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# Application of Taguchi Method for Optimization of Wave Soldering Process Parameters

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**Abstract -** **This paper highlights the application of Taguchi's orthogonal array (OA) experimentation for arriving at the optimum process parameter combination to keep the number of solder defects in printed circuit board (PCB) found after wave soldering, at a minimum level. Wave soldering machine provides technically a better substitute over the hand soldering process. The process parameters viz. solder temperature, contact time, preheat temperature setting, board thickness and wet flux amount need to be maintained at the optimum levels to get best results. Optimization helps in finding out and isolating the "effect of uncontrollable factors" and exploring the possible measures to counter them. The Design of Experiments method enables us to plan an experiment that simultaneously alters a number of variables in an experimental set-up to see how they interact with each other and affect responses. An experiment consists of testing combinations of different values (termed levels) of factors is likely to influence the characteristic (called response) of interest. If the factors are not independent, their interaction may also be considered. For experimentation, the effects on the five factors -- Solder Temperature (A), Contact Time (B), Preheat temperature (C), Board Thickness (D) and Wet Flux Amount (E) at three levels each, are simultaneously investigated by using the Taguchi Orthogonal Array experiments and analysis of variance (ANOVA). Some of the interactions are also to be considered. Hence, $L_{27}$ ($3^5$) orthogonal array design is chosen. The design has 5 factors at 3 levels each. Finally, signal-to-noise ratios, analysis of variance and response surface regression is carried out for analyzing the results and for obtaining insight into the process as a whole.**

*Key Words:* **Optimization, Design of Experiments (DOE), Orthogonal Arrays (OA), Signal-to-Noise Ratio, Analysis of Variance (ANOVA), Response Surface Regression.**

## 1. Introduction

To improve the quality of products design of experiment (DOE) methods have been widely used by industries. A DOE experiment can simultaneously alter a number of variables in an experimental system to see how they affect the responses [1]. Although the design of experiments concept was introduced by Fisher in the early 1920s, the most research on this topic was carried out in the academic environment [2]. The usefulness of DOE concept in agricultural experiments was demonstrated by Fisher [3] and he analyzed the optimum water, rain, sunshine, fertilizer, and soil conditions needed to produce the best crop. Taguchi [4] went further with the design of experiment concept by introducing his approach in 1986. The Taguchi approach is a special form of DOE with applications in manufacturing industries. The overall objective of the experiments is to make comparisons between the effects of different factors and then determine the best setting for each factor.

The wave soldered PCBs undergo various stages of testing or inspection and generally it is observed that no PCB is passed without some rework for soldering defects. Wu and Hamada [5] discussed a two-level factorial experiment to study the number of defects in a wave soldering process. Although there are many defects found in wave soldering process, however, Insufficient hole fill is seen as a major problem that occurs on PCBs with pre-drilled holes for components to be set or mounted onto the board. Normally, insufficient hole fill occurs when an inadequate amount of solder has covered the holes drilled for the components, meaning solder won't stick to the circuit board once it cools down. This problem may appear as a result of a temperature variations in the process setting and board problem. Wave soldering process has following variables that control the level of defects:

A = Solder Temperature ($^0$C); B= Contact time (s); C = Preheat Temperature ($^0$C);

D = Board Thickness (inches); E= Wet Flux Amount (mg/dm$^2$)

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The method proposed in this study uses an approach from robust design. Taguchi's design of experiment method using orthogonal arrays is used to determine the "optimal settings" of the discrete design parameters. In this paper, the optimal process parameters for a wave soldering process have been obtained using Taguchi Methods.

## 2. Literature Review

### DOE and Taguchi's Orthogonal Arrays in Optimization:

A full factorial experiment combines the levels of each factor with each of the levels of all the remaining factors. It is possible to estimate interactions between factors using the full factorial design. However, the no. of experiments in this design become very large as the number of factors and levels increases.

