COMPARING THE PERFORMANCE OF ENGINEERED TIN/COPPER ALLOYS IN SELECTIVE SOLDERING

Jason Fullerton and Chris Colindres
Alpha Assembly Solutions
South Plainfield, NJ, USA
Jason.Fullerton@AlphaAssembly.com

ABSTRACT

This paper details an experiment that compares the hole fill performance of two engineered tin-copper alloys in a selective soldering process. The test vehicle design incorporates features that are optimized for the selective soldering process. Two experiments are performed – one uses no preheat and no inner layer connections at the hole and the second uses preheat and thermally challenging inner layer connections. Hole fill is measured via X-ray software algorithm and the relative performance of each alloy is compared. The performance advantage observed with one alloy under design conditions that make soldering difficult demonstrate the need to evaluate the performance differences of even similar alloys due to the effects of small additives to standard alloys.

Key words: selective soldering, silver free

INTRODUCTION

Engineered tin-copper solder is commonly chosen for use in RoHS-compliant selective soldering applications due to the cost advantage compared to silver-bearing alternatives. The added metals alloyed with eutectic tin-copper provide benefits that can differentiate various alloys in the tin-copper family.

An experiment was conducted to compare the soldering performance of two tin-copper alloys in a commercial selective soldering system. The test vehicle was designed to incorporate all possible advantages to optimize the design for selective soldering. The assembly also contains features that represent thermally challenging designs that may be necessary, regardless of the detriment to the manufacturing process. The experiment examined the effects of changing preheat temperature, solder contact time, and solder pot temperature on the hole fill performance with each alloy.

EXPERIMENTAL METHOD

Test Vehicle

The test vehicle is a PCI form factor connector soldered to an FR4 PCB. The PCB is 2.4 mm thick with six 1-oz copper layers – four internal and two surface layers. Low surface energy matte black solder mask is applied and an OSP over bare copper final finish is present on the PCB.

The connector has 120 0.36 mm x 0.23 mm pins, with a length of 2.54 mm below the seating plane of the housing that provides 0.14 mm protrusion through the PCB. The pin is finished with matte tin over nickel for solderability.

There are a number of features in the test vehicle design that are optimized for selective soldering:

- Low protrusion connector pins to reduce bridging without violating J-STD-001F 6.1.2, with respect to minimum lead protrusion requirements
- Low surface energy solder mask to minimize flux spread after application[1]
- Black solder mask to maximize efficiency of infrared pre-heating

The hole design varies across the connector layout on the PCB. The 120 holes each have a finished diameter of 1.02 mm. They are laid out in two rows with a 0.254 mm annular ring (60 total) and two rows with a 0.381 mm annular ring (60 total).

Four different types of internal connections are present, as shown in Figure 1. These represent different degrees of challenge for soldering processes due to internal copper layer thermal capacity. The most challenging type is the direct connection variety, where the internal copper thieves heat from the soldering location. The short spoke variety reduces the thermal conductivity between the hole and the internal planes, and the long spoke variety reduce the thermal conductivity even further. The no connection variety is the least demanding design due to the insulating effect of the laminate between the hole and the internal copper planes.

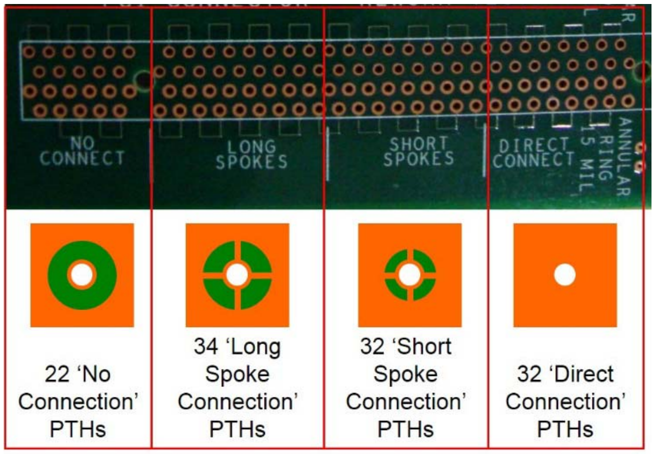
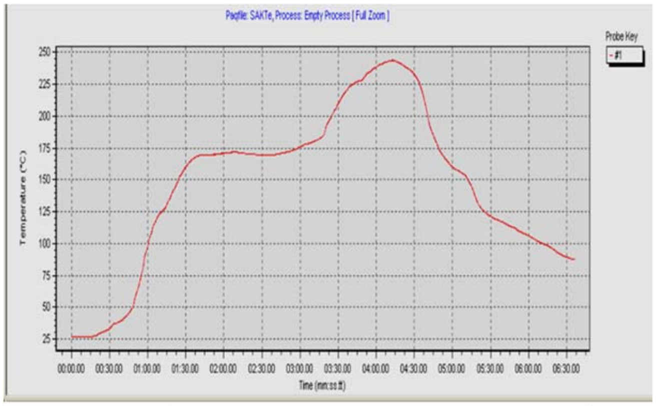


Figure 1. Test vehicle internal layer connection layout

The test vehicle was conditioned with two lead-free reflow profiles as shown in Figure 2. The PCBs and connectors were sourced within two weeks of assembly and were all from the same lot of production.



