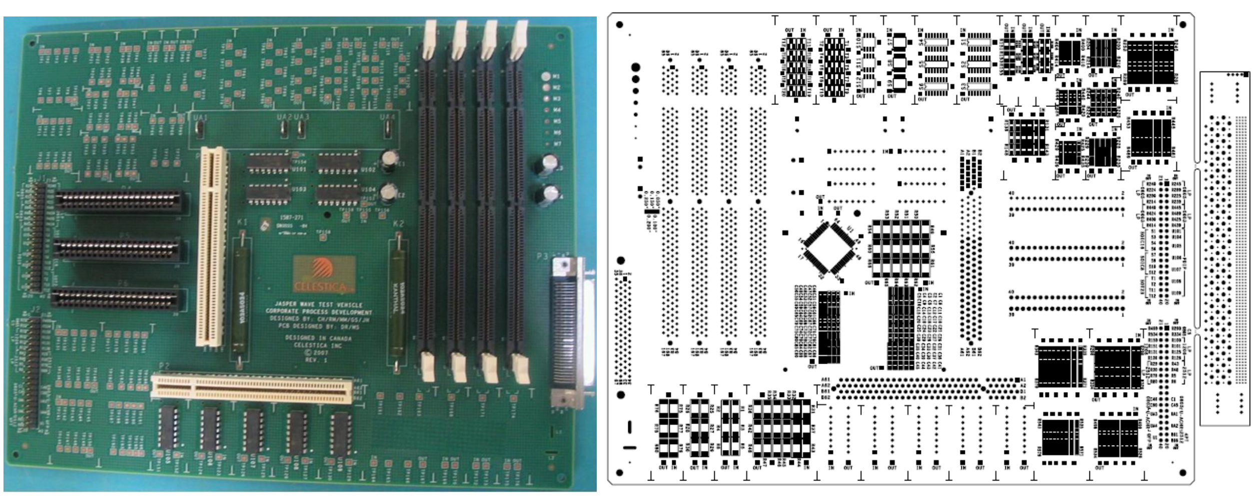
ALLOYS		MELTING RANGE
95.5Sn-3.8Ag-0.7Cu	(SAC405)	217°C to 220°C
99.1Sn-0.7Cu-0.05Ni-(<0.01)Ge[1]	(Sn-Cu-Ni)	227°C
99.1Sn-0.7Cu-X-Y	(Sn-Cu-X)	227°C
98.6Sn-0.3Ag-0.7Cu-Bi-X-Y[2]	(Sn-Ag-Cu-Bi)	217°C to 228°C
1. U.S. Patent #618055	2. Patent # PCT/GB2005/004609	

TEST VEHICLE

The test vehicle was designed with the intention to simulate representative component mixes in a 203.2mm x 254mm board. The board called "Jasper" is 12-layer and 2.34mm thick, with 4 copper layers (2 oz) acting as ground planes (Figure 3). The board finish was OSP with High Tg FR4, Polyclad 370HR Laminate.

The test vehicle was also used to test process parameters in a previous process optimization work and to test various solders for reliability; therefore other PWB features are not included in this paper as they are not relevant for the DFM study.

Board construction and component types used on the design features are shown in Figure 3 and Table 2 respectively.



(a) (b)

Figure 2: "Jasper" Test vehicle; (a) Topside; (b) Bottomside

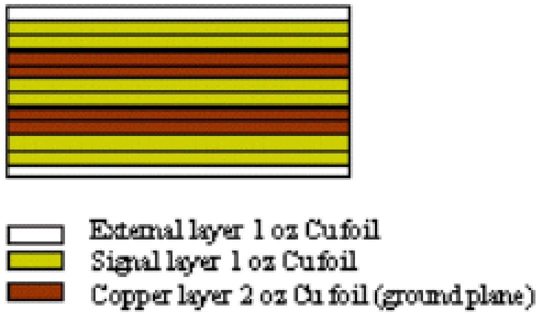


Figure 3: PWB construction

Table 2: Component types used for DFM feature analysis

Component Type	Pin Count	Pitch	Lead finish
Power Connector	20	2.54mm	Matte Tin over Nickel
DIMM Connector	168	2.29mm	Gold over Palladium Nickel
0805 Resistor	2	N/A	Tin over Nickel
0603 Resistor	2	N/A	Tin over Nickel
0805 Capacitor	2	N/A	Tin over Nickel
0603 Capacitor	2	N/A	Tin

EXPERIMENTAL DETAILS

Prior to the assembly of the test vehicle, the process parameters for each one of the alloys were defined through a previous experimental procedure. The same flux and soldering equipment was utilized and visual and x-ray inspection was performed on each board built with the four alloys to ensure quality joints that could be created for production boards.

A set of process parameters was found and set up in the soldering equipment for each alloy to process the boards in order to get the quality results related to the selected DFM features. The boards were assembled using an open wave pallet. Flux application settings and temperature profiles were developed to meet the parameters. For through hole components both hole fill and visual defects were included in the analysis while for SMT passives only visual defects expressed in DPMO's were considered.

The set points to run the experiment to study the DFM guidelines are shown in Table 3. The alternative alloys have been coded.

Table 3: Parameters used for all four alloys

Alloy	Pot Temp (°C)	Preheat Temp (°C)	Contact Time (Sec)
SAC405	**High**	**Low**	**High**
A	**High**	**Low**	**High**
B	**High**	**Low**	**High**
C	**High**	**Low**	**High**

DFM FEATURES

In order to understand if the same limits apply in the design of PWB's for the tin-lead process compared to lead free process, some characteristics were incorporated in the test vehicle (Figure 2) to test the capability of the process when using various lead free solder alloys, to produce good yields and acceptable quality for a high volume production process.

The DFM features included in the test vehicle are:

1) Power connector with different finished hole sizes and different number of large copper plane connections.
2) DIMM connector with different number of large copper plane connections and thermal relief variation.
3) 2012 (0805) and 1608 (0603) SMT discrete components with land pattern design variation.
4) 2012 (0805) and 1608 (0603) SMT discrete components with pad to pad spacing variation.

DFM FEATURES

a) Pin to hole ratio and large copper planes

A total of four 40-pin power connectors were used in the test vehicle to test the performance of the lead free alloys in an experimental matrix of 0 to 4 ground layer connections and 6 different pin to hole ratios. The pin diameter of the connector was 0.508 mm +/- 0.127mm.

The connector ran perpendicular to the wave solder with the arrangement of design features as depicted in Figure 4.

For lead free solders the expectation is that the wetting ability is lower than that of tin lead solders, therefore there is interest to assess the validity of the current pin to hole ratio guideline for lead free solders. Barrel fill analysis was performed in this connector using 3D X-Ray analysis to compare performance of the reference SAC405 alloy and the other three alternative alloys in the pin to hole/copper planes combinations. An IPC-A-610D, Class 3 criteria was used for the analysis of the results.

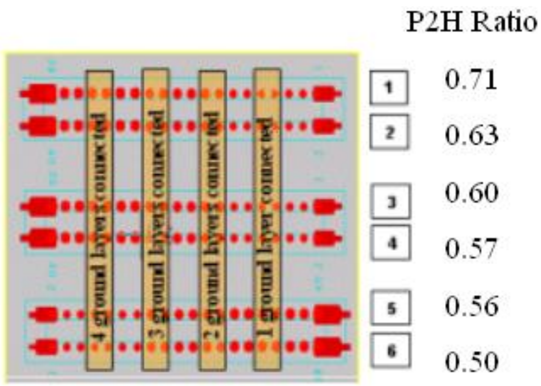


Figure 4: Power connector arrangement

A wetting balance test was performed in advance to identify if there was any major difference in wetting ability within the four lead free alloys (Table 4 and Figure 5). Maximum wetting force was reached by SAC405, then A, B and C with very tight margins. The quickest lead free alloys to wet were SAC405, then B, A and C.

Table 4: Wetting balance test results

	Fmax (mN)	Fend (mN)	Dif	t0 (s)	t1 (s)	t (s)	Sb (%)
SAC405	6.618	6.395	0.222	0.98	0.36	1.34	96.63
Alloy A	5.961	5.905	0.056	1.7	0.49	2.2	99
Alloy B	5.879	5.738	0.141	1.42	0.43	1.86	97.57
Alloy C	5.765	5.725	0.039	1.84	0.59	2.44	99.27

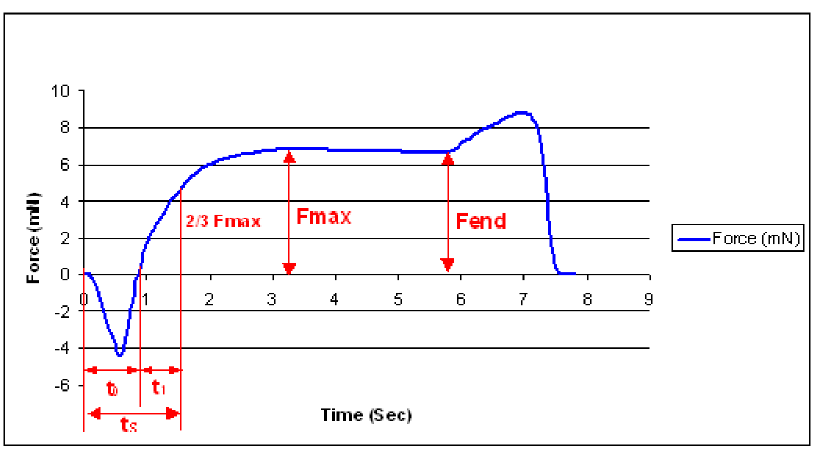


Figure 5: Wetting balance typical chart

As shown in Table 5, a Full Factorial DOE was followed to analyze the pin to hole ratio and large copper planes effect on barrel fill.

Table 5: Pin to hole ratio and large copper planes DOE

Factors	# Levels	Levels Values
Alloy	4	SAC405, Alloy A, Alloy B, Alloy C
Pin to hole ratio	6	0.71, 0.63, 0.60, 0.57, 0.56, 0.50
Quantity of ground planes	4	1, 2, 3, 4

b) Quantity of large copper planes and PTH connection types

Four DIMM connectors were used in the test vehicle to study the performance in an experimental matrix of two different PTH connection types, ranging from one to four ground layer connections. The DIMM connectors ran parallel to the wave solder as a worst case scenario. The arrangement of the design features are shown in Figure 6. Barrel fill analysis was performed using 3D X-Ray to compare performance of the reference SAC405 alloy and the other three alternative alloys in the quantity of ground planes and PTH connection type combinations. An IPC-A-610 D Class 3 criterion was used for the analysis of the results.

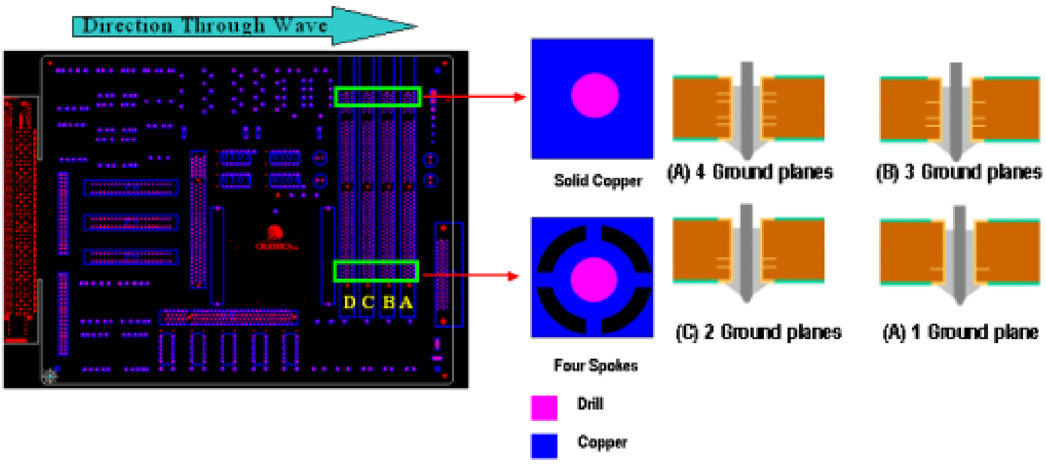


Figure 6: PTH connection - quantity of large copper planes arrangement

As shown in Table 6, a Full Factorial DOE was followed to analyze the effect of the experiment on barrel fill.

Table 6: Quantity of ground planes and copper connection DOE

	Quantity of ground planes			
Alloy	1	2	3	4
SAC405	Solid	Solid	Solid	Solid
	4 Spokes	4 Spokes	4 Spokes	4 Spokes
Alloy A	Solid	Solid	Solid	Solid
	4 Spokes	4 Spokes	4 Spokes	4 Spokes
Alloy B	Solid	Solid	Solid	Solid
	4 Spokes	4 Spokes	4 Spokes	4 Spokes
Alloy C	Solid	Solid	Solid	Solid
	4 Spokes	4 Spokes	4 Spokes	4 Spokes

c) Land pattern design variation

For Land pattern design variation, 2 components sizes were selected for the experiment, 0603 and 0805, resistor and capacitor were used for both sizes. The arrangement of the bank of components is shown in Figure 7. All defects were inspected based on Class 2, IPC-A-610D specifications.