The Taguchi method enables to plan experiments using a specially designed "Orthogonal Array" table to affect the design process, such that quality is built into a product during its design stage. For a multi-factor process, it is a very good technique for designing and executing experiments to investigate the processes without tediously and uneconomically running the process with all possible combinations of values. For most experiments carried out in the industry, the difference between the DOE and Taguchi approach is in the method of application [6]. Taguchi method reduces the number of experimental runs to maximum extent in terms of cost and time by making use of orthogonal arrays [7]. Due to systematically chosen combinations of variables it is possible to separate their individual effects. Taguchi method tests pairs of combinations instead of testing all possible combinations like the factorial design. The Factorial analysis can be used in order to find the best values for parameters to be used in the manufacturing process [8].

### Orthogonal Array:

An orthogonal array is an experimental design constructed to allow a mathematically independent assessment of the effect of the different factors affecting the experiment. OA is the matrix of numbers arranged in columns and rows [9]. These arrays allow for the maximum number of main effects to be estimated in an unbiased (orthogonal) manner, with a minimum number of runs in the experiment. Orthogonal arrays are used to design experiment and describe trial conditions.

The most suitable orthogonal array for experimentation in this case is $L_{27}(3^5)$ array as shown in Table 1. Therefore, a total twenty seven experiments are to be carried out. As depicted in the Table 1, the L-27 experiment consists of 27 rows and 5 columns where each row corresponds to a particular trial and each column identifies settings of experimental factors. In the first trial, for example, the five experimental factors are set at their low level (level = 1). In the second trial, the first 4 factors are set at level 1 and the remaining one factor is set to level 1, and so on.

| Run | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 2 |
| 3 | 1 | 1 | 1 | 1 | 3 |
| 4 | 1 | 2 | 2 | 2 | 1 |
| 5 | 1 | 2 | 2 | 2 | 2 |
| 6 | 1 | 2 | 2 | 2 | 3 |
| 7 | 1 | 3 | 3 | 3 | 1 |
| 8 | 1 | 3 | 3 | 3 | 2 |
| 9 | 1 | 3 | 3 | 3 | 3 |
| 10 | 2 | 1 | 2 | 3 | 1 |
| 11 | 2 | 1 | 2 | 3 | 2 |
| 12 | 2 | 1 | 2 | 3 | 3 |
| 13 | 2 | 2 | 3 | 1 | 1 |
| 14 | 2 | 2 | 3 | 1 | 2 |
| 15 | 2 | 2 | 3 | 1 | 3 |
| 16 | 2 | 3 | 1 | 2 | 1 |
| 17 | 2 | 3 | 1 | 2 | 2 |
| 18 | 2 | 3 | 1 | 2 | 3 |
| 19 | 3 | 1 | 3 | 2 | 1 |

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| | | | | | |
|---|---|---|---|---|---|
| 20 | 3 | 1 | 3 | 2 | 2 |
| 21 | 3 | 1 | 3 | 2 | 3 |
| 22 | 3 | 2 | 1 | 3 | 1 |
| 23 | 3 | 2 | 1 | 3 | 2 |
| 24 | 3 | 2 | 1 | 3 | 3 |
| 25 | 3 | 3 | 2 | 1 | 1 |
| 26 | 3 | 3 | 2 | 1 | 2 |
| 27 | 3 | 3 | 2 | 1 | 3 |

**Table 1. Standard L27 ($3^5$) orthogonal array**

The Taguchi method is used whenever the settings of interest parameters are necessary for manufacturing processes. Therefore, the Taguchi approach is used in many domains such as: environmental sciences [10, 11], agricultural sciences [12], physics [13], chemistry [14], statistics [15], management and business [16], medicine [17]. The challenge is to choose the proper orthogonal array suitable for the given problem of interest. The best use of Taguchi method comes with approximately an intermediate number of variables (3 to 50), with few interactions between variables, and when only a few variables contribute significantly and hence Taguchi is the preferable method among statistical experimental design methods [18].