Soak 160⁰C - 60sec, TAL 60sec, Peak 240⁰C

Figure 2. Lead-free preconditioning reflow profile

Solder Alloys

Two alloys were compared in this experiment. Each is an engineered variant of the eutectic Sn99.3Cu0.7. Both alloys contain additions of nickel (at <500 ppm) as a copper dissolution reducing agent. Each alloy contains an anti-oxidant agent (at <100 ppm), although the alloys use different materials for this purpose (germanium or phosphorus). Finally, one alloy uses bismuth (at <2000 ppm) as a wetting agent. The two alloys will be referred to as SnCuNi+Ge and SnCuBiNi+P. Each alloy manufacturer reports a melting point of 227⁰C for their respective alloys.

Flux

A common flux was used for the entire experiment. The flux is an alcohol-based, low-rosin, no-clean flux with 3.6% solids content and is characterized as ORL0 by J-STD-004B 1.3.

Selective Soldering Process

The selective soldering system used was a semi-automatic system with manual loading and unloading and automated preheat, flux, and soldering functions. The flux application was performed using a programmed drop-jet flux system. The preheater consisted of an infrared source with a non-contact temperature sensor for closed-loop control of PCB topside surface temperature. The soldering module used a wettable nozzle with a 12 mm outside diameter and surrounded by a local nitrogen blanket. The assembly was held in a fixed position and the solder fountain was programmed to move in three axes.

The flux application was adjusted based upon typical levels used with the flux in practice with the system used in the experiment. This level was maintained constant during all soldering of the test vehicles.

The closed-loop control of the preheat system was calibrated during experiment setup, using a hard-wired thermocouple embedded under the PCI connector at the locations with no internal connections to copper planes. The non-contact sensor was directed at an open area at the center of the PCB and fixed in place for the entire experiment. The temperature read by the soldering system's non-contact sensor was noted when the temperature measured under the connector was the intended target temperature. This temperature as measured the selective soldering system was programmed as the trigger temperature for initiating the soldering cycle. See Table 1 for actual temperatures used.

Table 1. Wire thermocouple temperature measurement and non-contact sensor equivalent temperature reading

Thermocouple wire measurement under connector (⁰C)	**Non-contact sensor measurement at PCB surface (⁰C)**
70	74
100	110
130	150

The soldering contact time was controlled by adjusting the traverse speed as the solder fountain travelled across the connector pattern. The true contact diameter was determined by using a glass plate. This was determined to be 10.5 mm when programmed to the pump speed and approach distance used on the test vehicle.

The soldering movement of the fountain was programmed to start at the less thermally demanding end of the connector pattern and traverse at a constant speed through the pattern. This is done to maintain the preheat temperature for the entire connector pattern, including the thermally demanding end of the pattern, as found by Murphy, *et al.*[2] See Figure 3. The solder fountain was programmed to make initial contact and final withdraw from the PCB at a location that is fully out of contact with the connector pin pattern. This is done to ensure that each pin receives the same contact time across the entire connector and all contact with the fountain was as it was traversing across the connector (and not stationary or moving vertical).

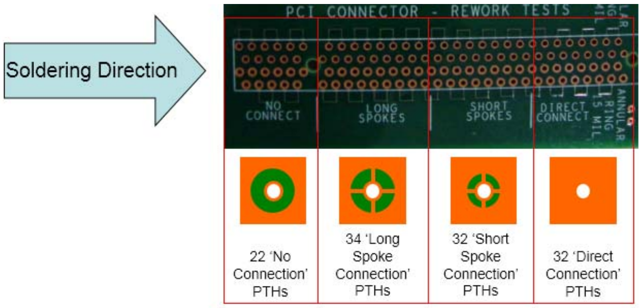


Figure 3. Soldering direction

The traverse speed was calculated assuming that each pin contacted the solder fountain in a manner that provided 10.5 mm of contact length through the fountain. The following formula shows how the values in Table 2 were calculated (using the inch/min speed in the programming interface):

$$\mathbf{X} \text{ in/min} = (10.5 \text{ mm}/\mathbf{Y} \text{ sec}) \times 60 \text{ sec/min} \times 0.0394 \text{ in/mm}$$
$$\mathbf{X} = 24.8/\mathbf{Y}$$

where **X** is the programmed traverse speed of the solder fountain and **Y** is the contact time

Table 2. Traverse speeds and equivalent contact times

Fountain traverse speed (in/min)	Calculated contact time (sec)
5.0	5.0
7.1	3.5
12.0	2.1
12.4	2.0
18.0	1.4

X-ray Measurement System

The hole fill was measured using a transmissive X-ray inspection system. The system utilized an image analysis algorithm to measure the percentage of solder fill observed on selected holes. Each measurement location was programmed and fixed for all measurement samples. The measurement system operator drew the inspection area (shown as the clear area in Figure 4) for each image individually to ensure the entire series of holes is properly fully analyzed.