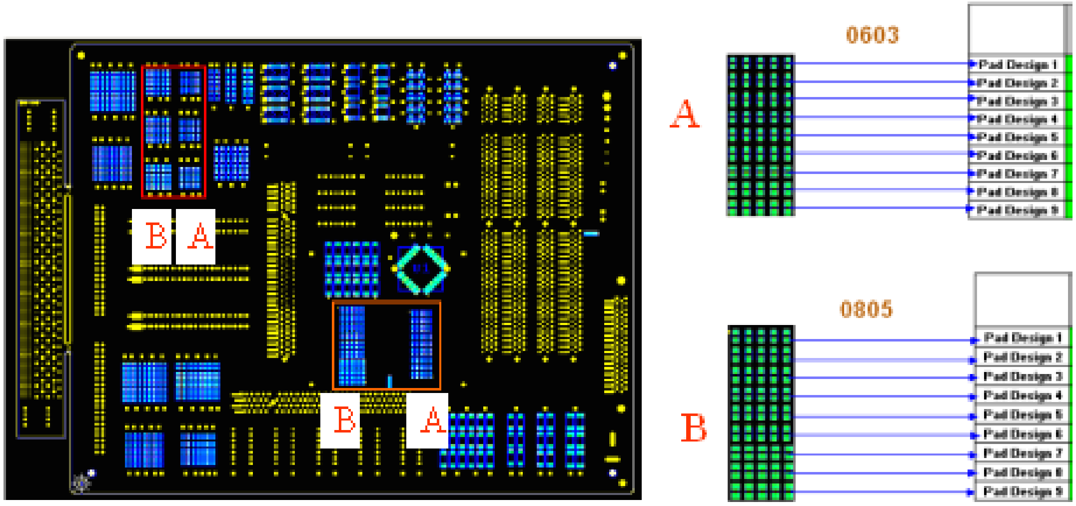


Figure 7: Land pattern design arrangement

A full factorial DOE was run, choosing pad width and pad length as factors and three levels for each one of them (Table 7), the outputs were DPMO on visual inspection and maximum shear force. The analysis of the results was performed for the 4 lead free alloys studied with the purpose of determining applicability of current SnPb land pattern designs for lead free wave soldering while also trying to identify the more robust performance alloy for the scope of the experiments.

Table 7: Land pattern DOE

Pad Design	X Width	Y Length
1	Low	Low
2	Low	Med
3	Low	High
4	Med	Low
5	Med	Med
6	Med	High
7	High	Low
8	High	Med
9	High	High

Low: Dimension below standard guideline for reflow pad design
Med: Dimension slightly below standard guideline for reflow pad design
High: Dimension at standard guideline for reflow pad design

Shear Force Test

- For each of the 9 land pattern designs five components of both 0603 and 0805 were tested (Figure 8).
- The test plan is illustrated in Table 8 below. The maximum force readings were recorded for each combination of component type, pad design and solder alloy (SnPb was also tested).
- The Shear force test was performed according to ASTM F1269. Even though discrete SMT devices are outside the scope of this test method, the test was still performed in order to provide a relative comparison between each of the wave alloys tested via a glue and wave process.
- The set-up of the test is illustrated in Figure 9 below.

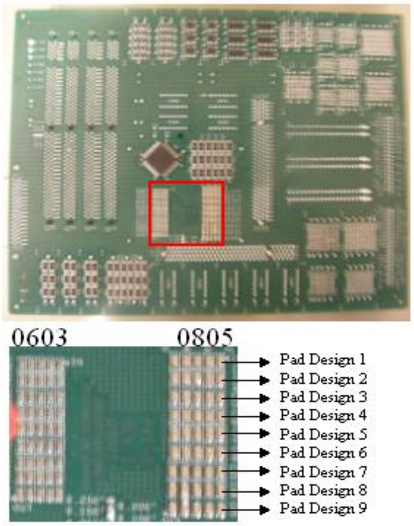


Figure 8: 0603 and 0805 components

Alloy	Land pattern design	Component	Sample Size
SnPb SAC405 Alloy A Alloy B Alloy C	1	0603	5
		0805	5
	2	0603	5
		0805	5
	3	0603	5
		0805	5
	4	0603	5
		0805	5
	5	0603	5
		0805	5
	6	0603	5
		0805	5
	7	0603	5
		0805	5
	8	0603	5
		0805	5
	9	0603	5
		0805	5

Table 8: Shear force test matrix

Figure 9: Shear force test set-up

d) Pad to pad spacing variation

Several pad to pad spacing for 0603 and 0805 components were used to evaluate the performance of the lead free alloys with different distance between solderable surfaces. Four different pad to pad spacing on the X (pad width) and Y (pad length) axis were used for both 0603 and 0805 components. The banks of components are shown in Figure 10. A DOE was performed to optimize wave solder parameters prior to run the boards. All defects were inspected based on Class 2, IPC-A-610D specifications.

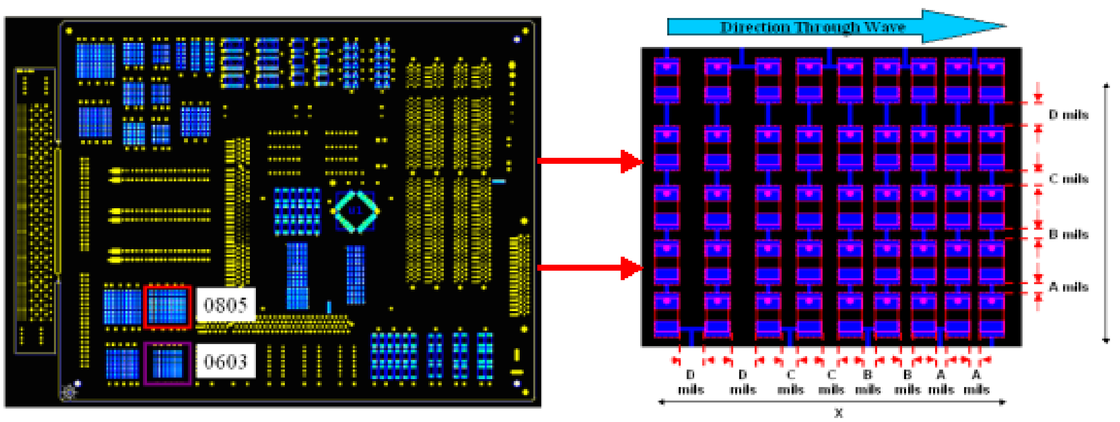


Figure 10: Pad to pad spacing variation

As shown in Table 9, a Full Factorial DOE was followed, the output was DPMO and the analysis of the results was performed for the 4 alloys studied.

Table 9: Pad to pad spacing DOE

	Component	
Alloy	**0603**	**0805**
SAC405	A	A
	B	B
	C	C
	D	D
Alloy A	A	A
	B	B
	C	C
	D	D
Alloy B	A	A
	B	B
	C	C
	D	D
Alloy C	A	A
	B	B
	C	C
	D	D

A: Spacing slightly below 0.64mm
B: 0.64 mm
C: Spacing slightly above 0.64mm
D: Spacing above 0.64mm

RESULTS AND DISCUSSION

a) Pin to hole ratio and large copper planes

The ANOVA table of the DOE is shown in Table 10. The P-value of less than 0.05 indicates that the factor has statistical effect at the 95% confidence level. The statistical results indicate that alloy, pin to hole ratio, quantity of large copper planes as well as their interactions have a significant impact on the barrel fill defects.

Table 10: ANOVA statistical results

Analysis of Variance for Defects, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Alloy	3	224.479	224.479	74.826	149.65	0.000
Qty of ground planes	4	183.140	183.140	45.785	91.57	0.000
Pin to hole ratio	5	107.671	107.671	21.534	43.07	0.000
Alloy*Qty of ground planes	12	193.219	193.219	16.102	32.20	0.000
Alloy*Pin to hole ratio	15	109.646	109.646	7.310	14.62	0.000
Qty of ground planes* Pin to hole ratio	20	93.110	93.110	4.656	9.31	0.000
Alloy*Qty of ground planes* Pin to hole ratio	60	230.531	230.531	3.842	7.68	0.000
Error	120	60.000	60.000	0.500		
Total	239	1201.796				

S = 0.707107   R-Sq = 95.01%   R-Sq(adj) = 90.06%

The main effect plots from the DOE (Figure 11) illustrates that there is significant difference between the alloys used, Alloy B quantity of defects are comparable to those of SAC405 and they both provided fewer defects than Alloy A and C. There is significant difference among quantities of ground planes connected, however the trend across all the alloys indicated that the higher the quantity of ground planes, the higher the quantity of defects. The main effect plot also shows that there is significant difference among the pin to hole ratios in terms of defects, as the finished hole size decreases (higher pin to hole ratio), the quantity of defects increases.

It can be seen from Figure 12 that for each of the alloys, the lower the pin to hole ratio resulted in fewer defects. For the interaction between pin to hole ratio and quantity of ground planes, the overall trend indicates that for each quantity of ground planes used, the higher pin to hole ratio had a negative impact on the barrel fill defects. In addition, the interaction is stronger as the quantity of ground planes increases. For the three interactions there was a statistical significance on the output. Overall, Alloy A showed the higher quantity of defects followed by Alloy C, opposite to this, SAC405 performed the best, then Alloy B with very similar results. Examples of the barrel fill results using pin to hole ratio of 0.71 and four ground planes are shown in Figure 13.

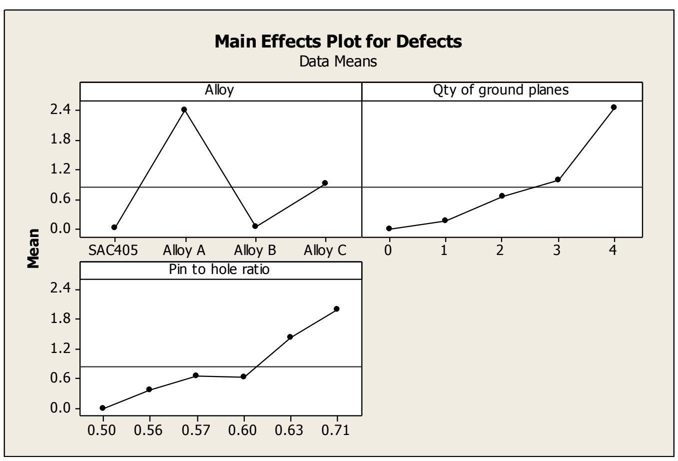


Figure 11: Main effects plot results – Effect of alloys, quantity of ground planes and pin to hole ratio on barrel fill defects.

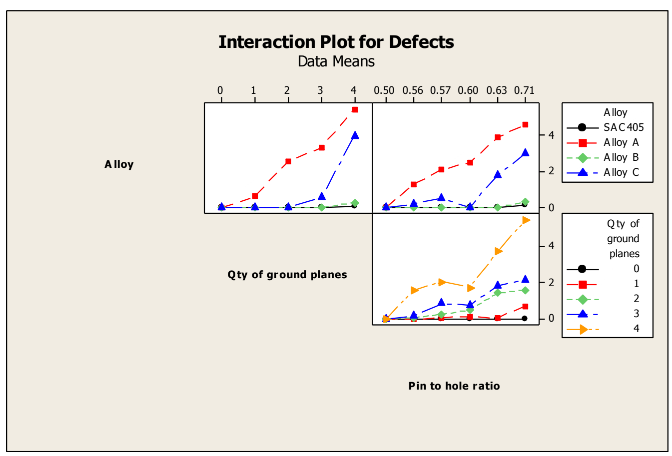


Figure 12: Interaction plot results – Effect of alloys, quantity of ground planes and pin to hole ratio on barrel fill defects.

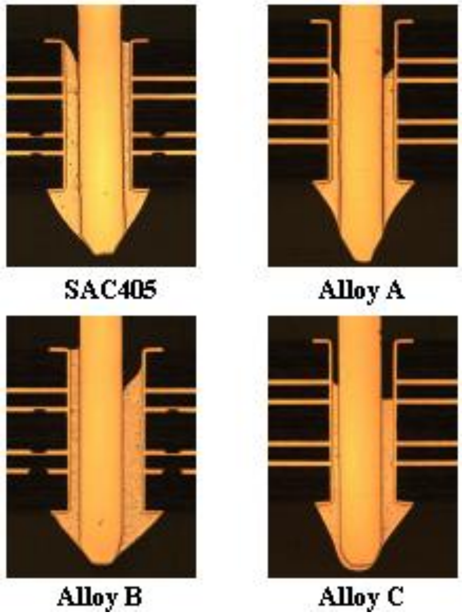


Figure 13: X Section Pb-free alloys at 0.71 Pin to hole ratio and 4 ground planes

Figure 14 shows the barrel fill defects at different pin to hole ratios with different quantity of ground planes connected. The barrel fill improves with decreasing pin to hole ratio (increasing the clearance between pin and barrel wall). It can also be seen that with no ground planes connected, there is no impact of pin to hole ratio on defects.

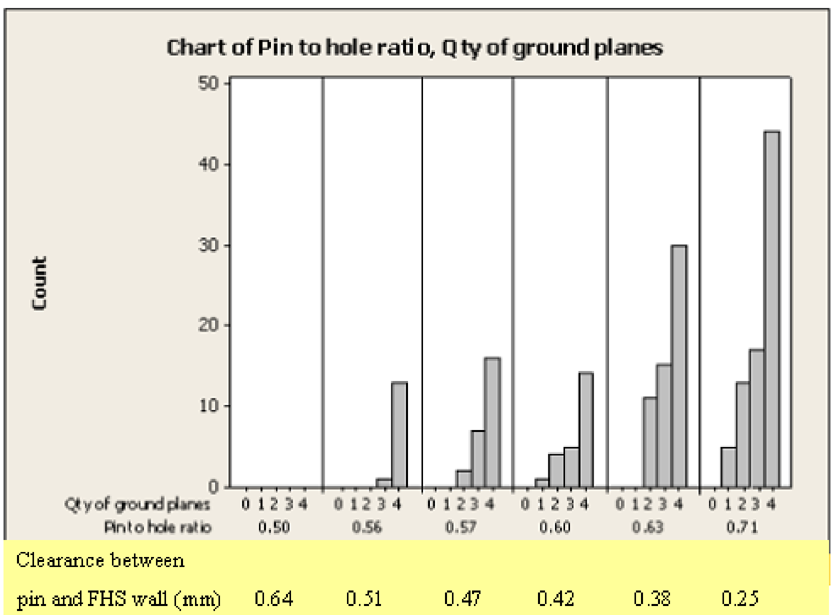


Figure 14: Defects at different pin to hole ratios with 0 – 4 ground planes connected

Since the amount of superheat (heat above liquidus) is low in the wave soldering process for electronics assembly, the ability for the solder to flow and fill the barrels is important. Relatively quick heat dissipation and solidification occurs during the process of soldering connection on a PCB, therefore there is limited time for the solder to flow before the crystal formation reaches a critical point that stops the flow. The dimension of the hole to be filled is important as it interacts with the solidification process.

