ACHIEVING EXCELLENT VERTICAL HOLE FILL ON THERMALLY CHALLENGING BOARDS USING SELECTIVE SOLDERING

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ABSTRACT
The continuous drive in the Electronics industry to build new and innovative products has caused competitive design companies to develop assemblies with consolidated PCB designs, decreased physical sizes, and increased performance characteristics. As a result of these new designs, manufacturers of electronics are forced to contend with many challenges. One of the most significant challenges being the processing of thru-hole components on high thermal mass PCBs having the potential to exceed 20 layers in thicknesses and have copper mass contents of over 40oz. High thermal mass PCBs, coupled with the use of mixed technologies, decreased component spacing, and the change from Tin Lead Solder to Lead Free Alloys has lead many manufacturing facilities to purchase advanced soldering equipment to process challenging assemblies with a high degree of repeatability.

Enter Selective Soldering; A technology combining the repeatability of a fully automated machine, with the flexibility of hand soldering, which can easily accommodate mixed technology components on highly complex PCB's.

While the introduction of the selective soldering process has provided the industry with a valuable tool for overcoming many challenges associated with PTH processing, equipment alone will not ensure the ability to solder a high thermal mass PCB. These difficult applications have proven that advancements in our techniques and process knowledge are just as critical as the advancements in equipment. With process development through experimental design in combination with the flux application, preheating combinations, and soldering techniques available on today's Selective Soldering machines, excellent vertical hole fill on high thermal mass PCBs can be achieved.

Key words: Selective Soldering, High Copper Mass PCB's, Thermally Challenging PCB's

INTRODUCTION

The challenge of soldering PCB's containing high copper mass is not new to the electronics manufacturing industry. Over the past two decades, however, facing this challenge has become increasingly common as the average PCB becomes more thermally challenging as a result of greater complexity.

With each increase of assembly complexity the process window for achieving sufficient vertical hole fill becomes more narrow and difficult to maintain. As a result, processes and practices which allow for reliable soldering of PCBs of 4 to 8 layers, with 100% vertical hole fill, will often yield 50% or less when applied to a PCB of 12 or more layers. To meet this challenge, many in the electronics manufacturing industry have turned to the selective solder.

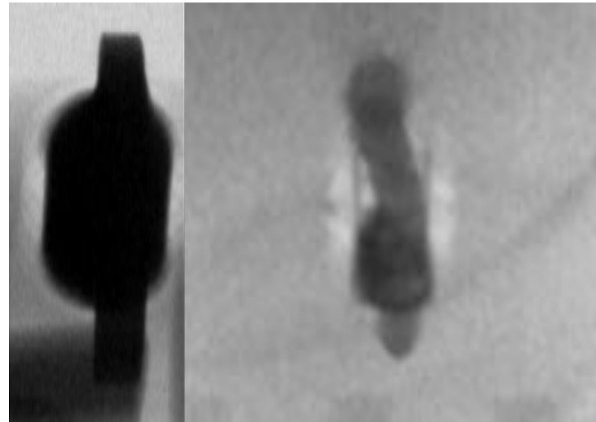

Figure 1, Comparison of Vertical Hole Fill on Low (Left) and High (Right) Thermal Mass Assemblies.

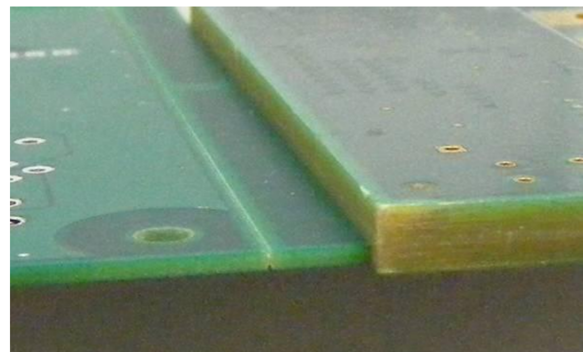

Figure 2, Comparison of Low and High Thermal Mass PCB Fabrication Thickness

There are numerous selective solder manufactures offering equipment with the potential to give greater control over all aspects of the soldering process than traditional wave machines. The flux delivery mechanism in selective soldering equipment has the ability to spray directed, custom quantities of flux on each lead of a PTH. Solder

pots and nozzles on movable gantry systems allow for precise placement of solder and customizable dwell times. No longer requiring selective wave pallets, the selective solder is able to substantially reduce thermal mass and allow for a more balanced pre-heat. Each of these controls potentially make selective solder, a process typically known for soldering difficult to access and temperature sensitive components [1], a valuable tool for soldering high thermal mass assemblies.

