An Effective Design of Experiment Strategy to Optimize SMT Processes

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Abstract

It is now widely accepted that using designed experiments is the most effective way to optimize surface mount technology (SMT) processes. This situation begs the question "what is an effective strategy in implementing this powerful tool?" This paper will present such a strategy that incorporates Taguchi's approach for screening, full factorial analysis for optimization and central composite design for precise modeling. We will present these techniques using MINITAB^{TM} Release 13 statistical software and printed circuit board industry applications.

Key words: design of experiments, DOE, line optimization, continuous improvement, process modeling, process improvement.

Introduction

Some have argued, and we strongly support this sentiment, that the greatest invention of humankind is the experimental method. However, from the first systematic experiments by Galileo in the 1600s, 300 years were to pass before statistics were consistently combined with experiments. By the 1920s when designed experiments were coming into their own, the statistical analysis of experimental results was very difficult. Consequently, data collection was designed to simplify calculations. With modern tools like Minitab 13[i] the data analysis is quite simple, so the experiment is designed around minimizing the work involved in data collection. A recent course was developed at Dartmouth College, building on preliminary work from Binghamton University and Indium Corp., to clarify the most effective design of experiment (DOE) techniques for optimization of SMT assembly.

Many people, casually familiar with DOE, have heard of Taguchi designs, full and fractional factorial designs and central composite designs. We list two excellent references on DOE at the end of this paper.[ii] [iii] Our work, mentioned above, concluded that these different approaches could be systematically used together in an effective and simple approach to experiments relating to SMT assembly. This paper will be about this work and will use illustrative examples in its explanation.

DOEs: The Basics

The benefit of DOEs is the ability to analyze the effect or "response" of many factors and levels with a minimum amount of experimentation. Factors are the independent variables that are expected to affect the response whereas levels are the quantitative or qualitative settings which will be tested.

Examples of SMT factors in stencil printing would be the type of solder paste used, squeegee speed, stencil type, and stencil separation speed. The response might be printed "brick" volume. Examples of levels for the above factors would be three paste types, two squeegee speeds, three stencil types, and two separation speeds.

Full Factorial Designs

Full factorial designs (FFDs) use all factors at all levels. FFDs can quickly become quite large. Consider the aforementioned printing experiment. The total number of "runs" that we would have to perform for one replicate (one experiment at each condition) would be:

Number of Runs = 3 x 2 x 3 x 2 = 36

For an experiment with many factors, the number of runs can be impractical. With 10 factors at four levels each, the total number of runs required is:

Number of Runs = 4^{10} = 1,048,576

This inordinate amount of work has driven the development in techniques for screening experiments, of which some of the most common designs were proposed by Taguchi.

Taguchi Designs

Let's assume we have an experiment with 8 factors, each with 3 levels. A full factorial design would require:

Number of Runs = 3^8 = 6,561 runs

Taguchi developed an approach following the work of Plackett-Burman and Latin square fractional factorial designs that enables the user to evaluate the effect of these 8 factors with only 27 runs. In this analysis, Taguchi calculates a metric called the signal-to-noise ratio to determine the effects of the factors. While Taguchi designs (TD) do not provide as much statistical information as FFDs, they are ideal to screen the factors to determine which are most important. A smaller FFD can then be performed to determine a more precise model of the effects of the significant factors.

Central Composite Designs

Many experimenters will find an approach of TDs for screening and FFDs for more detailed analysis of the effects of the factors adequate. A third approach called central composite designs (CCDs) can be used to find very accurate models of the effects of critical factors. CCDs are three level designs that are weighted with data points near the center of the factor levels.

Let's now use these three approaches to design and analyze SMT experiments.

SMT Printing DOE

Voiding on ball grid arrays (BGAs) has become a problem on an assembly line, so a four factor, four level experiment is to be performed to minimize BGA voiding. The factors are solder paste brand (1, 2, 3, 4), temperature profiles (A, B, C, D), storage humidity (0, 20, 40, 60 %RH) and solder paste type (2, 3, 4, 5).