The composition of the alloy plays an important role, since the viscosity of the material will increase when crystal growth occurs during solidification. The alloy temperature is also significant because it determines the amount of initial superheat ($T-T_{liq}$) for a given alloy. Thermal mass connected to the channel will determine the time that the solder in the liquidus phase can go through, therefore the higher heat transfer rate created by the amount of copper mass connected to the joint affects adversely the fluidity of the alloy.

Previous studies have deduced that the fluidity of an alloy is strongly influenced by the mode of solidification (whether growth is planar, columnar, equiaxed or mixed) and in the case of dilute alloys, the flow behavior of solidifying solder and the fluidity play a significant role in the capacity of a solder to fill through-hole joints.

Cross sections of the PTH solder joints were performed in order to evaluate hole fill, solder microstructure and intermetallic formation. Figure 15 shows the microstructure images of the four evaluated alloys, where the difference of dendritic growth and the distribution of IMC into the interdendritic spaces between the alloys can be appreciated. These images show a mixed behavior in the four studied alloys. However, the alloy B presented the most columnar microstructure with lower interdendritic space and the IMC distribution most regular, followed by alloy C with and finally by alloy A, which presented big areas of interdendritic space with an irregular IMC distribution.

The results show a relation between the barrel fill defects number and the mode of solidification, the more columnar solidification mode in the alloy, the less quantity of barrel fill defects. In the case of the control sample (SAC405), even though the microstructure presented an intermediate columnar growth like the one found in the alloy C, the fluidity in this alloy is improved due to the amount of Silver close to 4 %.

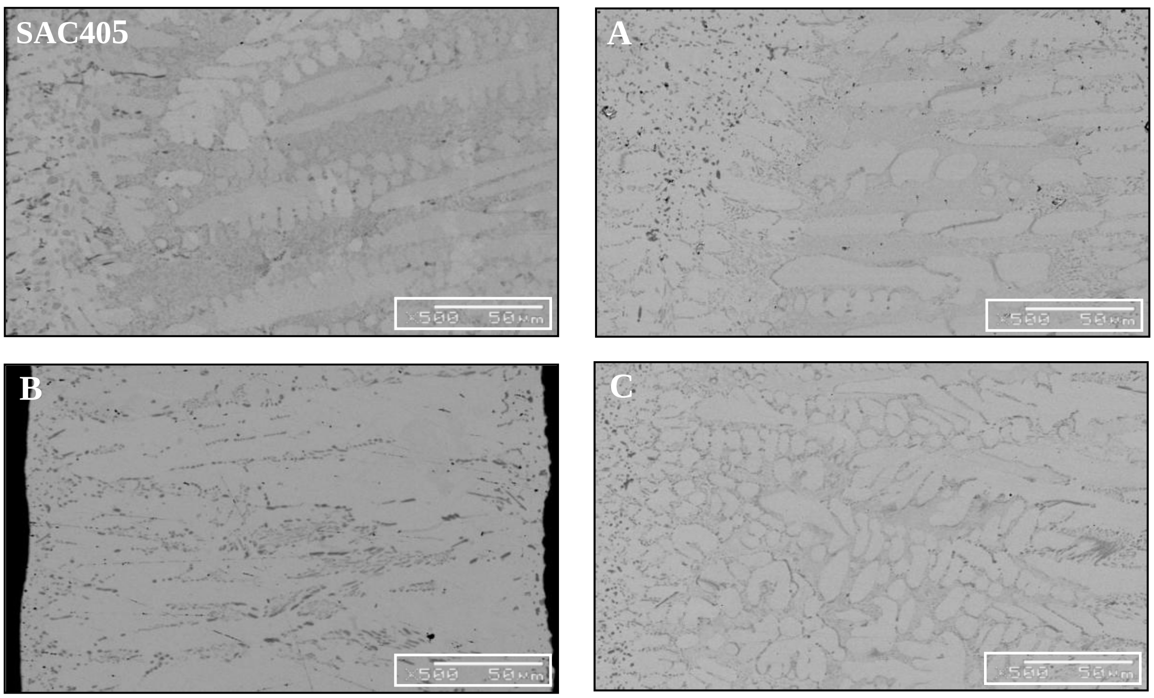


Figure 15: Microstructure of lead free alloys taken with SEM at 500x (alloys A, B, C and SAC405).

Figure 16 shows the intermetallic compound (IMC) in the solder to copper interface with different thickness values among the four evaluated alloys; these values were from 1.11 microns to 3.62 microns.

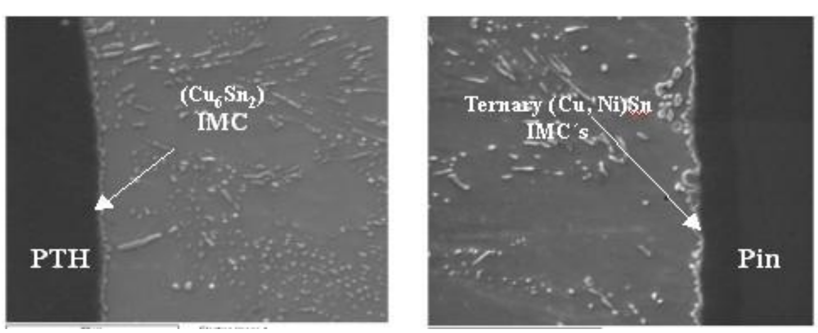


Figure 16: Cross section images showing the IMC in the solder joint taken with SEM at 2500x.

b) Quantity of large copper planes and PTH connection

Figure 17 indicates that there is no statistical difference between ground planes ranging from 1 – 3. However, a statistical difference between this group and four ground planes is observed.

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                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N   Mean  StDev   ---+---------+---------+---------+------
1      32  0.969  2.446   (------*------)
2      32  1.000  2.394   (------*------)
3      32  1.406  2.758     (------*------)
4      32  7.062  7.087                        (------*-----)
                          ---+---------+---------+---------+------
                            0.0       3.0       6.0       9.0
```

Figure 17: Quantity of ground planes ANOVA

Figure 18 shows that Alloy B results are similar to SAC405 results and these alloys provided fewer defects than Alloy A and C. Alloy A provided by far the higher quantity of defects. Again, there is a significant difference among the quantity of ground planes in terms of defects, with four ground planes the quantity of defects increases dramatically. It can also be seen that solid copper has a major impact on the barrel fill defects.

It can be observed from Figure 19 that across all of the Pb-alloys, the higher quantity of ground planes resulted in the highest quantity of defects. For each of the alloys the results show that incorporating 4 spokes thermal relief helps to improve barrel fill compared to having a direct solid connection. For the interaction between quantity of ground planes and PTH connection type, the overall trend indicates that for each quantity of ground planes used, the solid copper connection has a negative impact on the barrel fill, in addition, the interaction is stronger as the quantity of ground planes increases showing again the importance of having thermal relief to minimize the quantity of barrel fill defects. For the three interactions there was a statistical significance on the output. Overall Alloy A showed the higher quantity of defects followed by the Alloy C, opposite to this, SAC405 and Alloy B performed the best. Examples of the barrel fill results using four ground planes and solid connection (worst case scenario) are shown in Figure 20.

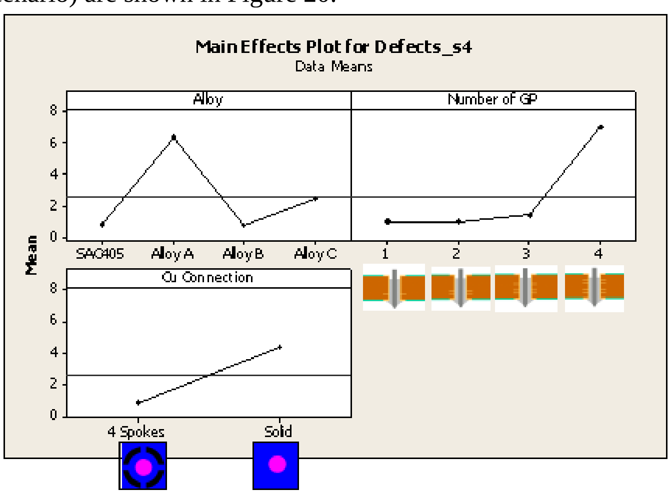


Figure 18: Main Effects Plot results – Effect of Alloys, quantity of ground planes and PTH connection type on barrel fill defects.

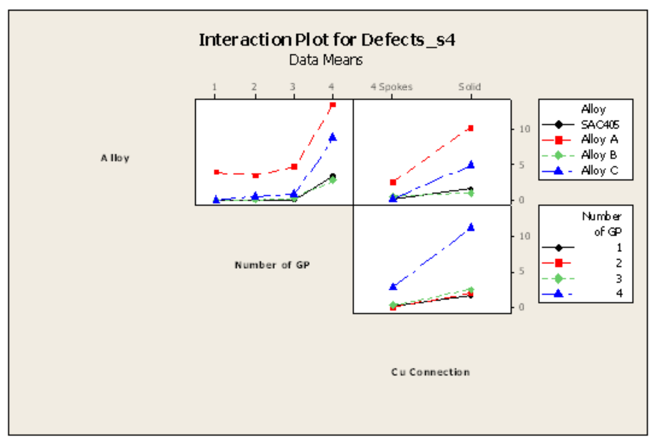


Figure 19: Interaction Plot results – Effect of Alloys, quantity of ground planes and pin to hole ratio on barrel fill defects.

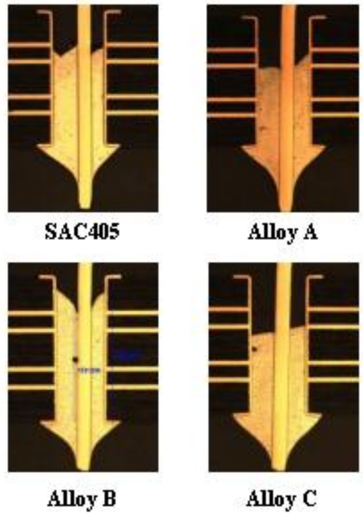


Figure 20: X Section Pb-free alloys using 4 ground planes and solid connection

c) Land pattern design variation for 0603 and 0805 discrete components

Visual inspection

Nine different land patterns were tested for capacitor and resistor chips as defined in Table 7. Dimensional variation in both X (pad width) and Y (pad length) on the pads was incorporated into the test vehicle to observe the behavior of all size variations on the process yield and resistance to shear stress with the 4 different alloys. The DPMO comparison of visual defects for all the lead free alloys is shown in Figure 21. The boards were built with the optimized settings determined through DOE as explained before.

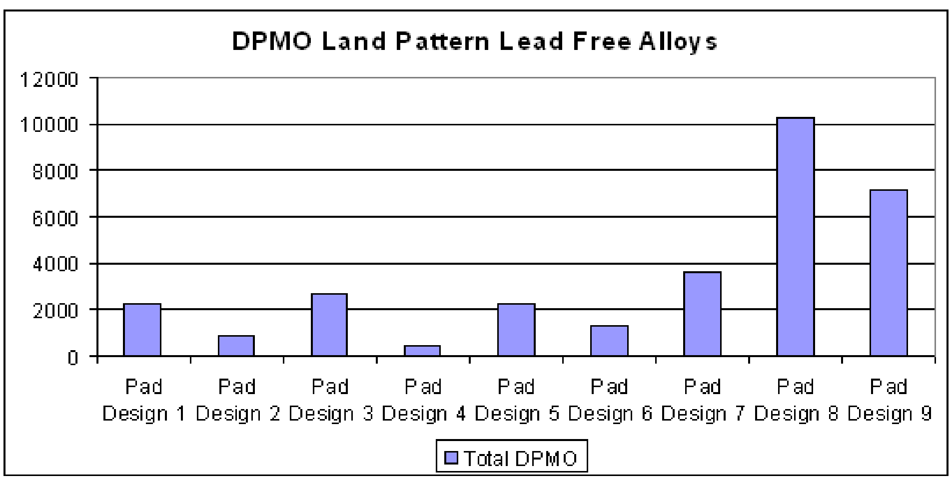


Figure 21: Combined results for 9 different land patterns (0603 and 0805)

Land pattern designs 7, 8 and 9 have the higher quantity of defects while the results of designs 1 to 6 are similar and better than 7 to 9. The results show that designs 2 and 4 have the fewest defects, hence are the overall winners.

The main effects and interaction plots in Figure 22 show that 0603 components and resistors deliver the lowest defect count. Soldering defects are more sensitive to variations in the X (pad width) dimension. Alloys B, C and SAC405 performed statistically at the same level. Where as, alloy A outperformed the other three alloys in this test cutting the number of defects in more than half. However, the spread of data does not allow us to establish a statistical difference between alloys.

For all alloys the best land pattern found had the pad width dimension at the medium level of the experiment which is a size slightly lower than the standard land pattern width used for reflow. In the Y dimension (length) there was some variation in the best performing dimension to produce less defects by alloy but it was not significant among all four alloys.

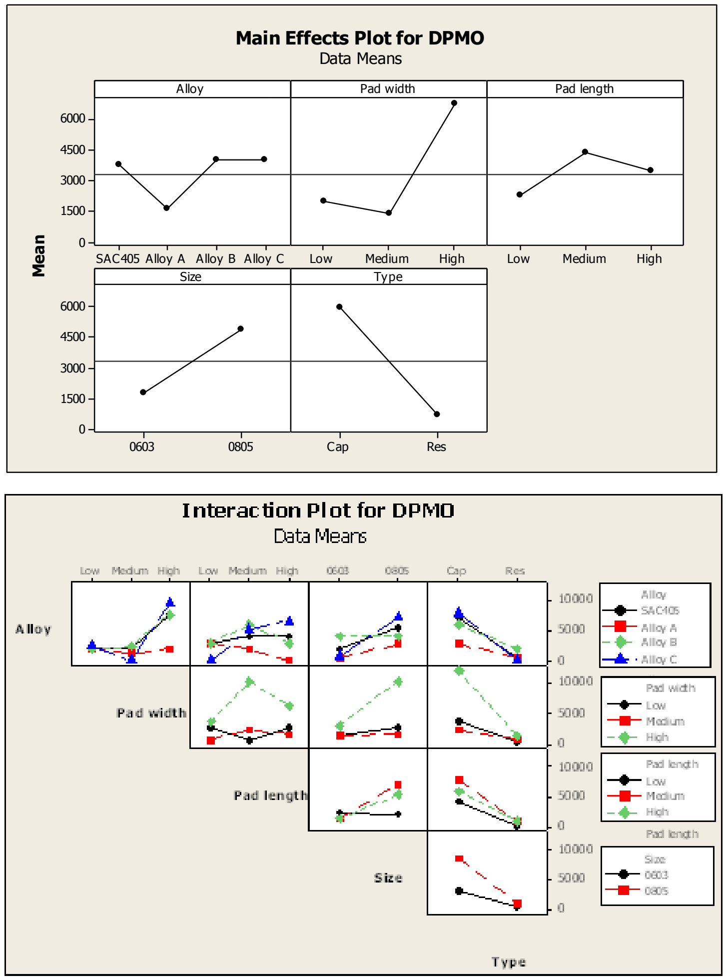


Figure 22: Main effects and interactions plots for land pattern DOE (visual inspection)

<u>Shear Force</u>

There is a dependency of the solder joints shear strength on the microstructure of the solder (finer grain will result in higher force), the inter-metallic compound formation, the thickness and the volume of the bulk solder. In our study the first two were set through the DOE for profile definition described before, focusing in the search for a pad design geometry that provides the solder fillets with better outputs for the lead free solders tested.

For each of the 9 land pattern designs five components of both 0603 and 0805 were tested. The maximum force readings were recorded for each combination of component type, pad design and solder alloy.

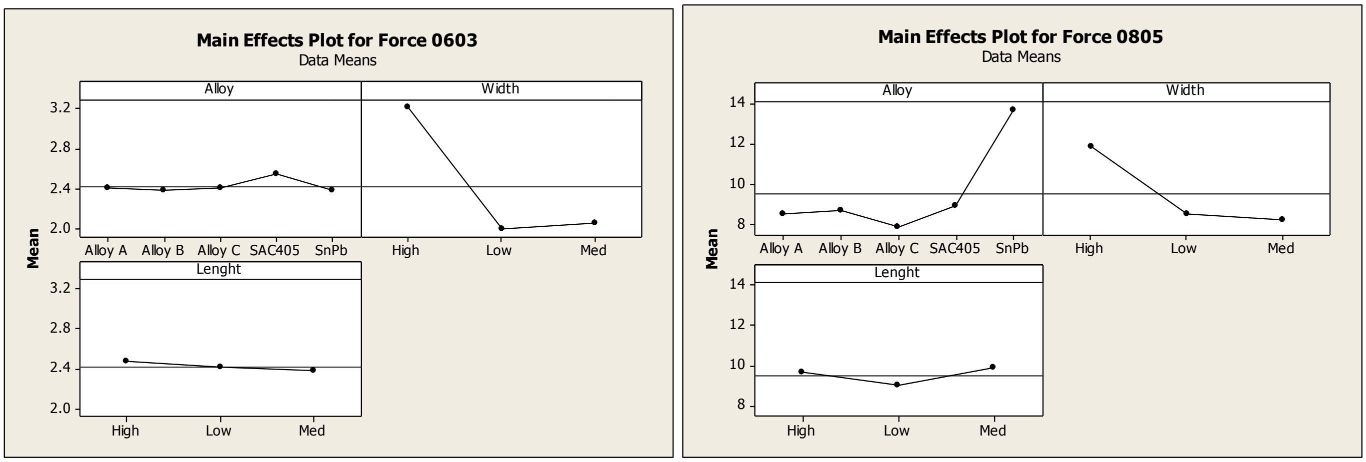
Land patterns 7, 8, and 9 had the largest strength (Figure 23). The common condition is that all three designs have the high width value which is reasonable to think since a larger width will provide more contact area for the solder joint to provide an opposing force to the shear anvil.

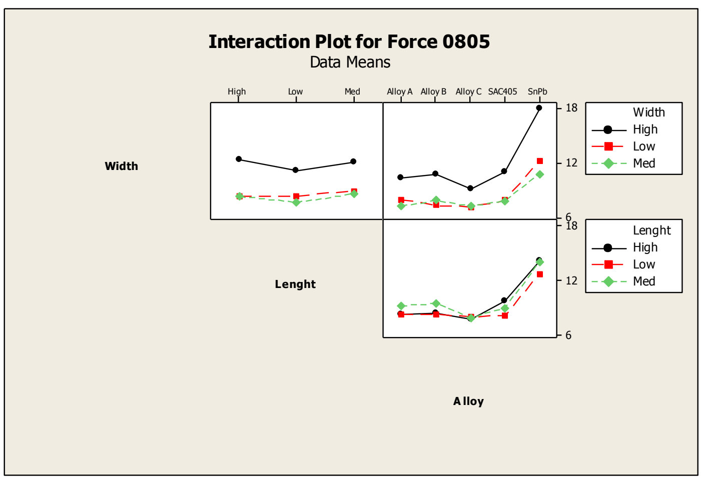
Figure 23: Confidence intervals for Shear Force by Pad design