Regardless of the selective solder equipment in use, characterization of each of the machines systems, as well as understanding the interactions between systems, is critical when developing a process for thermally challenging boards. This paper will focus on a design of experiment to characterize the systems of a selective soldering machine for use on high thermal mass assemblies. The results of this experimentation have subsequently been used to successfully solder thermally challenging PCBs in excess of 20 layers and 40oz of copper.

Note: For the purpose of this paper selective soldering will refer to a machine with a fluxer mounted to a X, and Y gantry system, preheat, wet-able nozzle, and a solder pot on a X, Y, and Z gantry system.

TEST VEHICLE

A PCB mimicking hole to lead ratios and thermal connectivity of thermally challenging PCBs was developed as a test vehicle for the Design of Experiment (DoE). The test vehicle has an ENIG surface finish with hole to lead ratios at 1.3, 1.4, and 1.6, as well as thermal connectivity ranging from 0 to 30 watts per meter kelvin. Six PTH locations on each test vehicle were stuffed with ten pin male headers, with tin plated brass pins.

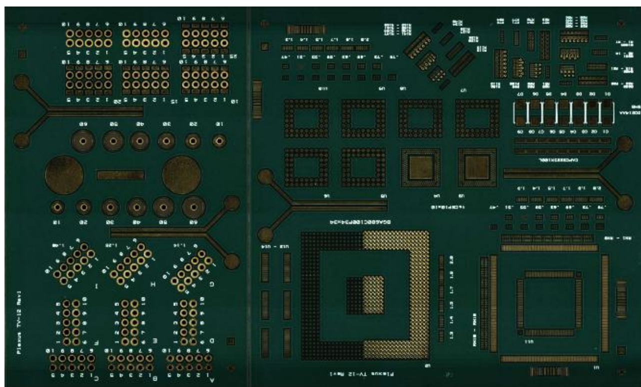

Figure 3, DoE Test Vehicle

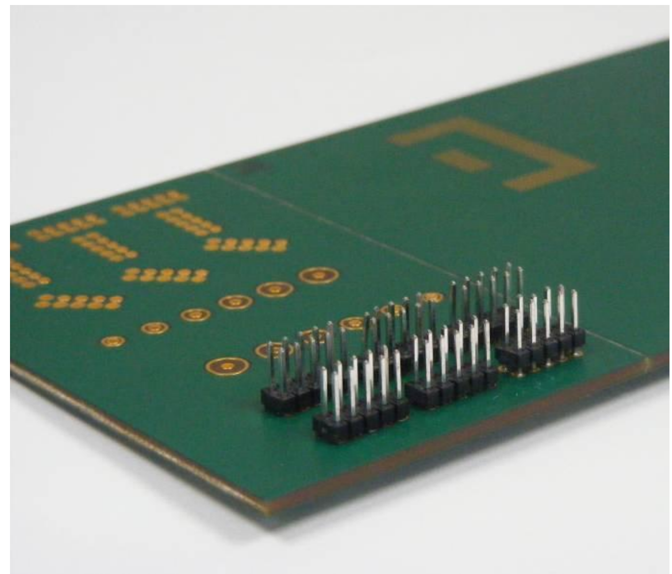

Figure 4, Components Placed in Test Vehicle

EXPERIMENTAL DESIGN

For the purpose of characterizing the selective soldering equipment, a quarter factorial DoE with a resolution of 4 was developed. Two settings for each of the following variables were explored: flux type, flux deposition, top side board temperature, time spent in the solder module, solder dwell time, and localized preheat time. Fixed parameters included: flux application pattern, wave height, solder wave peel off time, soldering method, solder pot temperature, nozzle size, and solder alloy. Each run exposed the test vehicle to different combinations of the variable settings. The DoE was completed with 16 soldering programs and 3 replications for a total 48 runs.