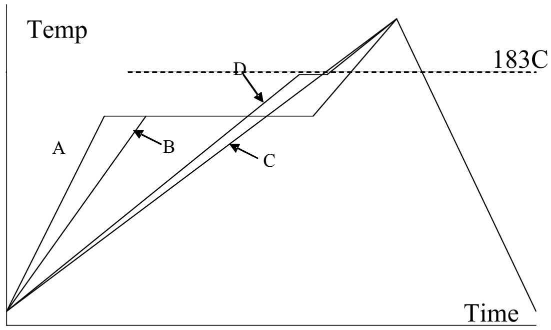
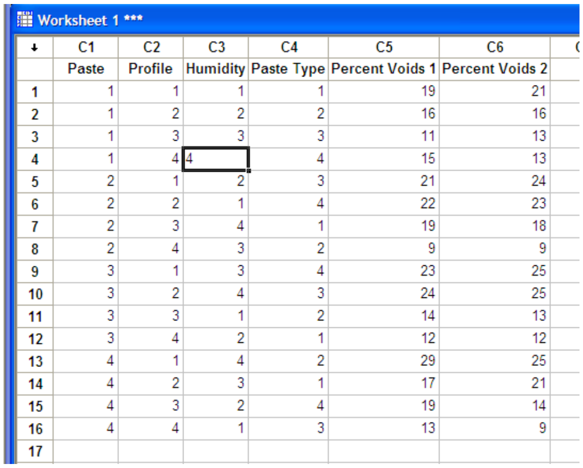


Figure 1 - The four reflow profiles used in the Taguchi experiment.

A full factorial experiment would require 4^4 = 256 runs. A Taguchi L_{16} screening experiment requires only 16 runs. We will perform two replicates (two runs at each experimental condition) to obtain greater precision in the analysis. Although the data used, shown in Figure 2, are not real, the data were generated from observed industry trends.



↓	C1	C2	C3	C4	C5	C6
	Paste	Profile	Humidity	Paste Type	Percent Voids 1	Percent Voids 2
1	1	1	1	1	19	21
2	1	2	2	2	16	16
3	1	3	3	3	11	13
4	1	4	4	4	15	13
5	2	1	2	3	21	24
6	2	2	1	4	22	23
7	2	3	4	1	19	18
8	2	4	3	2	9	9
9	3	1	3	4	23	25
10	3	2	4	3	24	25
11	3	3	1	2	14	13
12	3	4	2	1	12	12
13	4	1	4	2	29	25
14	4	2	3	1	17	21
15	4	3	2	4	19	14
16	4	4	1	3	13	9
17						

Figure 2 - Minitab 13 data input for the Taguchi L_{16} analysis of BGA voids.

The Minitab 13 analysis is shown in Figure 3.

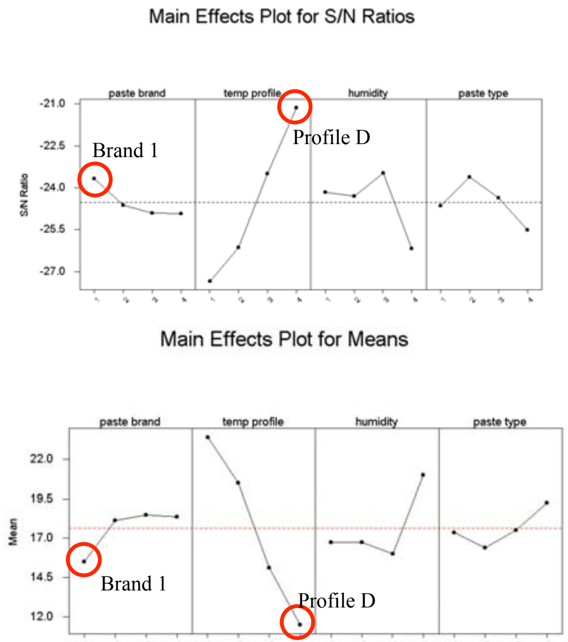


Figure 3 - The Minitab analysis of the Taguchi L_{16} experiment. The smaller magnitude S/N ratio and mean are both favorable.

Table 1 - The data from replicate 1 of the full factorial experiment.