### 3.1 Objectives of the Study

The objectives of the study are as under:

- Identifying the significant wave soldering parameters that most affect the process.
- Effect of these parameters on the quality of wave soldering with particular emphasis on insufficient solder fill and filling time.
- Optimum level of wave soldering process control parameters in order for setting-up of process & recommending the same for future production.

### 3.2 Preparation of Taguchi Experiment

The following needs to be established before starting Taguchi experiments - clear statements of problems, objectives, desired output characteristics and the method of measurement used to design the appropriate experiment. Afterwards, all the process parameters are identified and relevant factors affecting the outcome are defined. The two such important factors are:

- **Controllable factors**

These are set factors, but are not or can not be measured in-process so their variance is assumed to be zero or, if they are measured in-process, their variance is so small that it has a little effect on process performance. The mean of these controllable variables in-process should ideally be the same as their input set points and analysis of empirical data can be used to establish the nature of the functional relationship. The controllable factors in the study are as under:

A = Solder Temperature (C); B= Contact time (s); C = Preheat Temperature (C); and D = Board Thickness (inches); E= Wet Flux Amount (mg/dm$^2$)

- **Noise Factors**

Noise factors are various process variables that affect variation, but are not identifiable nor controllable. Changes in environment temperature, humidity, dust etc., during the production/experiment, are some of the examples of noise. No 'noise' element was factorized into the experiment for practical reasons.

### 3.3 Choice of Experimental Factors and Levels

The factors most affecting the outcome is due to Wave Soldering Machine Parameters. Accordingly, out of a number of possible parameters only four machine parameters were selected for experimentation: Solder Temperature(A), Contact Time(B), Preheat Process Temperature(C), Board Thickness (D) and Wet Flux Amount (E). Some of the interactions AXB, AXC and BXC are also studied under response surface regression. The material and environment related factors can be maintained at the most desirable conditions or can be treated as fixed.

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### 3.4 Experimental Layout and Design

According to Resit et al. [19], quality and cost are the two main ingredients in Taguchi's approach to design optimization. In order to create and analyze the experimental runs, signal to noise ratio and orthogonal arrays are two major tools used in this robust design. This study makes use of both the tools. The experimental design is shown in Table-1. Experiments were conducted using Taguchi's method with five factors at three levels each. The factors and their levels are shown in Table 2.

| Factors | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| A. Solder temperature ($^0$C) | 250 | 265 | 275 |
| B. Contact time(s) | 2 | 4 | 7 |
| C. Preheat Temperature ($^0$C) | 90 | 110 | 130 |
| D. Board Thickness(inches) | 0.063 | 0.122 | 0.236 |
| E. Wet Flux Amount (mg/dm$^2$) | 350 | 470 | 580 |

**Table 2. Factors and levels**

It is planned to study the effect of five main factors and their interactions. The $L_{27}(3^5)$ orthogonal arrays which provides the required number of degrees of freedom is selected. This array consists of 27 rows each representing an experiment with 5 factors at three levels.

Main effect is the change in the average response of a factor. Randomization and replication principles are to be followed in experimental trials to eliminate the effect of systematic changes.

It is possible to investigate the main and interaction effects of the factors and their levels using Taguchi experiments and response surface regression. These experiments are useful because they require much fewer runs, though they do not allow the separation of main effects from high-order interactions.

### 3.5. Analysis of Variance for Orthogonal Array Analysis

For the test, 27 experimental runs were conducted to obtain the data needed for orthogonal array analysis to achieve the following objectives:

- To estimate the significance of individual quality influencing factors.
- To obtain the optimum settings for process.
- To determine the variation each control parameter has contributed.