Variable	Setting 1	Setting 2
Flux Type	Flux 1	Flux 2
Flux Deposition	1000	3500
Top Side Board Temperature	110˚C	150˚C
Time Spent in Solder Module	336 Seconds	720 Seconds
Solder Dwell Time	3 Seconds	10 Seconds
Localized Preheat Time	0 Seconds	3 Seconds

Table 1, Design of Experiment Variable Settings

DESIGN OF EXPERIMENT EXECUTION

The machine used to complete the DoE was equipped with dual fluxer heads to allow both required fluxes to be run consecutively without changing the flux and purging the flux lines between runs. When the fluxes were loaded into their individual flux tanks the flux lines were charged and purged for a half hour.

Flux depositions were controlled using setting created in earlier experimentation. The earlier experimentation

consisted of measuring flux volumes per unit of time and spray widths at specific settings. From this data, in combination with fluxer travel speed, a table was created which gives the spray width and deposition for given machine settings. As each flux has its own flow characteristics and flux to carrier ratios, experimentation was completed and tables were created for both fluxes used in the DoE.

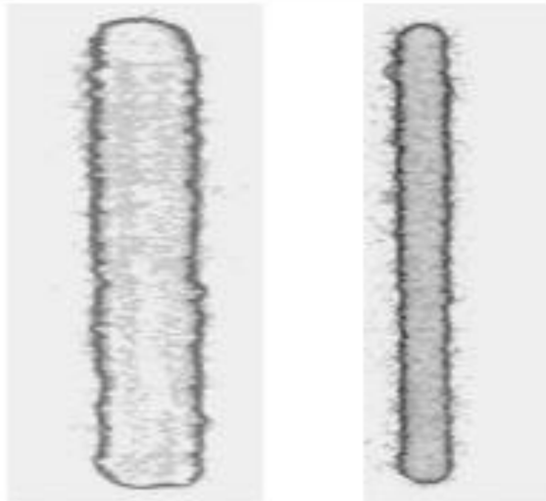

Figure 5, Comparison High (Left) and Low (Right) Spray Percentages at a Consistent Travel Speed.

Top side preheat board temperatures were obtained by attaching K-type thermocouples, using aluminum and kapton tape, to the top of the test vehicle and by using a data recorder to observe the temperatures during the preheat cycle. Using the data, the pre-heating program was adjusted until the desired temperatures were met. To avoid skin-effect measurements and ensure heat was permeating the entire thickness, the test vehicle was heated using only bottom side preheat. This exercise was performed for each of the required top side preheat board temperatures.

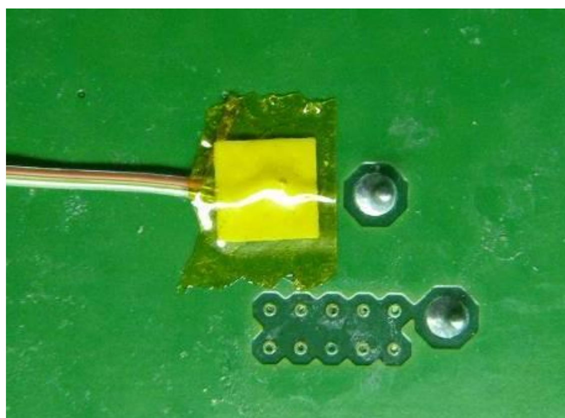

Figure 6, Thermocouple Attachment Method.