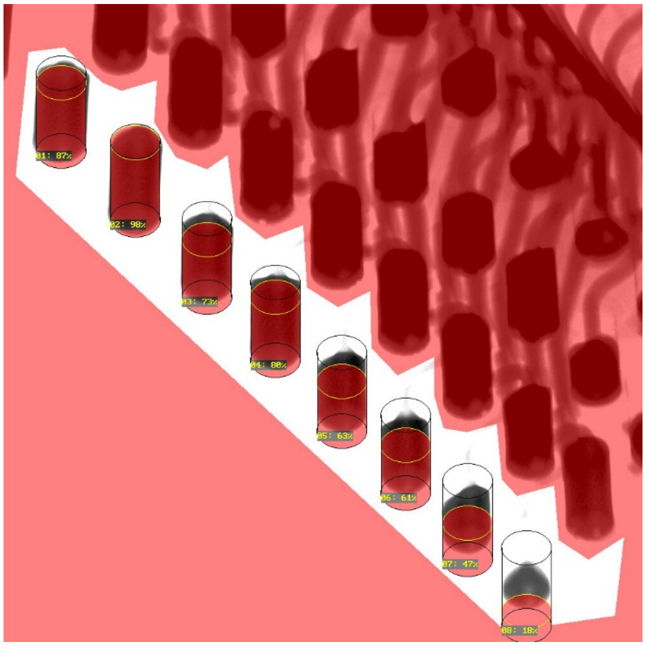


Figure 4. Sample X-ray hole fill measurement

Soldering Experiment #1 – Soldering Without Preheat

The first experiment performed was an experiment that did not utilize any preheating between flux application and soldering. Although all assemblies were soldered across the entire connector, this experiment only assessed locations without any connection to internal copper layers. This was intended to simulate processes where the typical assembly had low thermal challenges and where users typically decline to use preheat during the soldering processes.

This experiment was designed as a three-factor/two-level full factorial designed experiment, where the control factors were solder alloy, pot temperature, and solder contact time.

The levels for the pot temperature factor were 295°C and 330°C. The levels for the solder contact time factor were 1.37 sec. and 2.06 sec. Two replications were performed for each condition set. See Table 3 for experimental run order listing.

Hole fill measurements were performed on the outer rows of the no connection pin locations. The outer rows were chosen to ensure a clear view with the transmissive X-ray inspection system; the inner rows were likely to have other features in the same field of view which reduces the accuracy of the measurement algorithm to unacceptable levels. The average hole fill for the complete set of all holes analyzed (16 in total) was calculated for each test vehicle.

Table 3. Soldering without preheat experiment conditions

StdOrder	RunOrder	Pot Temp	Contact Time	Alloy
10	1	330	2.1	SnCuNi+Ge
12	2	330	1.4	SnCuNi+Ge
11	3	295	1.4	SnCuNi+Ge
3	4	295	1.4	SnCuNi+Ge
2	5	330	2.1	SnCuNi+Ge
4	6	330	1.4	SnCuNi+Ge
9	7	295	2.1	SnCuNi+Ge
1	8	295	2.1	SnCuNi+Ge
14	9	330	2.1	SnCuBiNi+P
6	10	330	2.1	SnCuBiNi+P
15	11	295	1.4	SnCuBiNi+P
13	12	295	2.1	SnCuBiNi+P
8	13	330	1.4	SnCuBiNi+P
16	14	330	1.4	SnCuBiNi+P
5	15	295	2.1	SnCuBiNi+P
7	16	295	1.4	SnCuBiNi+P

Soldering Experiment #2 – Soldering With Preheat

The second experiment performed was an experiment where preheat was utilized in the soldering process. The entire connector pattern was soldered, but the only area where hole fill was assessed was the direct connection variety. This was done to simulate the most challenging types of soldering processes, where users would typically require the use of preheat. This experiment was designed as a full factorial central composite response-surface experiment with three control factors: preheat temperature, solder pot temperature, and contact time.

The design of this type of experiment requires definition of the limits for each factor, and a center point is added as a third level. For preheat temperature, the lower and upper conditions were 70°C and 130°C with a center point of 100°C added. For solder pot temperature, the lower and upper conditions were 280°C and 310°C with a center point of 295°C added. For contact time, the lower and upper conditions were 2 and 5 seconds with a center point of 3.5 seconds added. See Table 4 for the experimental run order.

Hole fill measurements were performed on the outer rows of the direct connect pin locations. As with the prior experiment, the outer locations were chosen to avoid the background noise present in the images at the center rows. The average hole fill for the complete set of all holes analyzed (16 in total) was calculated for each test vehicle.

Table 4. Soldering with preheat experiment conditions

StdOrder	RunOrder	Preheat	Pot Temp	Contact Time	Alloy
6	1	130	280	5	SnCuNi+Ge
2	2	130	280	2	SnCuNi+Ge
17	3	100	295	3.5	SnCuNi+Ge
4	4	130	310	2	SnCuNi+Ge
15	5	100	295	3.5	SnCuNi+Ge
9	6	70	295	3.5	SnCuNi+Ge
12	7	100	310	3.5	SnCuNi+Ge
13	8	100	295	2	SnCuNi+Ge
11	9	100	280	3.5	SnCuNi+Ge
1	10	70	280	2	SnCuNi+Ge
5	11	70	280	5	SnCuNi+Ge
10	12	130	295	3.5	SnCuNi+Ge
8	13	130	310	5	SnCuNi+Ge
16	14	100	295	3.5	SnCuNi+Ge
20	15	100	295	3.5	SnCuNi+Ge
19	16	100	295	3.5	SnCuNi+Ge
14	17	100	295	5	SnCuNi+Ge
7	18	70	310	5	SnCuNi+Ge
3	19	70	310	2	SnCuNi+Ge
18	20	100	295	3.5	SnCuNi+Ge
35	21	100	295	3.5	SnCuBiNi+P
27	22	70	310	5	SnCuBiNi+P
33	23	100	295	2	SnCuBiNi+P
37	24	100	295	3.5	SnCuBiNi+P
32	25	100	310	3.5	SnCuBiNi+P
28	26	130	310	5	SnCuBiNi+P
21	27	70	280	2	SnCuBiNi+P
23	28	70	310	2	SnCuBiNi+P
40	29	100	295	3.5	SnCuBiNi+P
30	30	130	295	3.5	SnCuBiNi+P
36	31	100	295	3.5	SnCuBiNi+P
34	32	100	295	5	SnCuBiNi+P
38	33	100	295	3.5	SnCuBiNi+P
22	34	130	280	2	SnCuBiNi+P
39	35	100	295	3.5	SnCuBiNi+P
29	36	70	295	3.5	SnCuBiNi+P
31	37	100	280	3.5	SnCuBiNi+P
25	38	70	280	5	SnCuBiNi+P
24	39	130	310	2	SnCuBiNi+P
26	40	130	280	5	SnCuBiNi+P