A commonly applied statistical technique- The Analysis of Variance (ANOVA) is used to analyze the results of the OA experiment in product/process design, and to determine how much variation each process parameter has contributed. The main effects for each of the factors projects the general trend in the influencing factors. In a particular quality influencing factor, a lower or a higher value produces the preferred result. Thus, the optimum levels of influencing factors to produce the best outcome can be predicted.

ANOVA has been used to determine the influence of the main factors and their various levels.

## 4. Results and Discussion

The analysis of variance (ANOVA) and S/N ratio were evaluated to determine the effect of each selected factor on the optimization criteria. For these analyses, the Minitab14 software was utilized. The results of the ANOVA for SN ratios for determination of significant factors are shown in Section 4.1.3. In general, the F values would indicate the importance of these variables in the wave soldering process.

### 4.1 Linear Model Analysis: SN ratios versus Solder Temperature, Contact Time, Preheat Temperature, Board Thickness and Wet Flux Amount

#### 4.1.1 Estimated Model Coefficients for SN ratios

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|
| Constant | -35.4757 | 0.01965 | -1805.129 | 0.000 |

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| | | | | |
|---|---|---|---|---|
| Solder T 250 | 0.5773 | 0.02779 | 20.770 | 0.000 |
| Solder T 265 | 0.0901 | 0.02779 | 3.241 | 0.005 |
| Contact 2 | 0.2001 | 0.02779 | 7.198 | 0.000 |
| Contact 4 | -0.0003 | 0.02779 | -0.010 | 0.992 |
| Preheat 90 | -0.0873 | 0.02779 | -3.141 | 0.006 |
| Preheat 110 | 0.0435 | 0.02779 | 1.564 | 0.137 |
| Board Th 0.063 | -0.0646 | 0.02779 | -2.325 | 0.034 |
| Board Th 0.122 | 0.0174 | 0.02779 | 0.625 | 0.541 |
| Wet Flux 350 | 0.1057 | 0.02779 | 3.804 | 0.002 |
| Wet Flux 470 | -0.0633 | 0.02779 | -2.279 | 0.037 |

### 4.1.2 Model Summary

| S | R-Sq | R-Sq(adj) |
|---|---|---|
| 0.1021 | 97.99% | 96.73% |

### 4.1.3 Analysis of Variance for SN ratios

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Solder Temperature(C) | 2 | 7.08043 | 7.08043 | 3.54021 | 339.48 | 0.000 |
| Contact Time(s) | 2 | 0.71940 | 0.71940 | 0.35970 | 34.49 | 0.000 |
| Preheat Temperature(C) | 2 | 0.10292 | 0.10292 | 0.05146 | 4.93 | 0.021 |
| Board Thickness(inches) | 2 | 0.06039 | 0.06039 | 0.03019 | 2.90 | 0.084 |
| Wet Flux Amount(mg/dm$^2$) | 2 | 0.15288 | 0.15288 | 0.07644 | 7.33 | 0.005 |
| Residual Error | 16 | 0.16685 | 0.16685 | 0.01043 | | |
| Total | 26 | 8.28287 | | | | |

## 4.2 Linear Model Analysis: Means versus Solder Temperature(C), Contact Time(s), Preheat Temperature(C), Board Thickness(inches), Wet Flux Amount(mg/dm$^2$):

### 4.2.1 Estimated Model Coefficients for Means

| Term | Coef | SE Coef | T | P |
|---|---|---|---|---|


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| | | | | |
|---|---|---|---|---|
| Constant | 43.5417 | 0.095 78 | 454.616 | 0.000 |
| Solder T 250 | -2.5272 | 0.135 45 | -18.658 | 0.000 |
| Solder T 265 | -0.5383 | 0.135 45 | -3.974 | 0.001 |
| Contact 2 | -0.9533 | 0.135 45 | -7.038 | 0.000 |
| Contact 4 | 0.0000 | 0.135 45 | 0.000 | 1.000 |
| Preheat 90 | 0.3911 | 0.135 45 | 2.888 | 0.011 |
| Preheat 110 | -0.1517 | 0.135 45 | -1.120 | 0.279 |
| Board Th 0.063 | 0.3294 | 0.135 45 | 2.432 | 0.027 |
| Board Th 0.122 | -0.1294 | 0.135 45 | -0.956 | 0.353 |
| Wet Flux 350 | -0.4856 | 0.135 45 | -3.585 | 0.002 |
| Wet Flux 470 | 0.3011 | 0.135 45 | 2.223 | 0.041 |