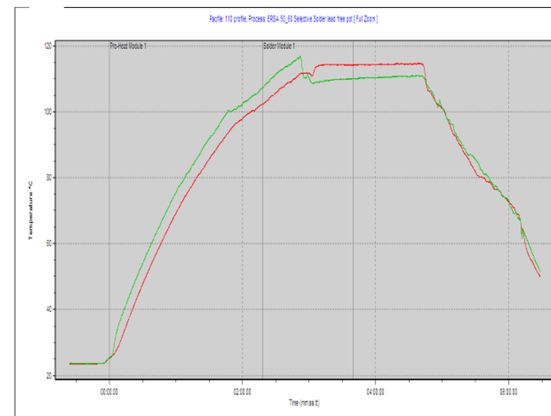

Figure 7, Top Side Board Temperature Thermal Profile.

Using top side solder module heaters to maintain PCB temperature during the soldering process, a soldering delay was added to the soldering program to achieve the correct time over solder module. The length of the delay was calculated by subtracting the total soldering time from the desired time over the solder module. The remaining time before soldering allowed the heaters to maintain the PCB board temperature and simulate extended soldering programs.

Localized preheats were completed by moving the solder nozzle to a location directly underneath a lead to be soldered. With a stable solder flow the nozzle was raised as close as possible to the bottom of the lead without having the meniscus of the solder contact the lead. After allowing heat to transfer, by nitrogen used to prevent dross formation on the wet-able nozzle, the solder nozzle was raised to a normal soldering position.

Figure 8, Localized Preheat

All soldering was completed as a point solder. When point soldering, the nozzle is moved to the correct soldering distance from lead. The wave height is then turned on to the correct height for soldering. After dwelling for a specific period of time the wave height is lowered inside the nozzle and the nozzle moves to the next location for soldering.

All 48 runs of the DoE were completed at random within a 24 hour time frame. After each program change a minimum of 15 minutes was given for all machine temperatures to normalize. There were no anomalies observed or recorded during the execution phase of the DoE.

DATA COLLECTION

After all runs of the execution phase of the DoE were completed, the test vehicles were subjected to 3D x-ray. Slices were x-rayed at 25% increment, for a total 5 slices per PTH location, and inspected for vertical hole fill. Data was then manually compiled and organized into a spread sheet for analysis.

Figure 9, 3D X-Ray Inspection Slice Image

ANALYSIS

The main tools used for analyzing the DoE data were Main Effects Plots, Pareto Chars of Standardized Effects, and Interaction Plots. Although these charts were created for each of the hole lead ratios and thermal connectivity combinations, this paper will only focus on the data collected for high thermal mass locations. This will limit the data sets to through holes locations with a thermal connectivity of 30 W/mk in combination with hole to lead ratios of 1.6 and 1.4.

Main Effects Plot

Means for vertical hole fill at the 1.6 hole to lead ratio ranged from approximately 40% to 60%. The most drastic improvement in vertical hole fill was observed as a result of flux selection. Usage of flux 2 showed a dramatic improvement in mean hole fill compared to flux 1. Increased flux deposition also yielded a notable mean vertical hole increase. The use of a localized preheat as well as increased solder dwell time offered only slight increases in vertical hole fill. Negative effects were observed in vertical hole fill as top side board temperature and time over the solder module increased.

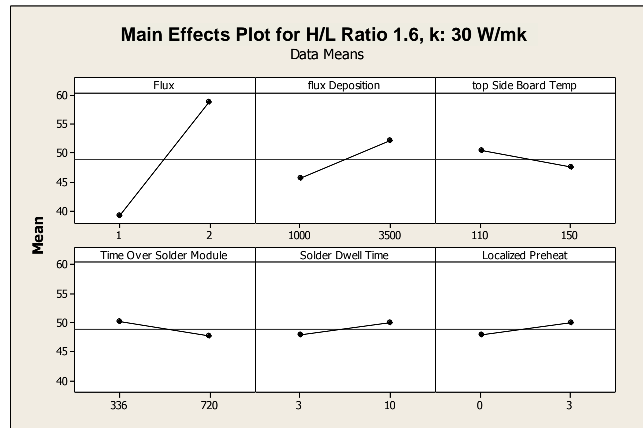

Figure 10, Main Effects Plot for Hole to Lead Ratio of 1.6 and 30 W/mk of Thermal Connectivity.