Hole Fill Correlation Using Thick Boards

The test vehicle in this experiment was 2.4 mm thick, but 1.6 mm thick PCBs are common. The hole fill performance on the thicker board can be used to predict hole fill on thinner boards using the correlation model developed by Ferrer, *et al.*[3] This correlates absolute vertical hole fill distance regardless of the actual PCB thickness. For an example, see Figure 5. Table 5 describes various equivalent hole fill measures for 2.4 mm thick boards and estimates for the corresponding hole fill for 1.6 mm boards.

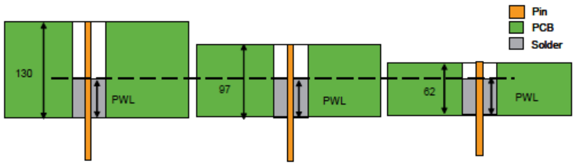


Figure 5. Hole-filling correlation model [3]

Table 5. Measured hole fill on 2.4 mm PCB thickness and equivalent hole fill for 1.6 mm PCB thickness

Hole Fill (mm on 2.4 mm PCB)	Hole Fill (% on 2.4 mm PCB)	Hole Fill (mm on 1.6 mm PCB)	Hole Fill (% on 1.6 mm PCB)
2.4	100%	>1.6	>100%
1.8	75%	>1.6	>100%
1.6	66.7%	1.6	100%
1.2	50%	1.2	75%

SOLDERING WITHOUT PREHEAT RESULTS

The main interaction plots (see **Figure 6**) demonstrates relative performance differences between the two alloys, with an apparent advantage when soldering with SnCuNi+Ge on a low thermal demand application. This is particularly apparent when soldering with lower solder pot temperatures and shorter contact times. In addition, the plots that separate performance by alloy (bottom row of plots in Figure 6) show that SnCuNi+Ge provides higher hole fill than SnCuBiNi+P under the conditions tested in this experiment.

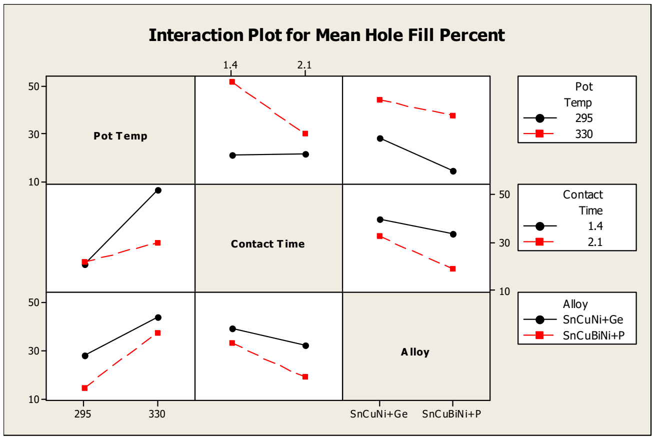


Figure 6. Interaction plot

However, closer examination of the results indicates that the results do not meet the minimum standard of acceptability for hole fill of >75%. This data is calculated using 2.4 mm thick boards and never exceeds 50% average hole fill. Notably, 50% hole fill on a 2.4 mm thick PCB is equivalent to 75% on a 1.6 mm thick PCB – and thus, none of the tested conditions in this experiment represent a process that is sufficient to produce acceptable solder joints on 1.6 mm or thicker PCBs.

SOLDERING WITH PREHEAT RESULTS

The central composite response surface type of designed experiment is used to build a quadratic regression model to predict the expected performance of the response variable given specific input factor values over the range of values used in the experiment. In an experiment of this type, with three input factors, a contour plot showing the relationship between predicted response and two factors can be generated when holding one factor at a fixed value. This analysis focuses on the effect of preheat temperature and contact time while holding solder pot temperature at three fixed values (280°C, 295°C, and 310°C).

Figure 7 shows the color key for the contour plots presented. Note that J-STD-001F 6.2.2 provides a minimum requirement of 75% hole fill for Class 3 assemblies. The same 75% minimum hole fill applies to Class 2 assemblies, with an exception for devices with 14 or more leads. That exception allows a minimum acceptable hole fill of 50% for PCBs that are 2.4 mm or less thick.