```
                              Individual 95% CIs for Mean Based on
                              Pooled StDev
Pad     N    Mean  StDev  --------+---------+---------+---------+-
1      20   7.427  1.168      (----*----)
2      20   8.134  1.196          (----*----)
3      20   7.202  1.663    (----*----)
4      20   7.044  0.993   (----*----)
5      20   7.942  1.368        (----*----)
6      20   7.646  1.580      (----*----)
7      20   9.850  1.511                      (----*----)
8      20  10.449  2.750                         (----*----)
9      20  10.639  2.265                          (----*----)
                          --------+---------+---------+---------+-
                                7.5       9.0      10.5      12.0
```

From the figure above we can see the effect of the pad width on the shear strength of the joint. With that in mind we can intuitively assume that component type will also reflect differences in shear strength, expecting 0805 being larger than 0603 for the same reason. Experimental data demonstrated such effect. The next point to evaluate is the relative performance of the solder alloys, for this particular point SnPb solder was included given the fact that some opposite and conflicting results have been presented with respect to the question of what alloy SnPb or SAC provide the larger shear strength.

The plots in Figure 24 show that all alloys, including SnPb, behave statistically similar for the 0603 component, with pad width being the main differentiator in shear force results. However, with respect to the 0805 component, solder alloys start to play a role in the output force, with SnPb being the alloy with the higher strength.





Factor	Type	Levels	Values
Alloy	fixed	5	Alloy A, Alloy B, Alloy C, SAC405, SnPb
Width	fixed	3	High, Low, Med
Lenght	fixed	3	High, Low, Med
Comp Type	fixed	2	0603, 0805

Analysis of Variance for Force, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Alloy	4	495.22	495.22	123.80	58.79	0.000
Width	2	549.27	549.27	274.63	130.42	0.000
Lenght	2	13.97	13.97	6.98	3.32	0.037
Comp Type	1	5669.28	5669.28	5669.28	2692.22	0.000
Alloy*Width	8	49.55	49.55	6.19	2.94	0.003
Alloy*Lenght	8	15.99	15.99	2.00	0.95	0.476
Alloy*Comp Type	4	509.79	509.79	127.45	60.52	0.000
Width*Lenght	4	10.11	10.11	2.53	1.20	0.310
Width*Comp Type	2	135.37	135.37	67.68	32.14	0.000
Lenght*Comp Type	2	15.23	15.23	7.62	3.62	0.028
Alloy*Width*Lenght	16	28.29	28.29	1.77	0.84	0.640
Alloy*Width*Comp Type	8	94.69	94.69	11.84	5.62	0.000
Alloy*Lenght*Comp Type	8	16.70	16.70	2.09	0.99	0.442
Width*Lenght*Comp Type	4	2.37	2.37	0.59	0.28	0.890
Error	376	791.78	791.78	2.11		
Total	449	8397.60				

Fig 24: Main effects and interaction plots for Shear force on 0603 & 0805

The obtained results suggest that effect of solder alloy microstructure on the shear strength of passive components takes place as the component size and its surface contact area increases. The wetted area by the solder is related to the ability of the solder to make intimate bonding quickly with the pad surface. For small devices differences expected are minimal or statistically not significant. With solder area increased, either by good solder wetting or by larger pad widths, the expected shear force will be increased. In our study lead free alloys did not show performance differences.

d) Pad to pad spacing variation