RH	Paste Type	Percent Voids
1	1	11.0
1	2	10.7
1	3	9.7
1	4	11.7
2	1	10.6
2	2	10.6
2	3	11.4
2	4	14.5
3	1	12.9
3	2	12.3
3	3	12.5
3	4	15.8
4	1	11.5
4	2	11.9
4	3	13.9
4	4	14.2
5	1	14.4
5	2	13.8
5	3	13.1
5	4	16.4

Table 1 shows the data of the first replicate of the full factorial experiment. All three replicates were analyzed by Minitab 13. The results of this analysis indicated that there was greater than a 99.9% probability that RH and paste type affected the void content. The averages of the data versus RH and paste type are shown in the Main Effects graph in Figure 4. These graphs suggest convincingly that both RH and paste type affect void formation. However, for paste types 2, 3 and 4 there appears to be no significant difference. The data suggest that by using these paste types and the lowest storage humidity possible, voids in BGA assembly will be minimized. The data also show a disadvantage in Taguchi analysis: the effect on voids at low RH was not detected with Taguchi's approach. Apparently, the small number of data points caused the RH-void relationship to be "lost in the noise."

Figure 4 - The Main Effects Plot for the full factorial experiment.

Central Composite Designs

Our BGA void experiment does not lend itself strongly to central composite designs (CCDs). CCDs are typically used when a precise relationship is desired between a response and the controlling factors.

Arguably, the most important metric in successful SMT assembly is precise volume control of the printed solder paste "brick." This type of experiment lends itself well to CCD. Let's assume we have a stencil aperture of 2000 cubic mils and we want to determine the effects of print head speed and separation speed on the printed brick volume. Total print speed is also an issue, so previous screening experiments have indicated that less than 8 to 9 inches per second (ips) print head speed and a separation speed of greater than 1 second are required to achieve our objective of 1925 +/- 75 mils^3.

Table 2 - The factor input and one response replicate for the stencil printing CCD.

Variables		Response
Print Speed	Seperation Speed	Printed Volume
6	0.8	1915.4
6	1.2	1929.3
10	0.8	1870.8
10	1.2	1892.7
8	1	1901.0
8	1	1900.4
8	1	1899.9
8	1	1899.7
8	1	1902.1
10.828	1	1872.7
5.172	1	1932.0
8	1.28	1919.0
8	0.72	1893.6
6	0.8	1910.3
6	1.2	1935.5

These preliminary results suggested that our CCD wants to center around a print speed of 8 ips and 1 second separation speed. We perform a 3 replicate CCD, with the factors shown in Table 2.

Minitab 13 analysis tells us that the relationship between printed brick volume (PV) and the print head speed (PS) and separation speed (SS) is:

$$PV = 1905 - 9.35\ PS + 105.1\ SS\ (\text{mils}^3) \qquad \text{[Eq. 1]}$$

The statistical confidence of the coefficients in equation 1 is greater than 95%. Since we want our printed brick volume to be greater than 1925 mils^3, the equation suggests that with an SS of 1.0 seconds and PS of 8 ips, we are dangerously close to our lower limit of 1925 at 1935.3 mils^3. Further statistical process control data collection experiments would be desired to refine the confidence of the above equation and support the 1925 mils^3 minimum requirement. However, the above equation is a good start down this road as shown by a normal probability plot of the residuals (actual value minus the value calculated from equation 1) shown in Figure 7. The normality of residuals indicates that the variation from the model may be attributed to experimental error.

Figure 5 - A probability plot of the residuals.

Conclusion

This paper provided a very brief overview of optimizing SMT processes through a series of designed experiments using Minitab 13 for statistical analysis. Because the number of runs is typically a key consideration and several replicates of each experiment are desired, it is important to choose an appropriate design of experiment.

Taguchi designed screening experiments were used to reduce the number of factors and levels to be tested in a subsequent full factorial experiment. Full factorial designed experiments provided statistical support of results and uncovered relationships hidden in the screening experiment. Central composite designs were used for models requiring greater accuracy in the model for quantitative factors.

Combinations of these designs allowed us to optimize SMT processes to target values in an experimentally efficient manner.

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[i] Information on Minitab 13 can be obtained from Minitab.com. A 30 day free trail of the software is available as a download.

[ii] Montgomery, D. C., *Design and Analysis of Experiments*, 5th edition, Wiley, NY, 2001.

[iii] Schmidt, Launsby, *Understanding Industrial Designed Experiments,* 4th edition, Air Academy Press, Colorado Springs, 2000.