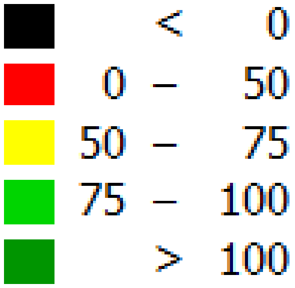


Figure 7. Hole fill percentage color key

The green categories correspond to the acceptable hole fill (>75%) for Class 3 and most Class 2 assemblies. The yellow category would be considered unacceptable except for the Class 2 exception described previously. The red and black categories indicate conditions that would be considered unacceptable for Class 2 and Class 3 assemblies.

Hole Fill on 1.6 mm Thick PCBs

Solder Temperature 280°C

Figure 8 shows the hole fill model at 280°C solder pot temperature for SnCuBiNi+P alloy with 1.6 mm thick PCBs, which predicts complete hole fill (>100%) at preheat temperatures up to 105°C and acceptable hole fill (>75%) at preheat temperatures up to 110°C, regardless of solder contact time. A very slight improvement in performance was seen with increased contact time. Unacceptable hole fill performance (<50%) was predicted at preheat temperatures above 120°C.

Figure 9 shows the hole fill model at 280°C solder pot temperature for SnCuNi+Ge alloy with 1.6 mm thick PCBs, which predicts acceptable hole fill performance at preheat temperatures up to 80°C regardless of solder contact time. Preheat temperatures up to 110°C can provide acceptable hole fill only when accompanied by increased contact times. Unacceptable hole fill performance is predicted at preheat temperatures above 120°C and with decreasing contact times as low as 100°C.

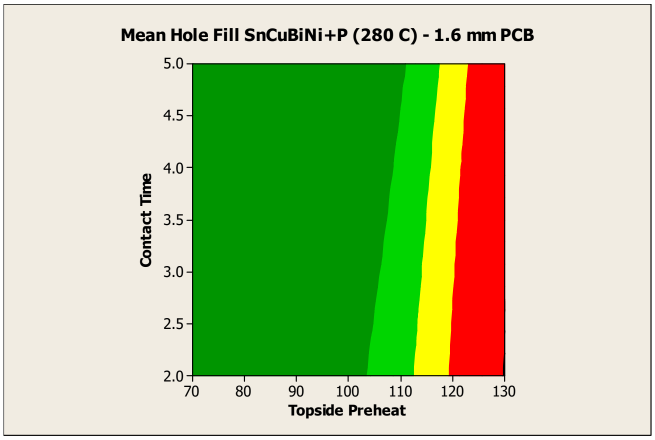


Figure 8. SnCuBiNi+P hole fill contour plot

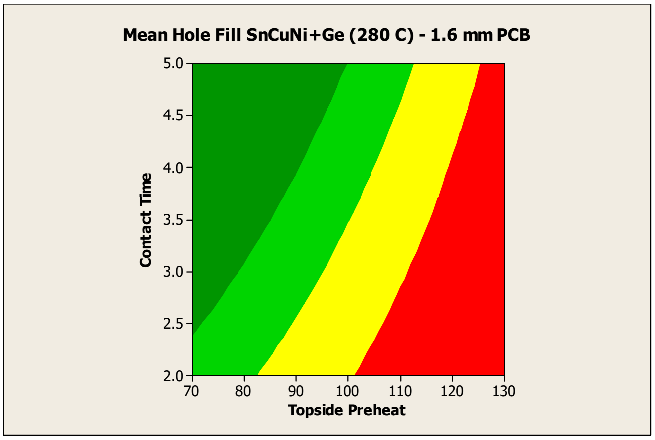


Figure 9. SnCuNi+Ge hole fill contour plot

Solder Temperature 295°C

Figure 10 shows the hole fill model at 295°C solder pot temperature for SnCuBiNi+P alloy with 1.6 mm thick PCBs, which predicts complete hole fill at preheat temperatures up to 105°C and acceptable hole fill at preheat temperatures up to 115°C, regardless of solder contact time. Unacceptable hole fill was predicted at preheat temperatures above 120°C.

Figure 11 shows the hole fill model at 295°C solder pot temperature for SnCuNi+Ge alloy with 1.6 mm thick PCBs, which predicts complete hole fill performance at preheat temperatures up to 80°C and acceptable hole fill performance at preheat temperatures just under 100°C. Increasing solder contact time improves the results, with complete hole fill predicted at 90°C and acceptable hole fill predicted just above 100°C when coupled with long contact times. Unacceptable hole fill was predicted at preheat temperatures above 120°C, regardless of contact time, and as low as 115°C with low contact times.