The main effects and interaction plots in Figure 25 show that component size and spacing are the two factors that significantly affected the occurrence of solder bridges, which is in this case the predominant defect. As expected, for all alloys the quantity of defects is reduced by increasing the spacing between components. It can also be seen that the quantity of defects increases dramatically with the use of 25 or 20 mils showing the importance of keeping enough distance between components for wave solder process. The 0805 components are more sensitive to the spacing variation while the 0603 components show a lower quantity of defects among the 4 different spacing used. The SAC405 alloy performed the best followed closely by Alloy A and Alloy B, with Alloy C delivering the higher quantity of defects.

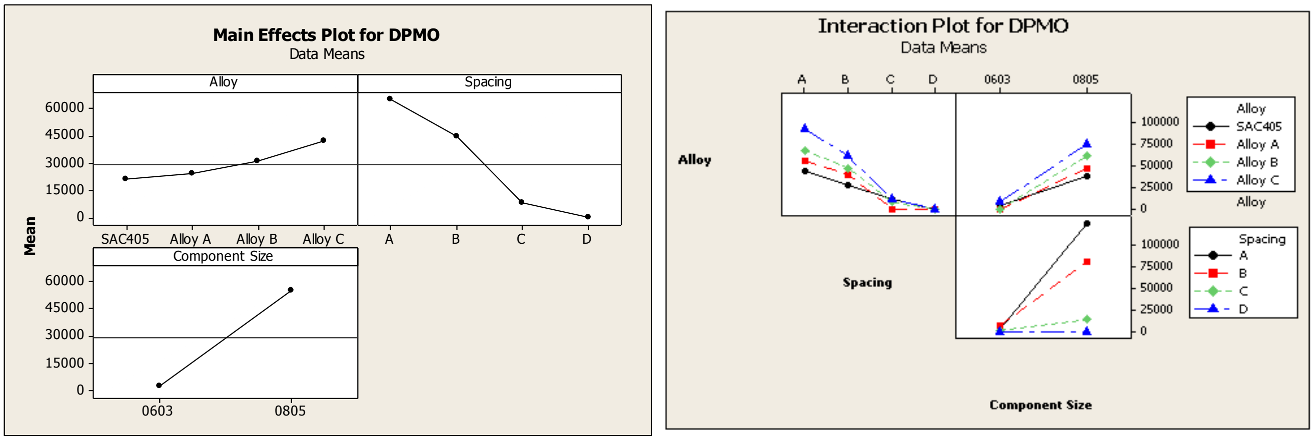


Fig 25: Main effects and interaction plots Pad to pad spacing DOE

CONCLUSIONS

With respect to the overall performance of the Pb-free alloys, exposed to the various design features incorporated into the test vehicle, it was seen that each of the three alternative alloys excelled in differing aspects. A summary table of the performance of the alloys is shown in Table 11.

- Overall, Alloy B resulted as the most robust alloy for all the characteristics tested, performing very similar to the SAC405 alloy on the majority of the tests.
- Alloy C had good performance with respect to hole fill analysis, but overall ranked low for the specific features tested.
- Alloy A had the worst performance on hole fill but showed the best results of the alternative alloys on the DFM features relating to discrete components.

Table11: Alloy Ranking by DFM feature

ALLOY	Pin to hole ratio and large copper planes	Quantity of large copper planes and PTH connection types	Land pattern design variation		Pad to pad spacing variation
			Visual	Shear Force	
SAC405	1st	1st	2nd	2nd	1st
Alloy A	3rd	3rd	1st	3rd	2nd
Alloy B	1st	1st	3rd	3rd	3rd
Alloy C	2nd	2nd	3rd	4th	4th
SnPb				1st	

Statistically similar to SAC405, based on a 95 % confidence interval

From the design guidelines standpoint, the effect of pin to hole ratio and number of ground planes on manufacturing quality was identified, showing an increase in defects with a design combination consisting of a higher number of ground planes with higher pin to hole ratios. In this test, Alloy B outperformed Alloy A and C, with differences in microstructure and solidification mechanisms affecting the ability for the solder to flow in its liquid state being a potential reason for this.

The same behavior was found in DIMM connectors tested which were designed with differing number of copper and PTH connection types, where the larger number of ground planes drove a higher number of defects. With solid copper PTH connection types, the quantity of defects increased dramatically as the quantity of ground planes increased, showing the importance of having a thermal relief design.

For wave soldering of passive components the sensitivity of shear stress resistance was identified only for 0805 components with pad width being the main variable under the process parameters set. All lead free alloys performed at the same level, with SnPb having a higher resistance to failure.

With respect to the pad-to-pad spacing, of the discrete 0603 and 0805 components, it was found that spacing C was the lower limit for lead free soldering guidelines. Alloy C was the worst performer in this test, with the other three alloys showing comparable results. In addition, the 0805 resistor was significantly more prone to defects at smaller spacing.