Means for vertical hole fill at the 1.4 hole to lead ratio ranged from approximately 65% to 95%. As with the 1.6 hole to lead ratio the most notable improvement in vertical hole fill was observed as a result of flux selection with flux 2 again producing the most desired results. Results for flux deposition, top side board temperature, time over solder module, and solder dwell time yielded results similar to the 1.6 hole to lead ratio. Localized preheat, however, was recorded to have a negligible effect on the mean vertical hole fill.

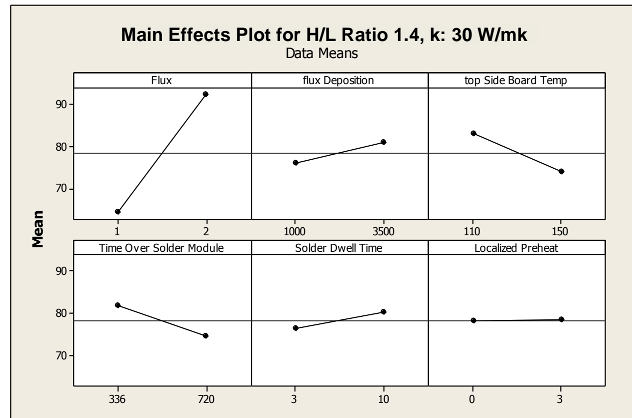

Figure 11, Main Effects Plot for Hole to Lead Ratio of 1.4 and 30 W/mk of Thermal Connectivity.

Interaction Plot

Several interactions were observed at the 1.6 hole to lead ratio. The top side board temperature showed interactions between the time over the solder module and localized preheat. The time over solder module and solder dwell time also interacted, as well as solder dwell time and localized preheat.

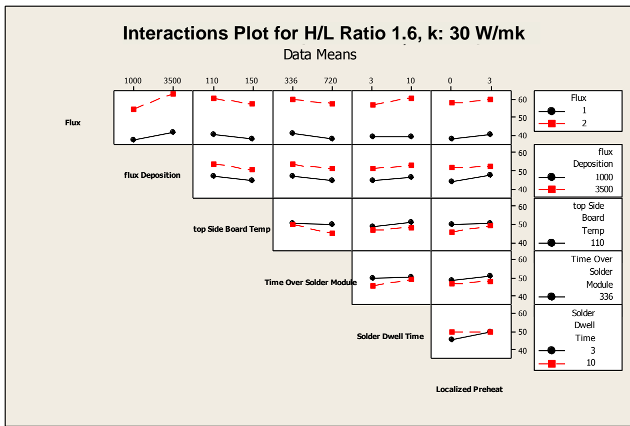

Figure 12, Interaction Plot for Hole to Lead Ratio of 1.6 and 30 W/mk of Thermal Connectivity.

Most interactions observed at the 1.4 hole to lead ratio were related to flux deposition. Flux deposition was shown to have interactions with the time over the solder module, solder dwell time, and localized preheat. Solder dwell time and localized preheat showed the only other interaction at the 1.4 hole to lead ration.

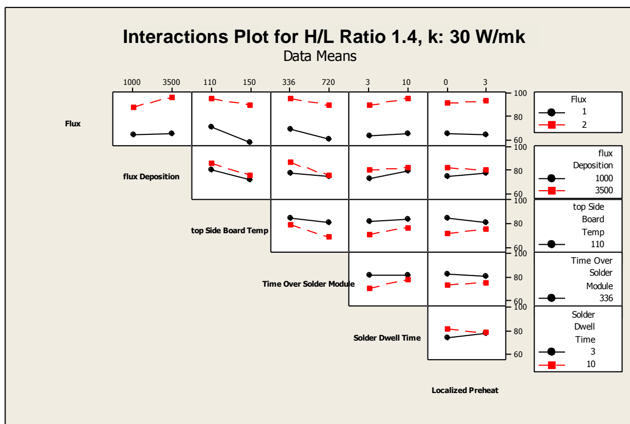

Figure 13, Interaction Plot for Hole to Lead Ratio of 1.4 and 30 W/mk of Thermal Connectivity.