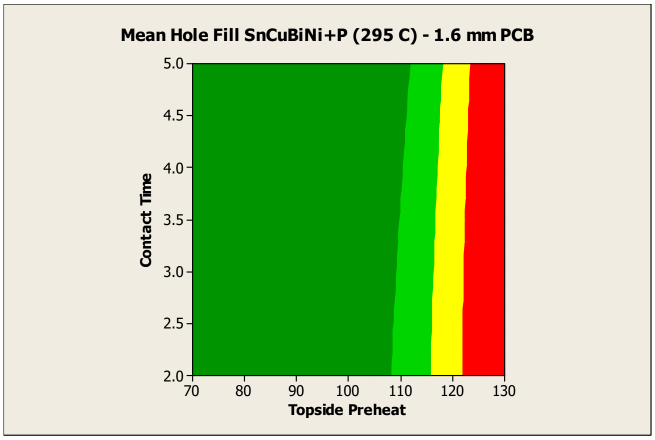


Figure 10. SnCuBiNi+P hole fill contour plot

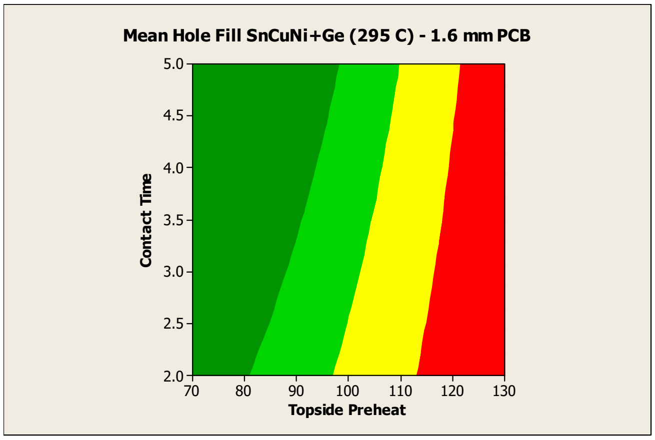


Figure 11. SnCuNi+Ge hole fill contour plot

Solder Temperature 310°C

Figure 12 shows the hole fill model at 310°C solder pot temperature for SnCuBiNi+P alloy with 1.6 mm thick PCBs, which predicts complete hole fill at preheat temperatures up to 110°C and acceptable hole fill at preheat temperatures up to 120°C, regardless of solder contact time. Unacceptable hole fill was predicted at preheat temperatures above 125°C.

Figure 13 shows the hole fill model at 310°C solder pot temperature for SnCuNi+Ge alloy with 1.6 mm thick PCBs, which predicts complete hole fill at preheat temperatures up to 95°C and acceptable hole fill at preheat temperatures up to 105°C, regardless of solder contact time. Unacceptable hole fill was predicted at preheat temperatures above 120°C.

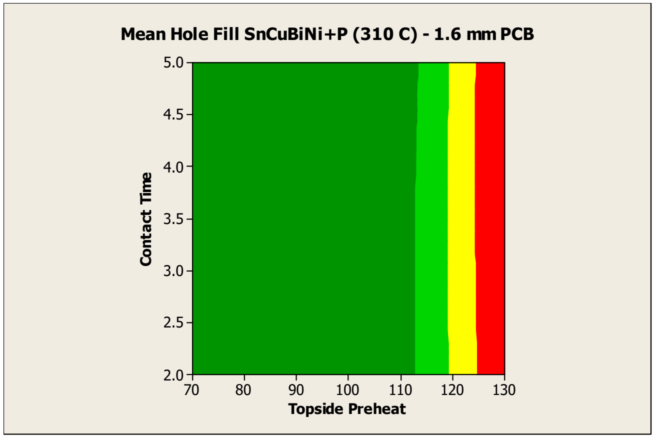


Figure 12. SnCuBiNi+P hole fill contour plot

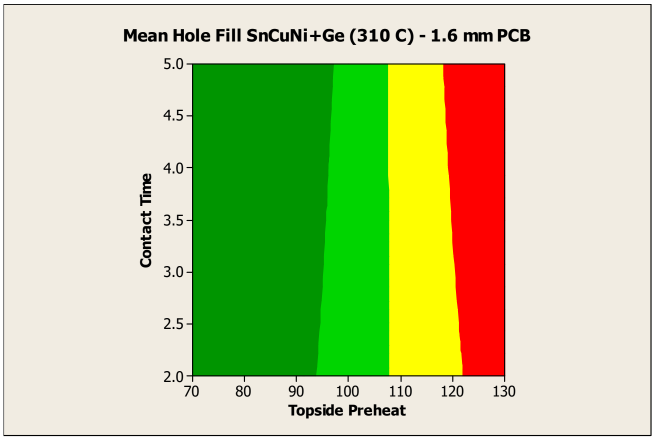


Figure 13. SnCuNi+Ge hole fill contour plot

Hole Fill on 2.4 mm Thick PCBs

Solder Temperature 280°C

Figure 14 shows the hole fill model at 280°C solder pot temperature for SnCuBiNi+P alloy with 2.4 mm thick PCBs, which predicts acceptable hole fill at preheat temperatures up to 100°C when coupled with contact times greater than 3 seconds. Acceptable hole fill can be achieved with contact times as short as 2 seconds when preheat is controlled between 75°C - 95°C. Unacceptable hole fill is predicted with any preheat temperature 115°C or greater.

Figure 15 shows the hole fill model at 280°C solder pot temperature for SnCuNi+Ge alloy with 2.4 mm thick PCBs. This combination produced complete hole fill with 70°C preheat temperature and 5.0 seconds contact time. Acceptable hole fill was predicted at 3.0 seconds contact time and 70°C preheat temperature, and with increasing contact time and preheat temperature proportionally up to 5.0 seconds and 90°C, respectively. Unacceptable hole fill was predicted at all preheat temperatures above 110°C; decreasing contact times result in unacceptable hole fill at preheat temperatures as low as 85°C.