The results from this paper set a reference for wave soldering lead free guidelines, and give us the insight of where the manufacturing yield problems related to board design features start to show up. In general, the DFM features evaluated in this study show the need to alter guidelines for the Pb-free wave solder process compared to SnPb. These results have to be evaluated with the reliability results that will come as a future part of this work. Further profile optimization is possible for every alloy tested; however general guidelines found provide directional support for further optimization. It is well known that the hole fill window shrinks when using lead free alloys, but having a well respected set of guidelines can make it possible to achieve an acceptable wave solder yield

FUTURE WORK

To conclude ATC, 0-100°C reliability testing.

ACKNOWLEDGEMENTS

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Design for Manufacturability in the Lead Free Wave Solder Process

Celestica

Presenter: Ramon Mendez

Thursday, April 3rd, 2008

Authors: Ramon Mendez, Mario Moreno, German Soto, Craig Hamilton

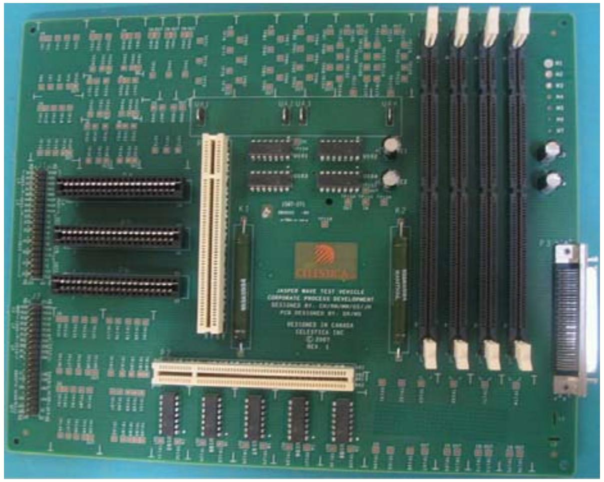
Background

It has been found that the Design for Manufacturability (DFM) guidelines for tin lead processes, in many cases do not result in the same quality level of solder joints when soldering with lead free alloys

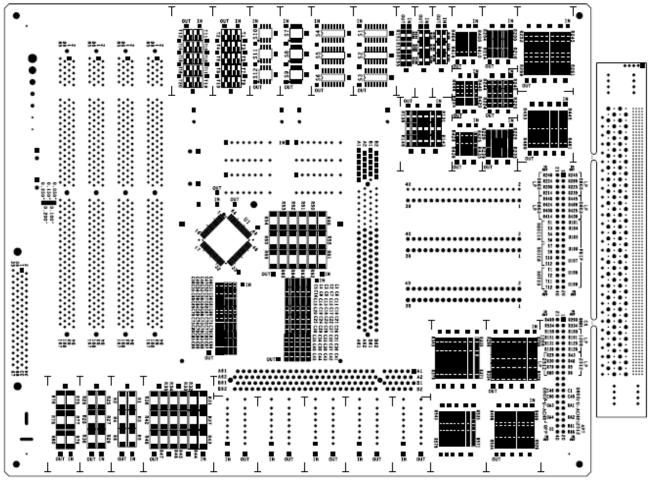
Objectives

- Evaluate the applicability of DFM guidelines established for SnPb in Pb-free process.
- Evaluate the performance of four Pb-free alloys through the DFM features studied.
- Set a reference to develop DFM guidelines for Pb-free wave soldering processes

Test Vehicle



Topside



Bottomside

- **Thickness:** 2.34mm (0.092")
- **Dimensions:** 203.2mm x 254mm (8" x 10")
- **Total Layers:** 12 layers
- **Ground Layers:** 4 layers (2oz Cu)
- **Surface Finish:** HighT OSP, Glicoat F2LX
- **Laminate:** High Tg FR4, Polyclad 370HR
- **Solder Mask:** Taiyo PSR-4000
- **Mid Complexity PCB**
- **Daisy chained**

Components Used for DFM Analysis

Component Type	Pin Count	Pitch	Lead finish
Power Connector	40	2.54mm	Matte Tin over Nickel
DIMM Connector	168	2.29mm	Gold over Palladium Nickel
0805 Resistor	2	N/A	Tin over Nickel
0603 Resistor	2	N/A	Tin over Nickel
0805 Capacitor	2	N/A	Tin over Nickel
0603 Capacitor	2	N/A	Tin

Experimental Details

ALLOYS		MELTING RANGE
95.5Sn-3.8Ag-0.7Cu	(SAC405)	217°C to 220°C
99.1Sn-0.7Cu-0.05Ni-(<0.01)Ge[1]	(Sn-Cu-Ni)	227°C
99.1Sn-0.7Cu-X-Y	(Sn-Cu-X)	227°C
98.6Sn-0.3Ag-0.7Cu-Bi-X-Y[2]	(Sn-Ag-Cu-Bi)	217°C to 228°C

Wave	Drilled Chip Bar and Lambda		
Preheaters		Top	Bottom
	Position 1	IR	IR
	Position 2	Convection	Convection
	Position 3		Concection
Atmosphere	Air		
Fluxer	Selective Spray		
Flux Volume	Supplier recommendation		

Machine Configuration

Process Optimization

DOE

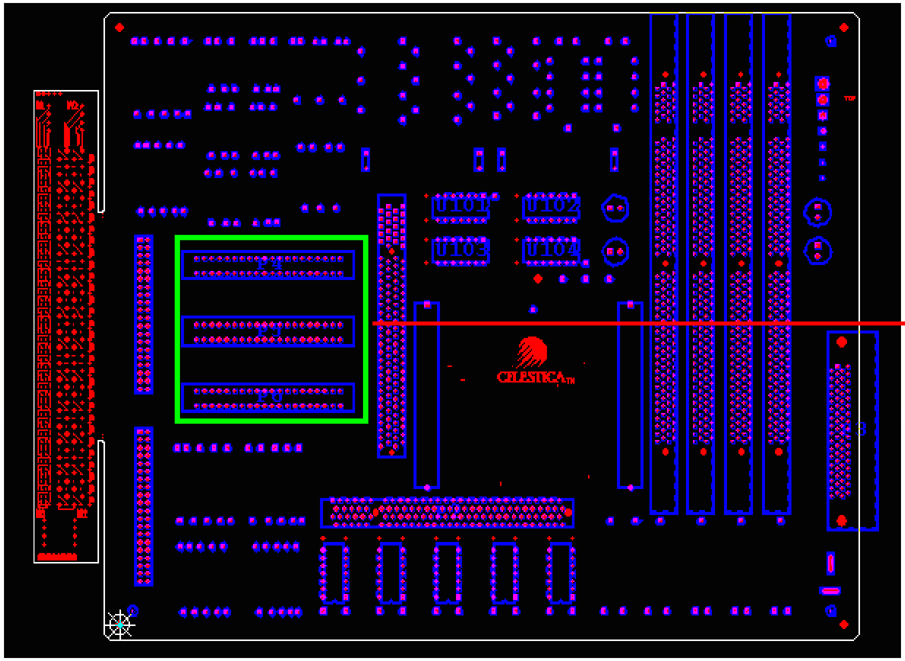
Factors	Levels		
	1	**2**	**3**
Pot Temperature	Low	Med	High
Preheat Temperature	Low	High	
Contact Time	Low	High	

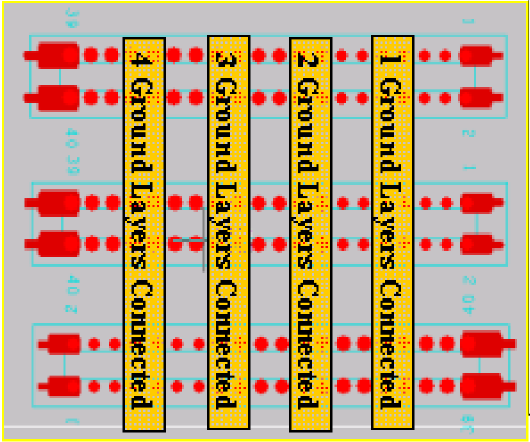
Optimal Setting

DFM Features

- Pin to hole ratio and qty. of large copper planes
- Quantity of large copper planes and PTH connection types
- Land pattern design
- Pad to pad spacing

Pin to Hole Ratio and Large Copper Planes



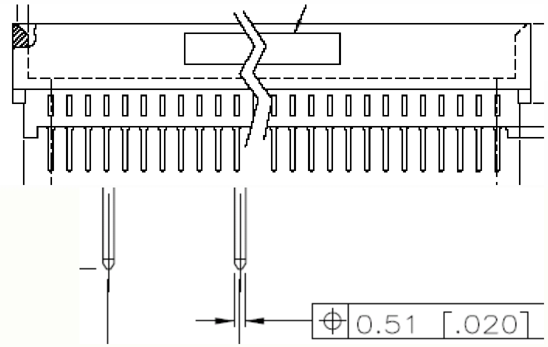


P2H Ratio
0.71
0.63

0.60
0.57

0.56
0.50

Power Connector



Lead Diameter = 0.508mm ± 0.127mm
0.020” ± 0.005”

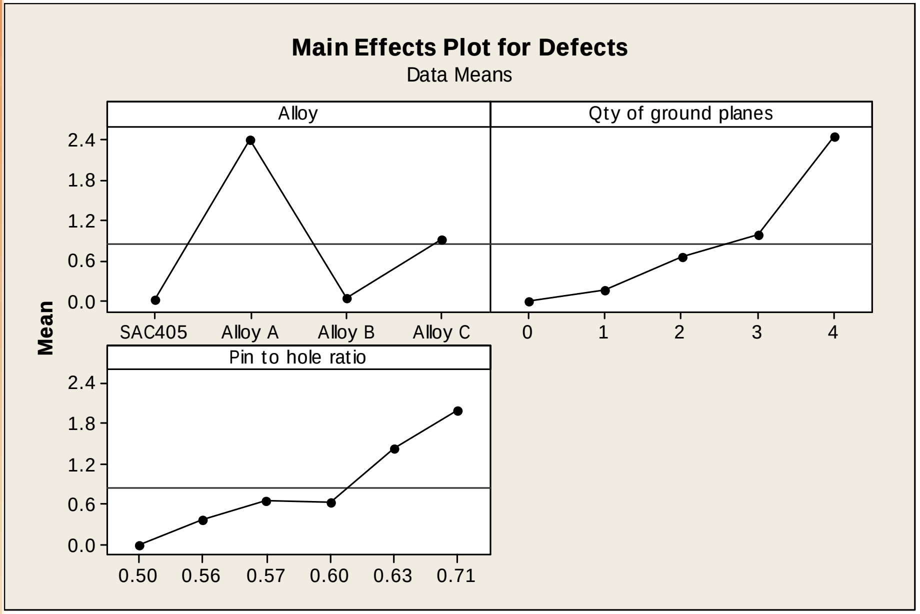
Pin to Hole Ratio and Large Copper Planes