Pareto of Standardized Effects

With a 95% degree of confidence (alpha .05) there were two factors at the 1.6 hole to lead ratio which showed statistical significance effects of vertical hole fill. The most significant effects on vertical hole fill was flux selection, which confirms observations made in the 1.6 hole to lead ration main effects plot. The other statistically significant factor was flux deposition, which is also in line with previous observations. No interactions were shown to be statistically significant.

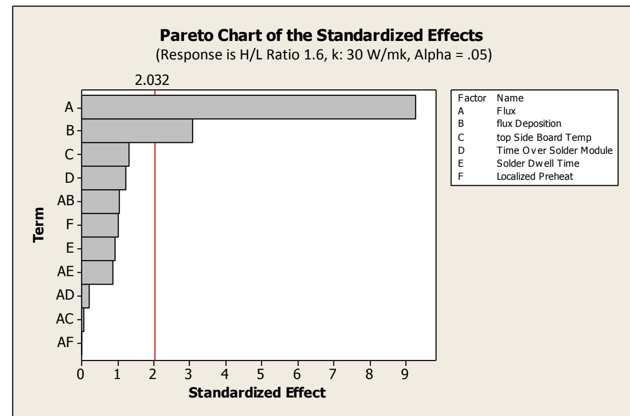

Figure 14, Pareto Chart of the Standardized Effects for Hole to Lead Ratio of 1.6 and 30 W/mk of Thermal Connectivity.

The Pareto of Standardized effects for the 1.4 hole to lead ration were also calculated with a 95% degree of confidence (alpha .05) and three factors were shown to have statistical significance. Flux selection was once again the most significant factor affecting vertical hole fill. Top side board temperature and time over solder module also show a statistical significance. Again, no interactions were shown to be statistically significant.

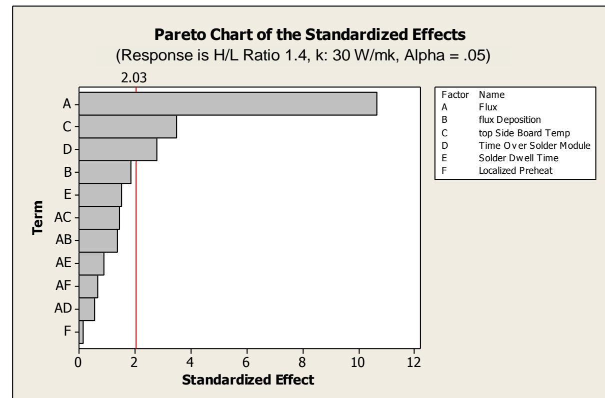

Figure 15, Pareto Chart of the Standardized Effects for Hole to Lead Ratio of 1.4 and 30 W/mk of Thermal Connectivity.

Optimization Model

An optimization model for the 1.6 hole to lead ratio was created with a target of 100% vertical hole fill but was only able to achieve 68.5%. Although the target was not achieved 68.5% hole fill can potentially be acceptable per IPC-A-610E if the PTH is connected to thermal or conductor layers that act as thermal heat sinks [2]. The optimized model used flux 2 with a high flux deposition. The model shows a minimized top side board temperature and the time over the solder module. These results are consistent with previous data. In addition, although both were considered statistically insignificant, solder dwell time was maximized and localized preheat was used.

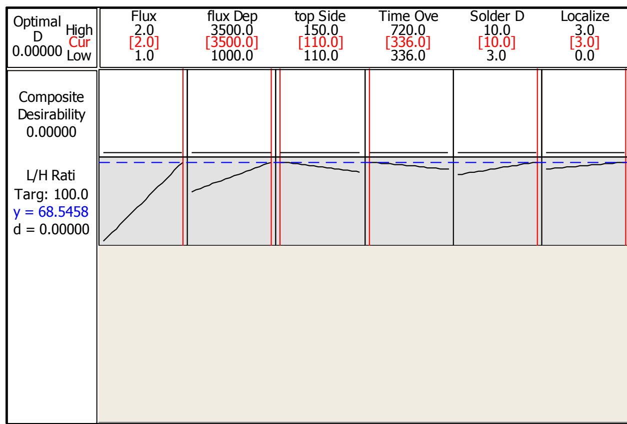

Figure 16, Optimization Model for Hole to Lead Ratio of 1.6 and 30 W/mk of Thermal Connectivity.