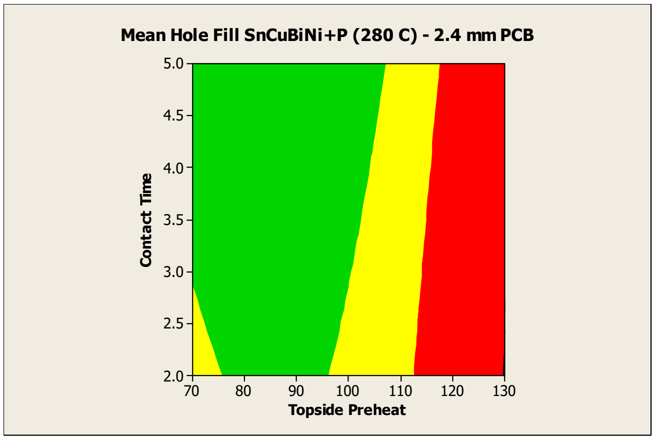


Figure 14. SnCuBiNi+P hole fill contour plot

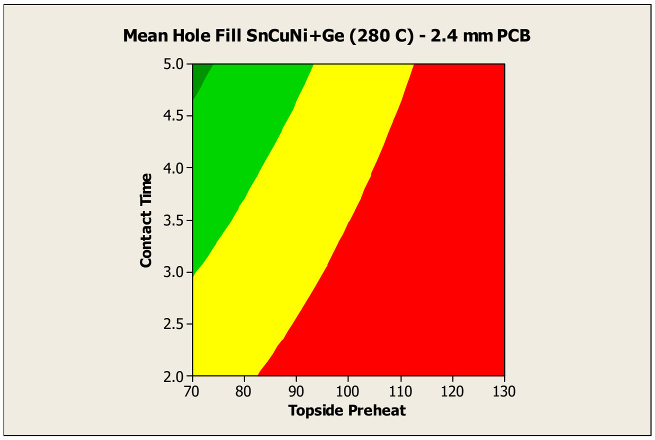


Figure 15. SnCuNi+Ge hole fill contour plot

Solder Temperature 295°C

Figure 16 shows the hole fill model at 295°C solder pot temperature for SnCuBiNi+P alloy with 2.4 mm thick PCBs, which predicts acceptable hole fill at preheat temperatures up to 105°C regardless of solder contact time. Complete hole fill was predicted with 4.75 - 5.0 seconds of contact and 80°C - 90°C preheat temperature. Unacceptable hole fill was predicted at preheat temperatures above 115°C regardless of solder contact time.

Figure 17 shows the hole fill model at 295°C solder pot temperature for SnCuNi+Ge alloy with 2.4 mm thick PCBs. The results are similar to the 280°C solder temperature results, with complete hole fill predicted at 70°C preheat temperature and 5.0 seconds solder contact time. Acceptable hole fill was predicted at 70°C with 2.0 seconds contact time, and with increasing contact time and preheat temperature proportionally up to 5.0 seconds and 90°C, respectively. Unacceptable hole fill was predicted at all preheat temperatures above 110°C; decreasing contact times result in unacceptable hole fill at preheat temperatures as low as 100°C.

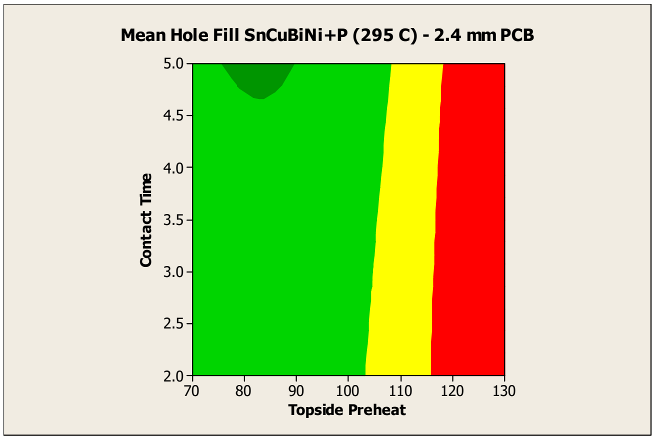


Figure 16. SnCuBiNi+P hole fill contour plot

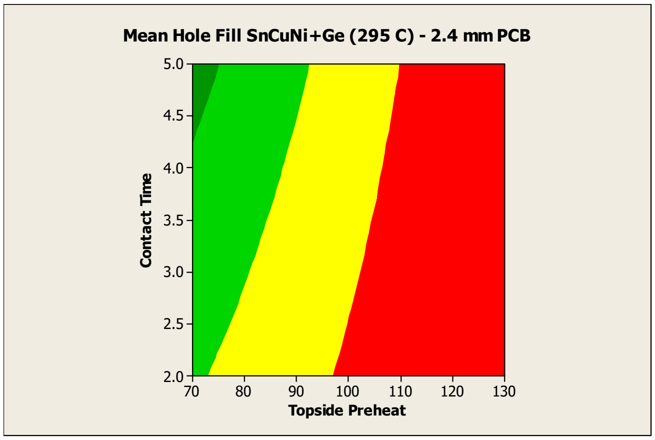


Figure 17. SnCuNi+Ge hole fill contour plot

Solder Temperature 310°C

Figure 18 shows the hole fill model at 310°C solder pot temperature for SnCuBiNi+P alloy with 2.4 mm thick PCBs, which predicts acceptable hole fill at preheat temperatures up to 110°C regardless of solder contact time. Complete hole fill was predicted with 4.5 seconds of contact or longer and 70°C - 95°C preheat temperature, and with 3.0 seconds or longer solder contact time and 80°C - 90°C preheat temperature. Unacceptable hole fill was predicted at preheat temperatures above 120°C regardless of solder contact time.