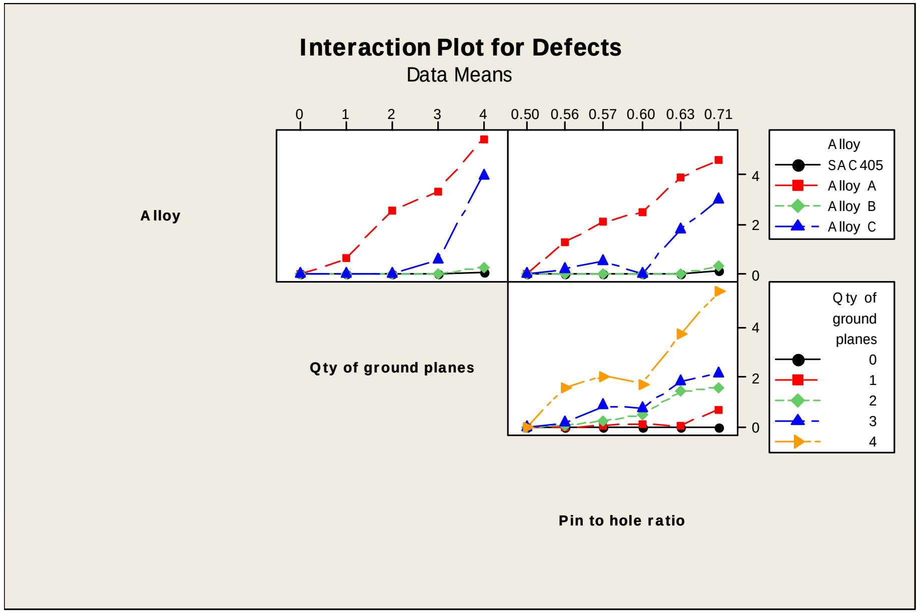
- A Full Factorial, 3 Factors DOE was used:

Factors	Levels					
	1	2	3	4	5	6
Alloy	SAC405	Alloy A	Alloy B	Alloy C		
Pin to Hole Ratio	0.50	0.56	0.57	0.60	0.63	0.71
Quantity of Ground Planes	0	1	2	3	4	

- **Response:** Barrel Fill Defects
- **Criteria:** IPC-A-610D Class 3

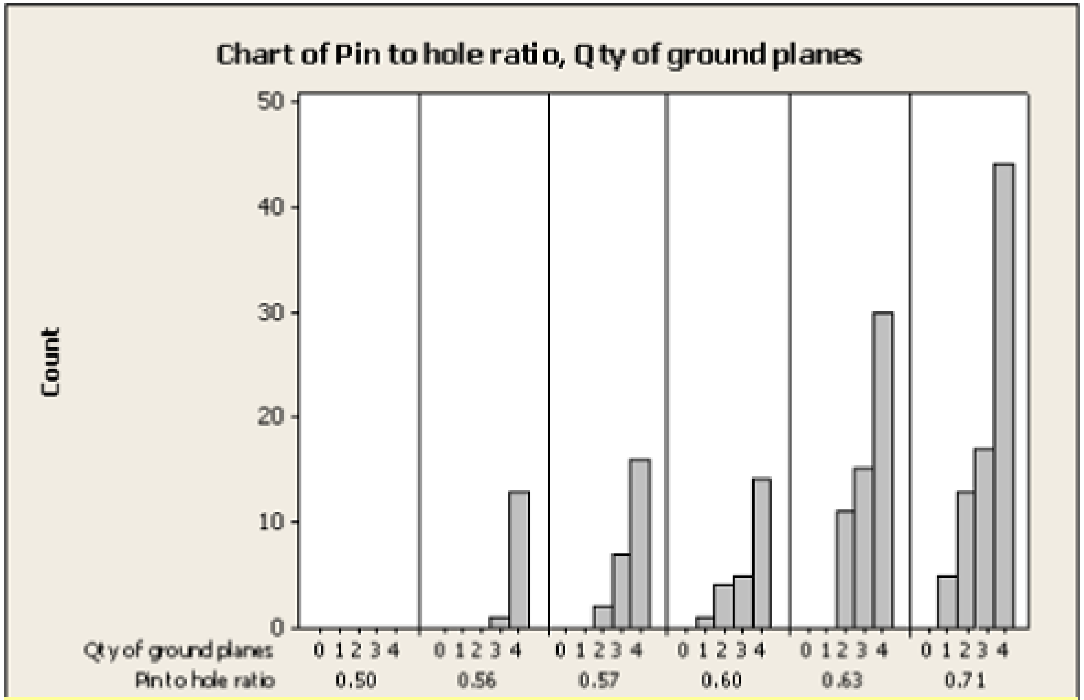
Pin to Hole Ratio and Large Copper Planes Results



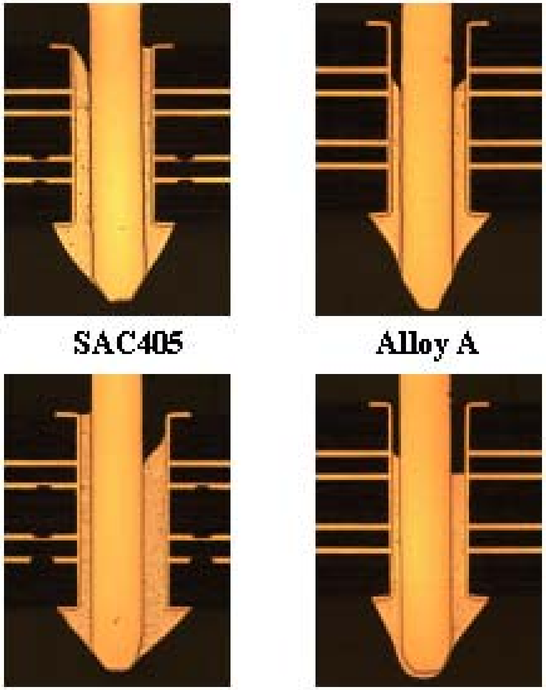


- **Alloy B is statistically similar to SAC405**
- **Alloy A showed the higher quantity of defects followed by Alloy C**
- **The higher the quantity of ground planes, the higher the quantity of defects**
- **As the finished hole size decreases (higher pin to hole ratio), the quantity of defects increases.**

Pin to Hole Ratio and Large Copper Planes Results



Clearance between pin and FHS wall (mm)	0.64	0.51	0.47	0.42	0.38	0.25

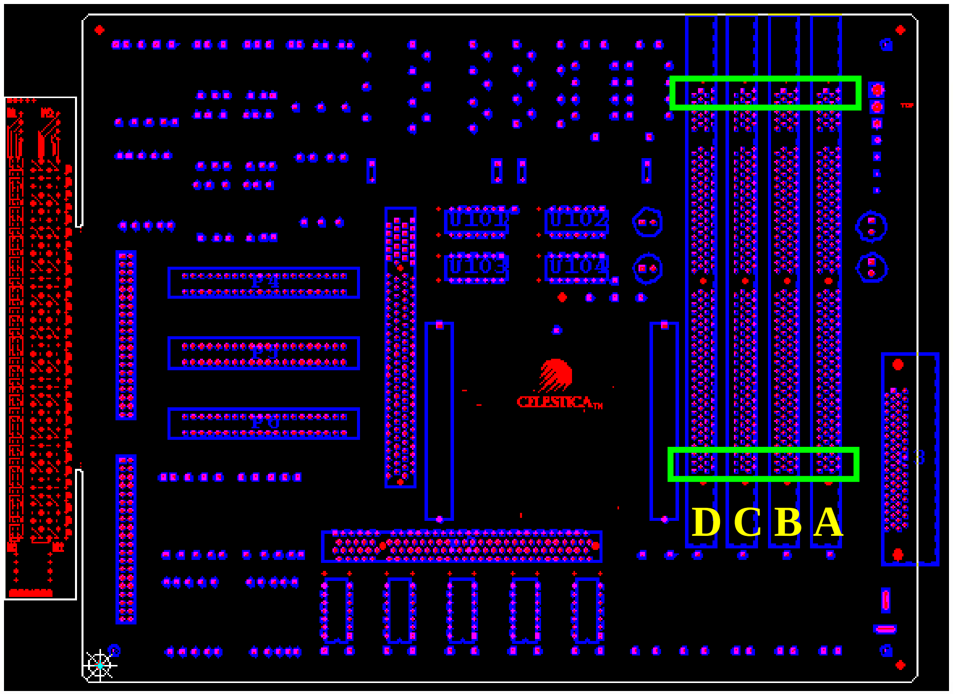


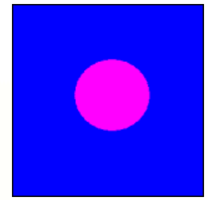
SAC405 | Alloy A

Alloy B | Alloy C

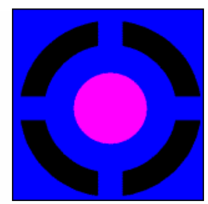
- **Barrel fill improves with decreasing P2H ratio**
- **With no ground planes connected, there is no effect of P2H ratio on defects**

Quantity of Large Copper Planes and PTH Connection Types

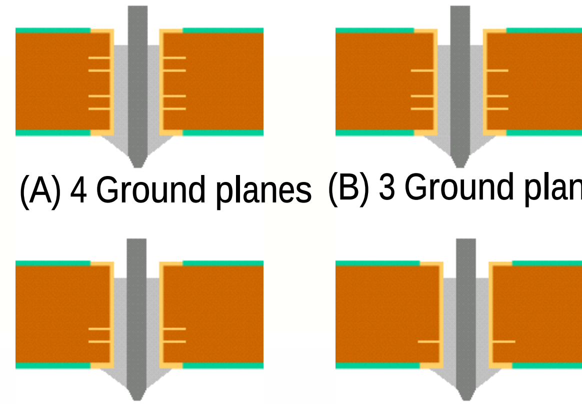




Solid Copper



Four Spokes



(A) 4 Ground planes (B) 3 Ground planes

(C) 2 Ground planes (D) 1 Ground plane

Drill

Copper

Quantity of Large Copper Planes and PTH Connection Types

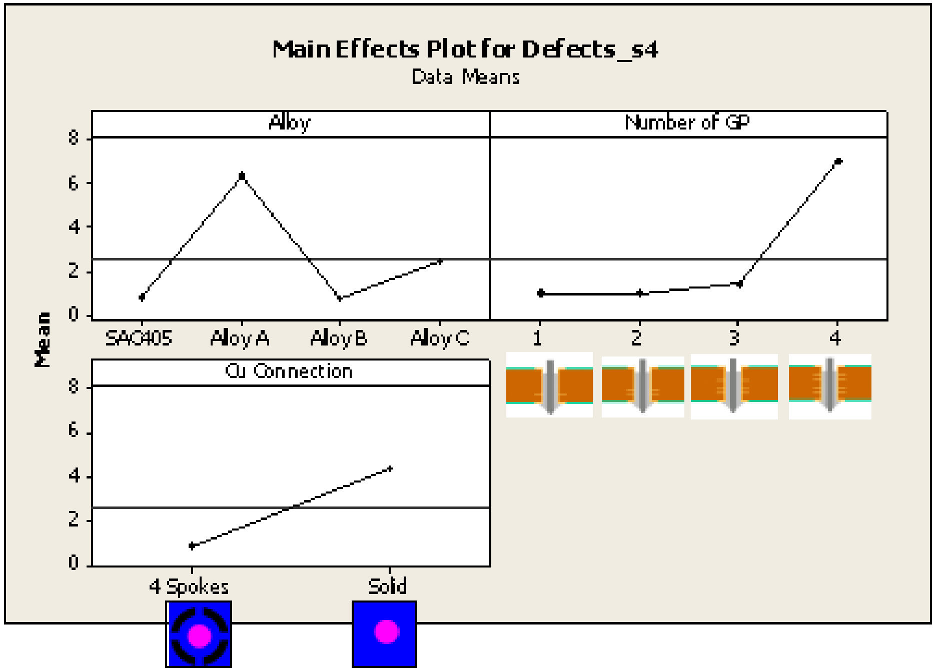
- A Full Factorial, 3 Factors DOE was used:

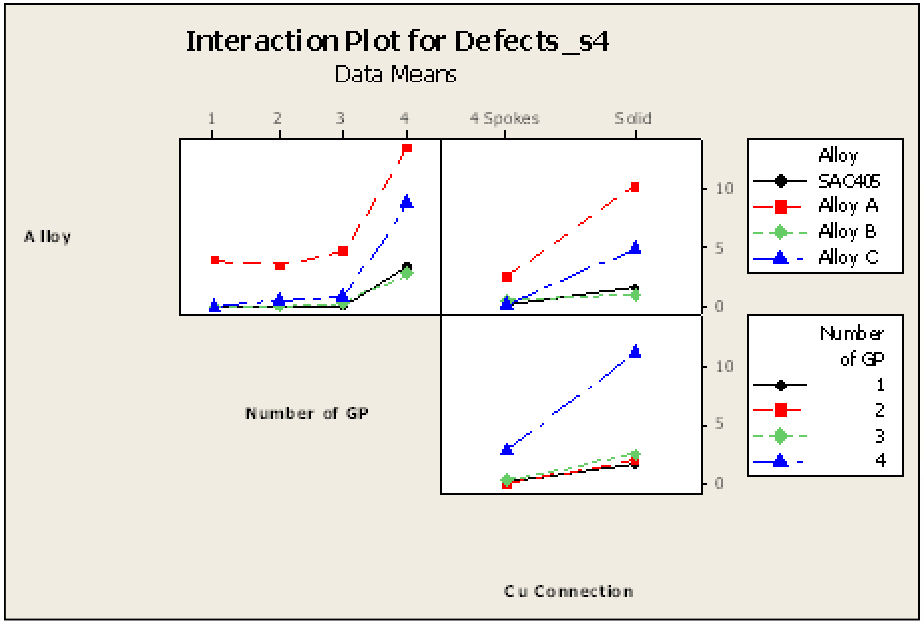
Factors	Levels			
	1	2	3	4
Alloy	SAC405	Alloy A	Alloy B	Alloy C
Quantity of Ground Planes	1	2	3	4
Ground Connection Type	4 spokes	Solid		

- **Response:** Barrel Fill Defects
- **Criteria:** IPC – 610D Class 3

Quantity of Large Copper Planes and PTH Connection Types

Results

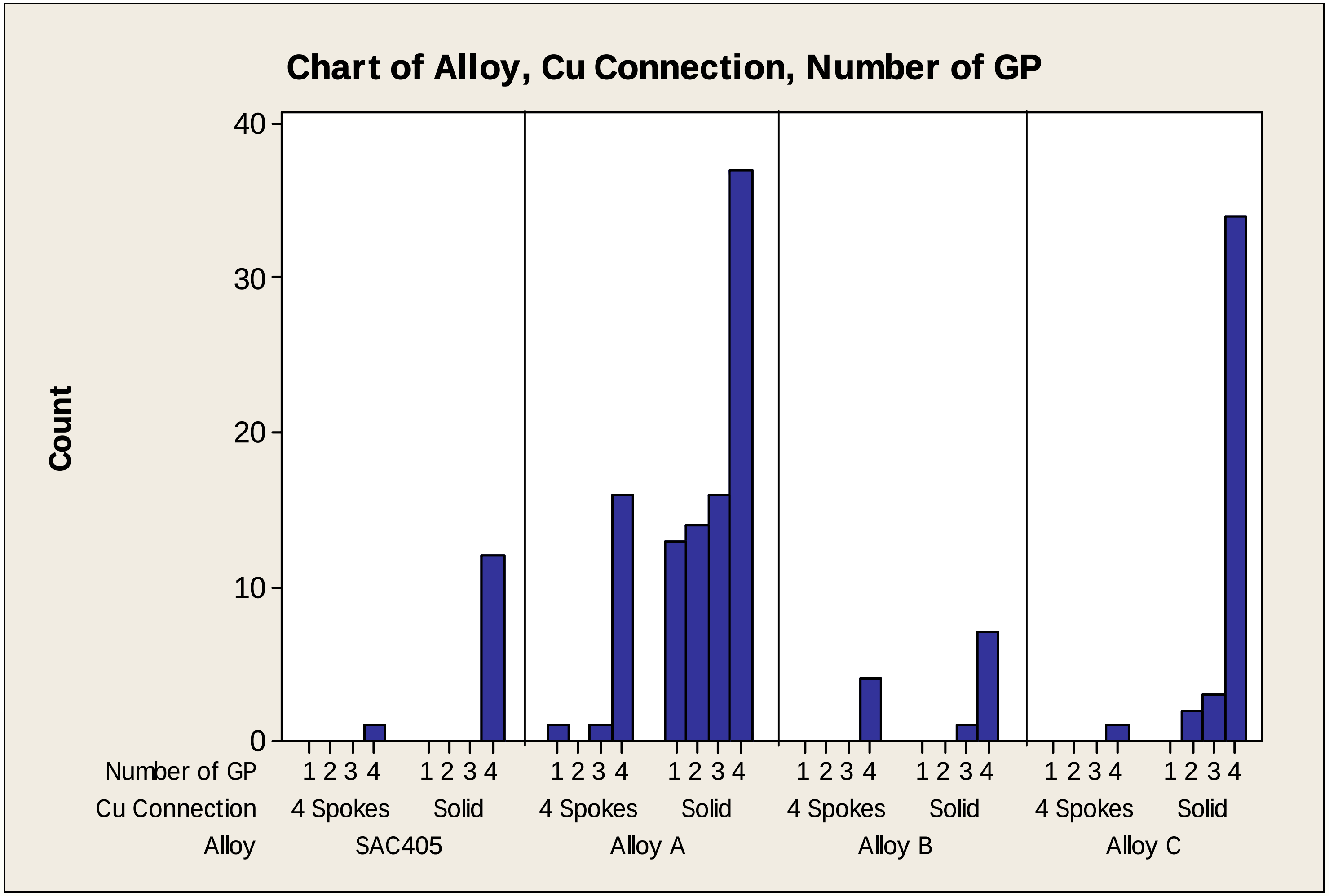




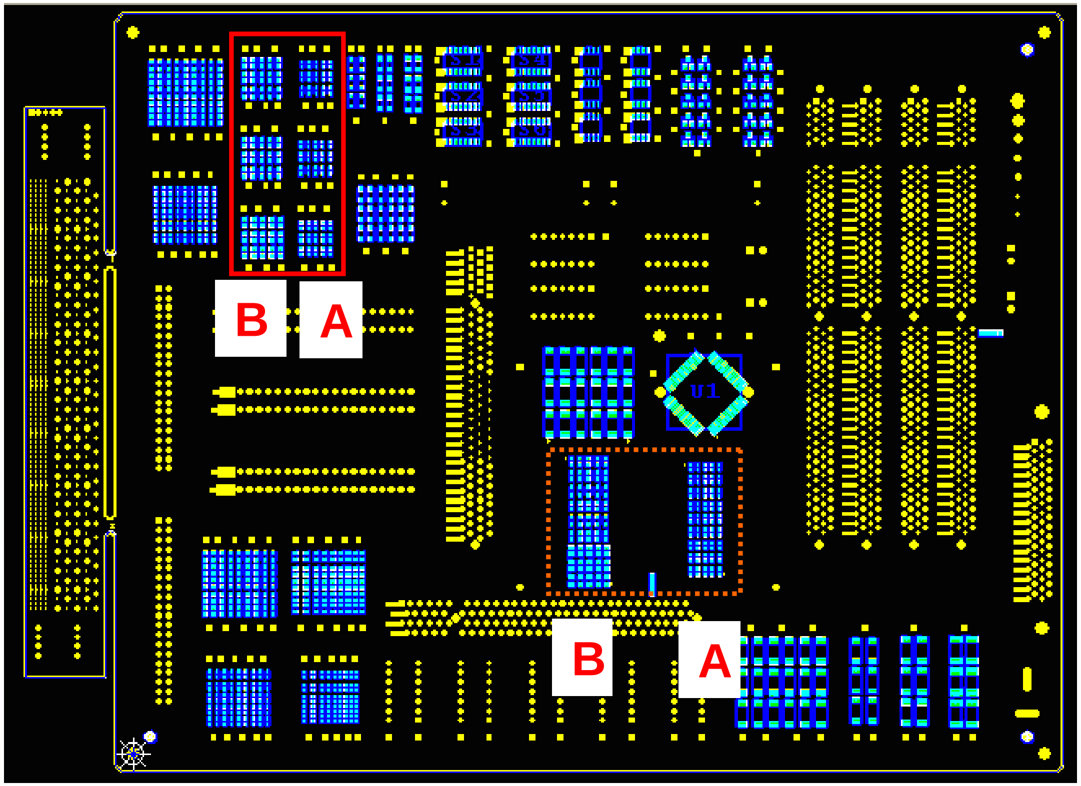
- **Alloy A showed the higher quantity of defects followed by Alloy C, SAC405 and Alloy B performed the best**
- **With four ground planes the quantity of defects increases dramatically**
- **4 spokes thermal relief helps to improve barrel fill, specially for 4 or more ground planes**

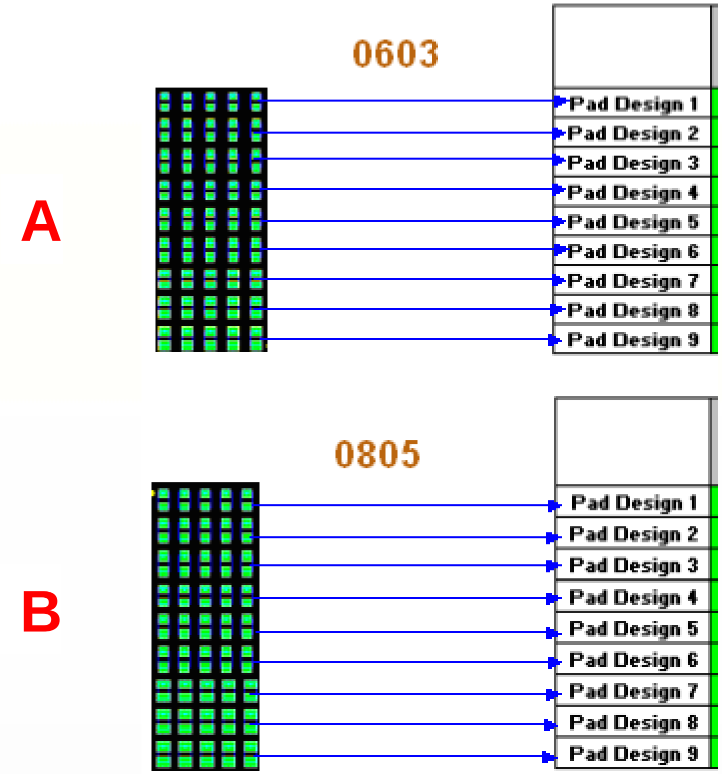
Quantity of Large Copper Planes and PTH Connection Types

Results



Land Pattern Design Variation





Resistors

Capacitors

Land Pattern Design Variation

DOE

Pad Design	X Width	Y Length
1	Low	Low
2	Low	Med
3	Low	High
4	Med	Low
5	Med	Med
6	Med	High
7	High	Low
8	High	Med
9	High	High

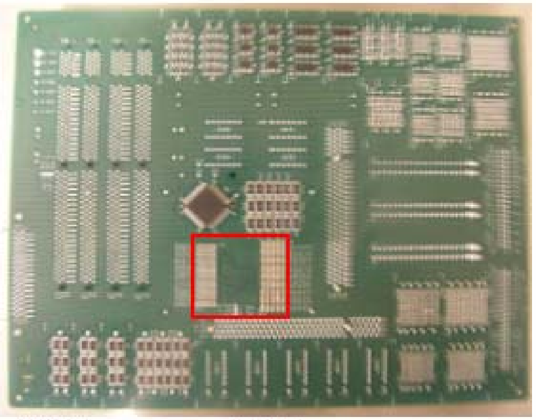
- Low: Dimension below standard guideline for reflow pad design
- Med: Dimension slightly below standard guideline for reflow pad design
- High: Dimension at standard guideline for reflow pad design

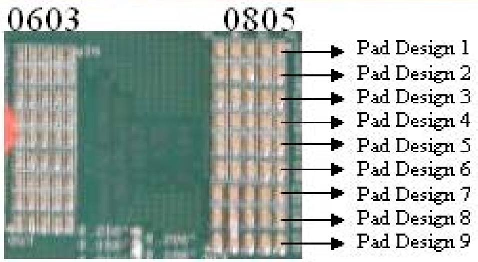
- **Solders:** SAC405, SnPb and the three alternative alloys were evaluated
- **Response:** DPMO on Visual Inspection (Class 2, IPC-A-610D) and Maximum Shear Force

Land Pattern Design Variation

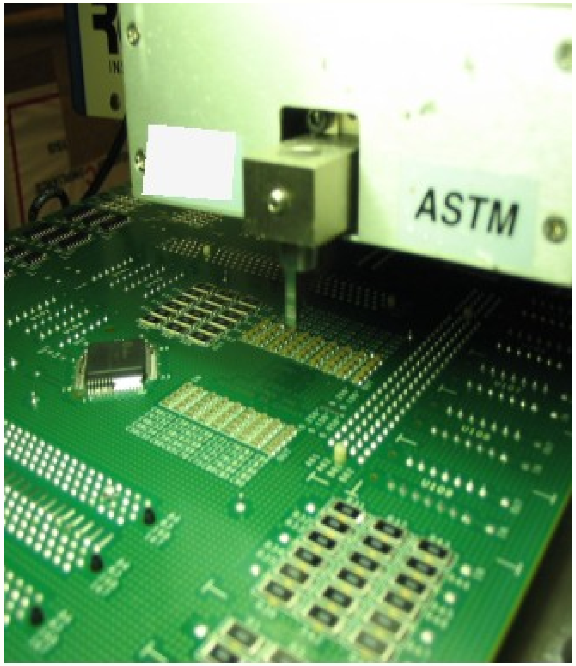
Shear Force Test

- SAC405, SnPb, Alloy A, Alloy B & Alloy C evaluated
- Five components of both 0805 and 0603 were tested for each of the 9 land pattern designs
- ASTM F1269 standard followed



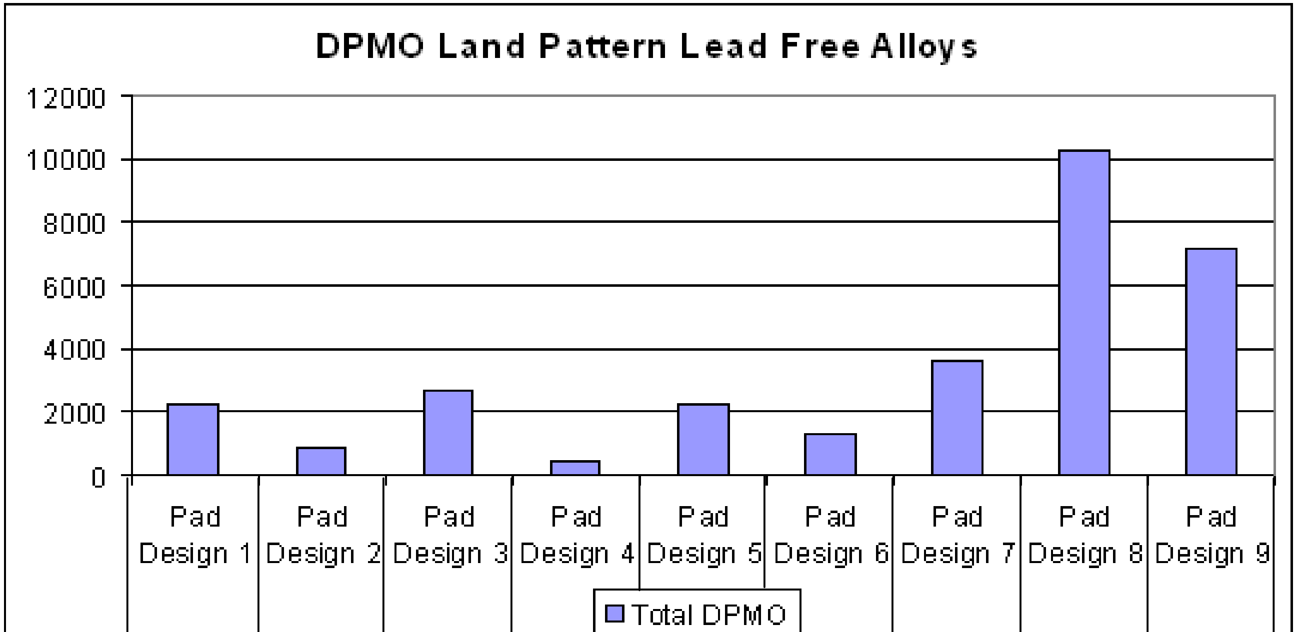


Alloy	Land pattern design	Component	Sample Size
SnPb SAC405 Alloy A Alloy B Alloy C	1	0603	5
		0805	5
	2	0603	5
		0805	5
	3	0603	5
		0805	5
	4	0603	5
		0805	5
	5	0603	5