The optimization model for the 1.4 hole to lead ration was created with a target of 100% vertical hole fill and was able to achieve the target. The model shows consistent results with the model for 1.6 hole to lead ratio. Solder dwell time was optimized between the two variable settings while localized preheat was unused. The optimization model also indicates if localized preheat and the maximized solder dwell time were to be used vertical hole fill could surpass 100%.

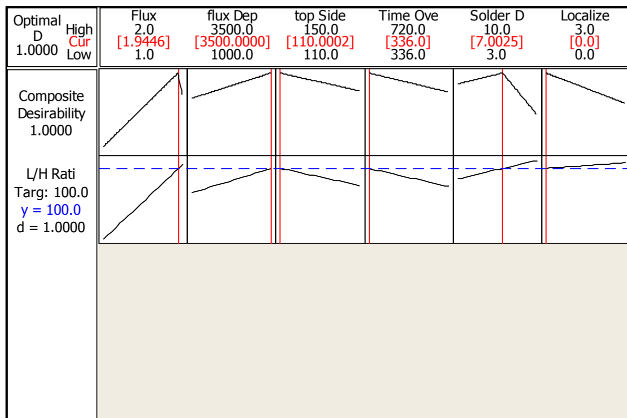

Figure 17, Optimization Model for Hole to Lead Ratio of 1.4 and 30 W/mk of Thermal Connectivity.

CONCLUSIONS

In order to achieve excellent vertical hole fill on thermally challenging assemblies, the data has shown there are many factors which must be considered. The most prominent of these factors is flux selection. Optimization modeling has shown increased flux deposition also has the potential to improve vertical hole fill.

Due to analyses of the main effects plots, negative effects of increased top side board temperature and time the over solder module have been revealed. Therefore, to increase vertical hole fill top side board temperatures and time of the solder module must be minimized. Confirmation of this is found in optimization modeling.

Through the Pareto charts of standardized effects, the effects of increased solder dwell time and localized preheat have been shown to be statistically insignificant. However, optimization models reveal these factors still play a role in achieving maximum vertical hole fill. Due to this, increased dwell time and localized preheat should be considered viable options for soldering a high thermal mass assembly.

INTRODUCTION OF ERROR

After analysis was completed, two observations were made which could have introduced error into the data collection. To create the different hole to lead ratios the size of the through hole drill diameter was changed while maintaining the lead size. While the diameter of the hole changed, the soldering pad size remained the same. By failing to scale the pad size with the hole size, thermal transfer characteristics between the pad and copper layers are not maintained, potentially introducing error.

In addition, each soldering program was written to solder all thermal connectivity and hole lead ratios on each test vehicle. It is possible soldering of one lead hole combination could transfer energy to unsoldered through hole locations. The additional thermal energy could have the potential to prematurely activate the flux and promote corrosion of the barrel or lead. This would then affect the maximum potential vertical hole fill for the soon to be solder connection. Because of this no definitive correlation can be made between through hole locations with different hole to lead ratios.

PROSPECTS FOR ADDITIONAL STUDY

Several variables related achieving optimal vertical hole fill on high thermal mass assemblies were not addressed in this paper, but warrant further study. The effects of the relationship between flux penetration, controlled by machine settings, to PCB thickness and hole to lead ratios on vertical hole fill could yield valuable data for the creation of fluxing programs. Study of effects of solder programming order on vertical hole fill could provide techniques for non-thermally balanced assemblies. Also, the effects of the relationship between hole to lead ratio and PCB thickness, especially when soldering with lead free solder, on vertical hole fill could provide data for new DFM guidelines.

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REFERENCES

[1] Niemeier J. and Seliger, G., “Simulation of the soldering process” *annals of the CIRP,* 47/1:27-30, (1998)
[2] IPC “IPC A-610E, Acceptability of Electronic Assemblies” (2010)