Figure 19 shows the hole fill model at 295°C solder pot temperature for SnCuNi+Ge alloy with 2.4 mm thick PCBs PCBs, which predicts acceptable hole fill at preheat temperatures up to 90°C regardless of solder contact time. Complete hole fill was predicted at 70°C preheat temperatures and contact times longer than 3.0 seconds. Unacceptable hole fill was predicted at 110°C preheat temperature, regardless of solder contact time.

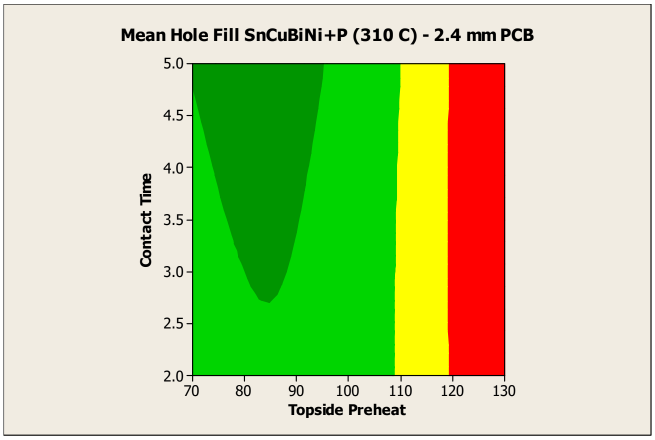


Figure 18. SnCuBiNi+P hole fill contour plot

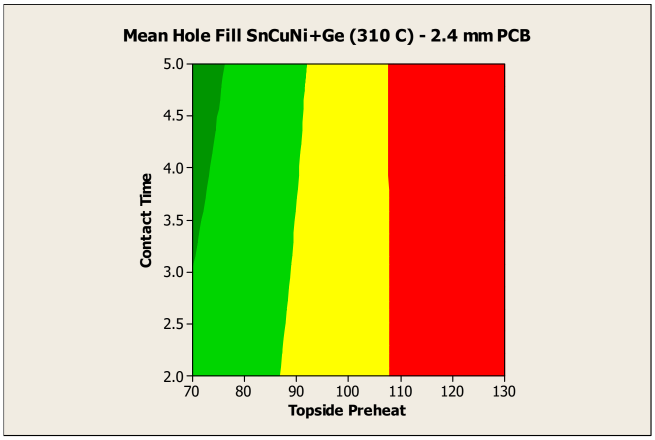


Figure 19. SnCuNi+Ge hole fill contour plot

CONCLUSIONS

Soldering Without Preheat

This experiment demonstrated that neither alloy was able to produce acceptable hole fill performance under the conditions tested in this experiment. Further investigation would be necessary to determine the main factor(s) that need to be optimized to ensure acceptable hole fill performance under these conditions, including the control factors of solder pot temperature and contact time but also potentially including aspects that are out of scope for the project as planned (flux, PCB finish, alternate alloys).

Selective Soldering With Preheat

The contour plots comparing the two alloys demonstrate a significant performance advantage when selective soldering with the SnCuBiNi+P alloy over the SnCuNi+Ge alloy under conditions that are thermally challenging.

With 1.6 mm thick boards, the performance of SnCuBiNi+P was consistent across a wide range of solder contact times. For the tested range of 280°C - 310°C solder temperature and 2.0 – 5.0 solder contact seconds, any preheat temperature between 70°C - 100°C is expected to provide complete hole fill. Even the best results for the SnCuNi+Ge alloy, at the highest solder temperature of 310°C, was only expected to provide complete hole fill at preheat temperatures between 70°C - 90°C.

In addition, the SnCuBiNi+P alloy was predicted to provide acceptable hole fill at consistently higher preheat temperatures than the SnCuNi+Ge alloy under similar solder temperature conditions, particularly with low solder contact times.

The 2.4 mm thick board results, as expected, showed a reduced window of conditions that are predicted to provide acceptable hole fill results. With 2.4 mm thick boards, the SnCuBiNi+P alloy had a wider range of conditions that are expected to produce acceptable hole fill results when compared to the SnCuNi+Ge alloy under all solder temperature conditions tested.

For all solder pot temperature conditions tested, the SnCuBiNi+P alloy was predicted to result in acceptable hole fill when solder contact time was between 3.0 - 5.0 seconds and preheat temperature was between 70°C - 100°C. With the SnCuNi+Ge alloy, the only conditions that resulted in acceptable hole fill over all solder temperatures tested are those with preheat temperatures between 70°C - 80°C and solder contact time between 4.0 - 5.0 seconds.

REFERENCES

[1] Diepstraten, Gerjan. 2016. "Design Improvements for Selective Soldering Assemblies." *IPC APEX Expo.* Las Vegas, NV: IPC

[2] Mike Murphy, Russell Maynard, Laxminarayana Pai, Corné Hoppenbrouwers, Ansuman Das, Anubhav Rustogi. 2013. "Liquid Flux Selection and Process Optimization for Selective Soldering Applications." *IPC APEX Expo.* San Diego, CA: IPC.

[3] Ernesto Ferrer, Elizabeth Benedetto, Garry Freedman, Francois Billaut, Helen Holder. 2006. "Reliability of Partially Filled SAC305 Through-Hole Joints." *IPC Printed Circuits Expo® and the Designers Summit.* Anaheim, CA: IPC