		0805	5
	6	0603	5
		0805	5
	7	0603	5
		0805	5
	8	0603	5
		0805	5
	9	0603	5
		0805	5



Land Pattern Design Results

Combined results for the 9 different land patterns (0603 and 0805)

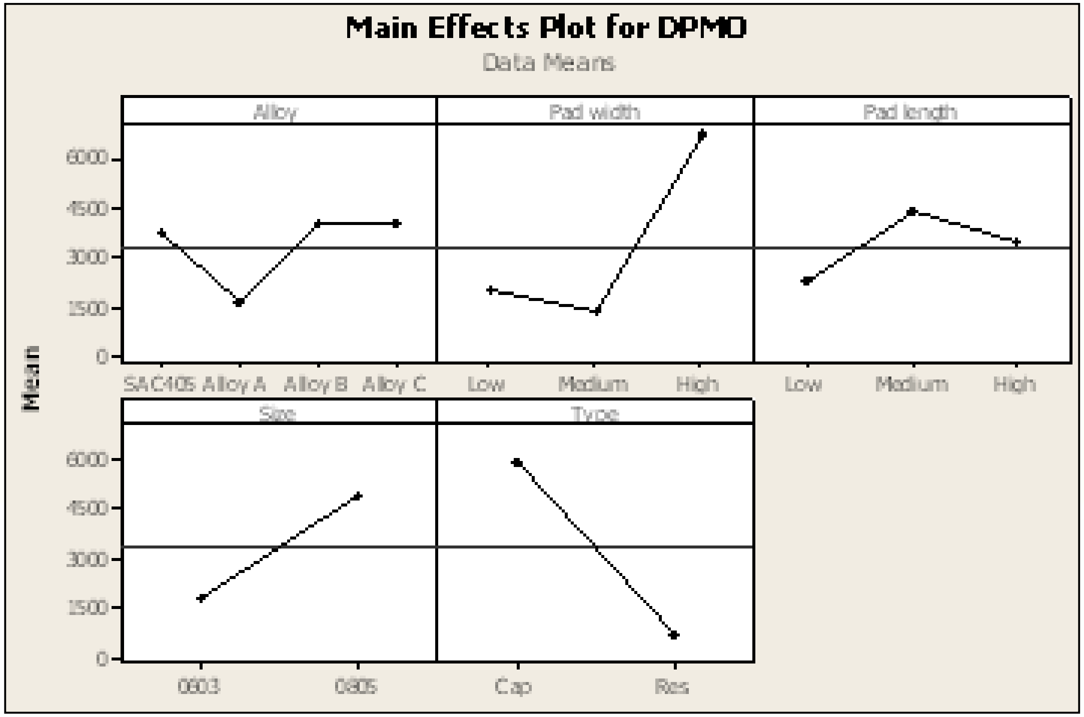


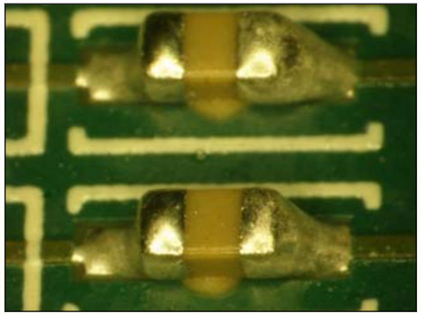
Width	Low	Low	Low	Med	Med	Med	High	High	High
Length	Low	Med	High	Low	Med	High	Low	Med	High

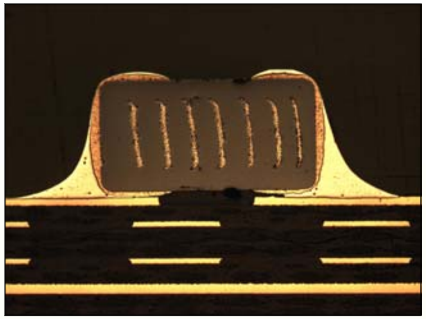
- **Land pattern designs 7, 8 and 9 (widest pad) have the higher quantity of defects**
- **Pad designs 4 and 2 performed the best**

Land Pattern Design Results

- **Best Pad width is the medium level (slightly lower than pad width used for reflow)**
- **Pad lengths used were statistically similar**
- **0603 capacitors and resistors deliver the lowest defect count**
- **Alloys B, C and SAC405 performed statistically at the same level. Alloy A performed the best**

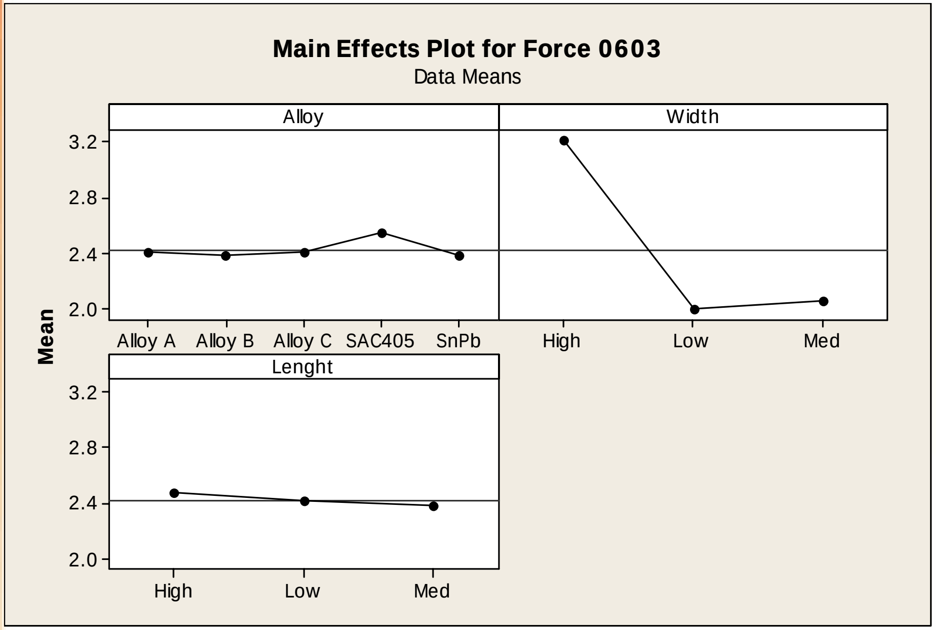


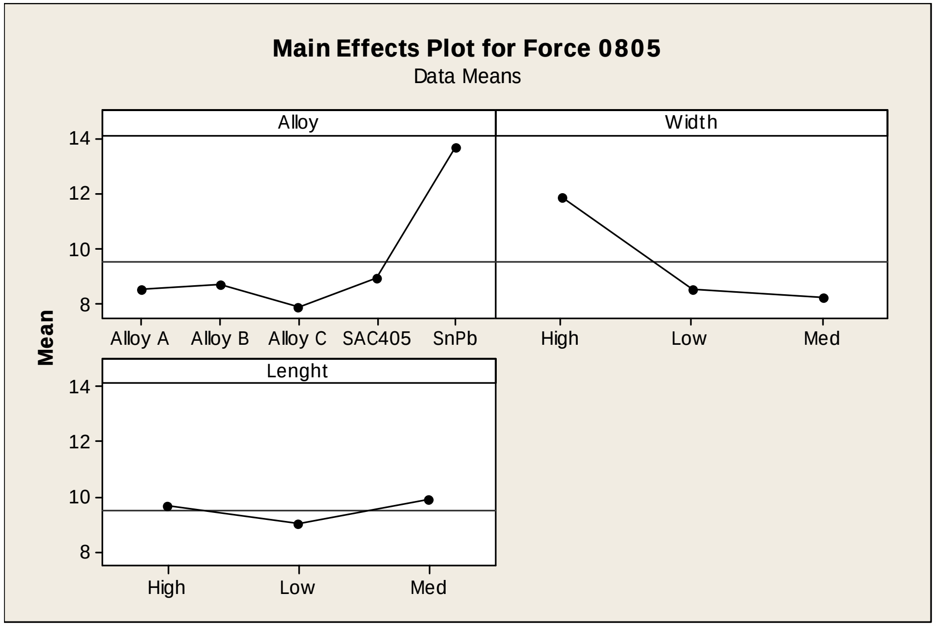




Land Pattern Design Results

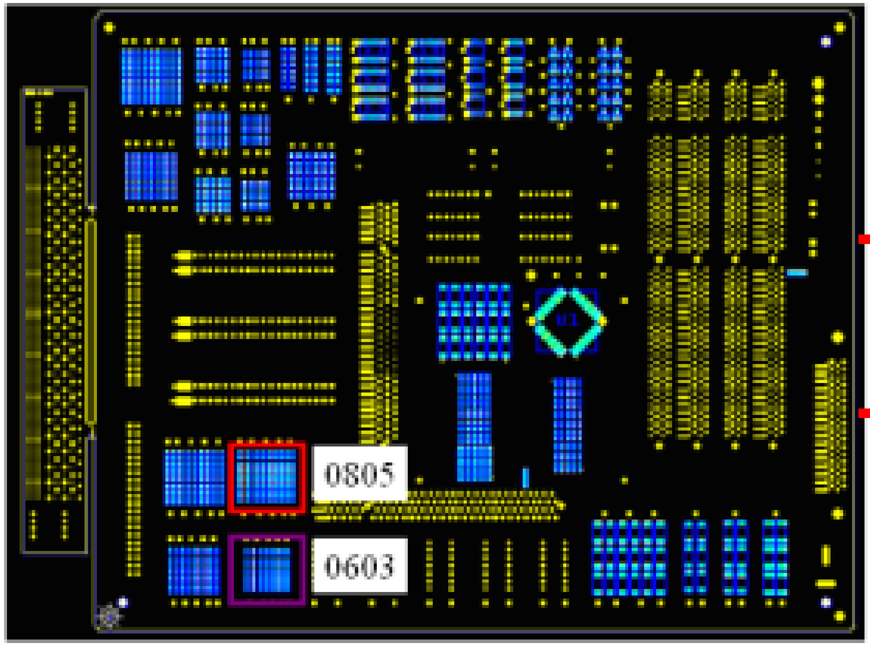
Shear Force Test

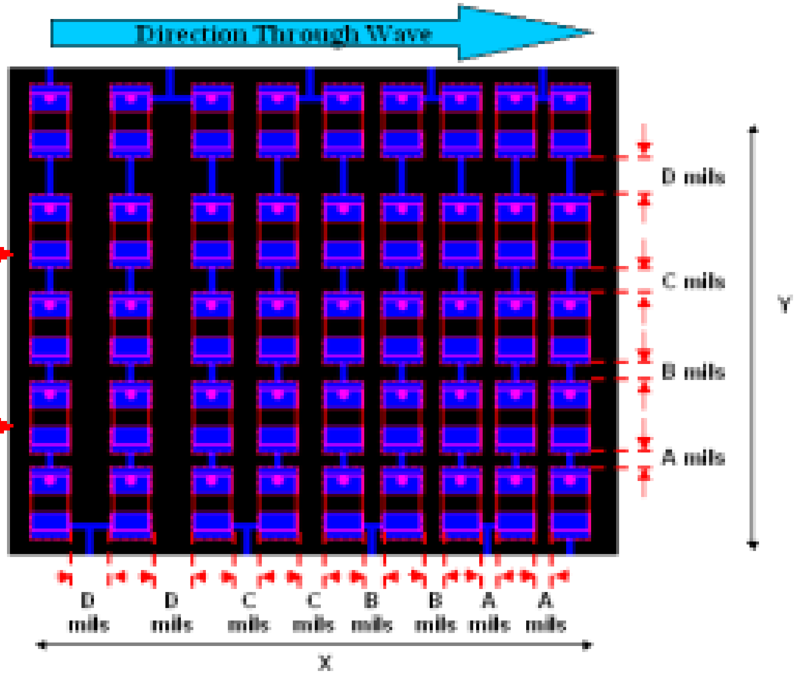




- **High width levels provided the largest strength for both, 0603 and 0805**
- **0805 strength larger than 0603 due to more contact area for the solder joint**
- **SnPb behaves statistically similar than SAC alloys for 0603 component**
- **For 0805 component, SnPb is the alloy with the higher strength.**

Pad to Pad Spacing Variation





- 0805 and 0603 components tested
- Four distances used on the X and Y axis

Pad to Pad Spacing Variation

- A Full Factorial, 3 Factors DOE was used:

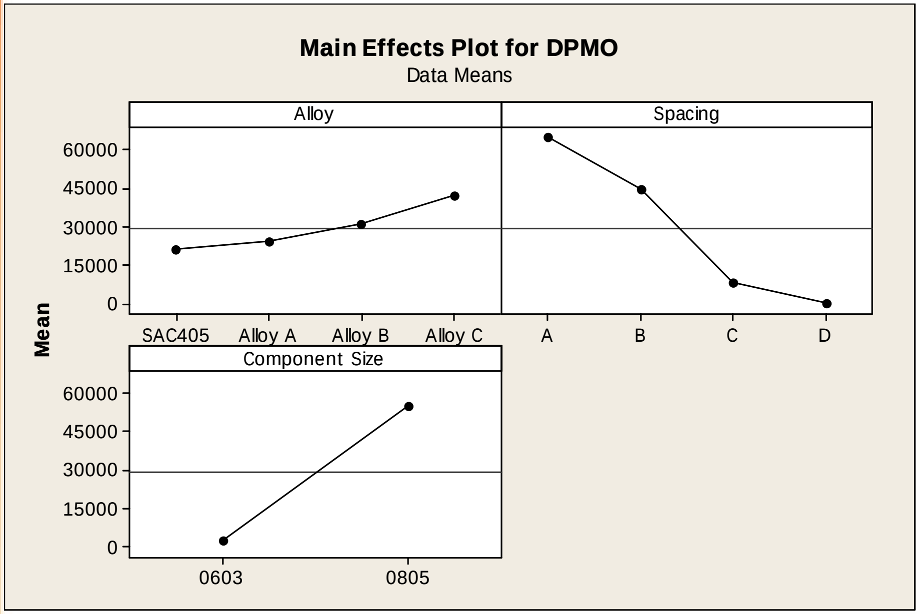
DOE

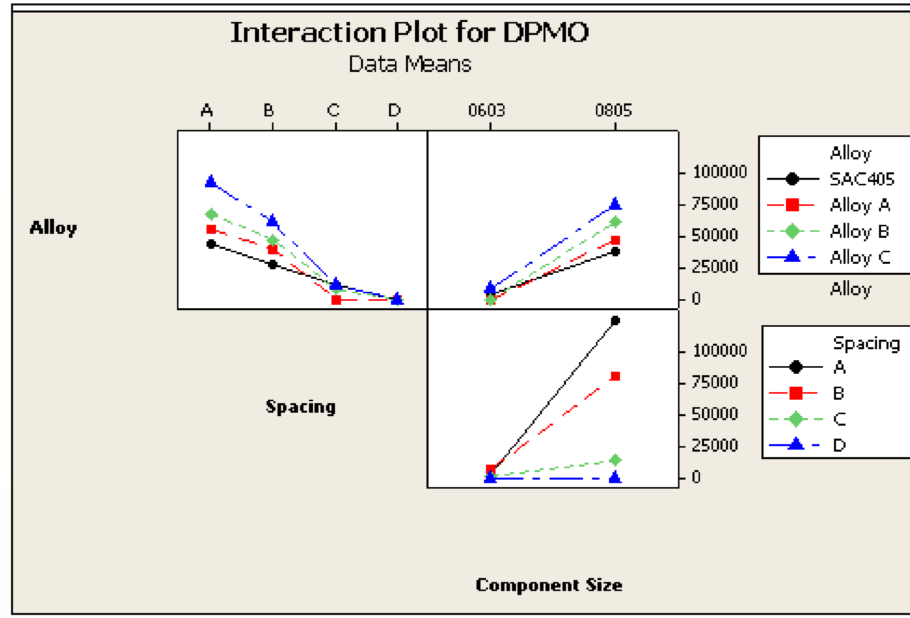
	Component	
Alloy	**0603**	**0805**
SAC405	A	A
	B	B
	C	C
	D	D
Alloy A	A	A
	B	B
	C	C
	D	D
Alloy B	A	A
	B	B
	C	C
	D	D
Alloy C	A	A
	B	B
	C	C
	D	D

A: Spacing slightly below 0.64mm
B: 0.64 mm **(0.025")**
C: Spacing slightly above 0.64mm
D: Spacing above 0.64mm **(0.025")**

- Response: DPMO on Visual Inspection (Class 3, IPC-A-610D)

Pad to Pad Spacing Variation Results





- **SAC405 performed the best followed closely by Alloy A**
- **0603 components show a lower quantity of defects among the 4 different spacing used**
- **With spacing A (0.5mm) and spacing B (0.64mm) the quantity of defects increased a lot**

Conclusions

<table>
<tr><td>Pin to Hole Ratio</td><td colspan="2">P2H ratio between 0.50 & 0.60 (equivalent to a clearance of 0.64 mm to 0.42 mm) is recommended
May not apply for larger pin areas</td></tr>
<tr><td>Ground Planes
(from 0 to 4 used)</td><td colspan="2">3 or less ground planes are recommended when using four spokes thermal relief and the P2H ratios mentioned above</td></tr>
<tr><td>PTH Connection Types</td><td colspan="2">Recommend incorporating 4 spokes thermal relief to minimize barrel fill defects. This recommendation takes more relevance as the quantity of ground planes increases</td></tr>
<tr><td>Land Pattern Design</td><td><u>Visual Inspection</u>
Pad Width slightly below reflow design standard is recommended
Pad Length doesn’t affect</td><td><u>Shear Force</u>
Shear Force increases with increasing pad width
No statistical difference for 0603 components among SnPb and LF Alloys</td></tr>
<tr><td>Pad to Pad Spacing</td><td colspan="2">Recommend having distances higher than 0.64mm to minimize solder bridges</td></tr>
<tr><td>Alloys</td><td colspan="2">Alloy B resulted as the more robust Pb-free alloy among the three alternatives, performing very similar to the SAC405</td></tr>
</table>