### 4.2.2 Model Summary

| S | R-Sq | R-Sq(adj) |
|---|---|---|
| 0.497 7 | 97.69 % | 96.25% |

### 4.2.3 Analysis of Variance for Means

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Solder Temperature(C) | 2 | 144.66 9 | 144.6 69 | 72.334 3 | 292.0 5 | 0.00 0 |
| Contact Time(s) | 2 | 16.359 | 16.35 9 | 8.1796 | 33.03 | 0.00 0 |
| Preheat Temperature(C) | 2 | 2.100 | 2.100 | 1.0499 | 4.24 | 0.03 3 |
| Board Thickness(inches) | 2 | 1.488 | 1.488 | 0.7438 | 3.00 | 0.07 8 |
| Wet Flux Amount(mg/dm$^2$) | 2 | 3.244 | 3.244 | 1.6220 | 6.55 | 0.00 8 |
| Residual Error | 16 | 3.963 | 3.963 | 0.2477 | | |
| Total | 26 | 171.82 2 | | | | |

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**Discussion:**

In the variance analysis for S/N ratios (section 4.1.3), SS stands for sum of squares (factors) between groups and the sum of squares in the group (error). MS stands for sum of squares divided by the number of degrees of freedom of the mean square, F stands for test statistics, p stands for significance level. If p value is smaller, the influence is more significant. When the general P value is less than 0.05, it just means the factor has a significant effect. Thus, the factors which are less than 0.05 in the analysis of variance (for S/N ratios) are significant. Similar conclusion can be drawn with regard to section 4.2.3, where the factors solder temperature, contact time, preheat temperature and wet flux amount are significant.

**4.3 Signal to Noise Ratios:**

**Response Table for Signal to Noise Ratios**

Nominal is best (-10×Log10(s^2))

| Level | Solder Temperature(C) | Contact Time(s) | Preheat Temperature(C) | Board Thickness(inches) | Wet Flux Amount(mg/dm$^2$) |
|---|---|---|---|---|---|
| 1 | -34.90 | -35.28 | -35.56 | -35.54 | -35.37 |
| 2 | -35.39 | -35.48 | -35.43 | -35.46 | -35.54 |
| 3 | -36.14 | -35.68 | -35.43 | -35.43 | -35.52 |
| Delta | 1.24 | 0.40 | 0.13 | 0.11 | 0.17 |
| Rank | 1 | 2 | 4 | 5 | 3 |

**Response Table for Means**

| Level | Solder Temperature(C) | Contact Time(s) | Preheat Temperature(C) | Board Thickness(inches) | Wet Flux Amount(mg/dm$^2$) |
|---|---|---|---|---|---|
| 1 | 41.01 | 42.59 | 43.93 | 43.87 | 43.06 |
| 2 | 43.00 | 43.54 | 43.39 | 43.41 | 43.84 |
| 3 | 46.61 | 44.49 | 43.30 | 43.34 | 43.73 |
| Delta | 5.59 | 1.91 | 0.63 | 0.53 | 0.79 |
| Rank | 1 | 2 | 4 | 5 | 3 |

**Discussion:**

The ranks in a response table identify which factors have the largest effect. The factor with the largest delta value is given rank 1, the factor with the second largest delta is given rank 2, and so on. Thus, in the response table for Signal to Noise Ratios and for Means, solder temperature is ranked 1, contact time ranked 2, followed by factors 3, 4 and 5.

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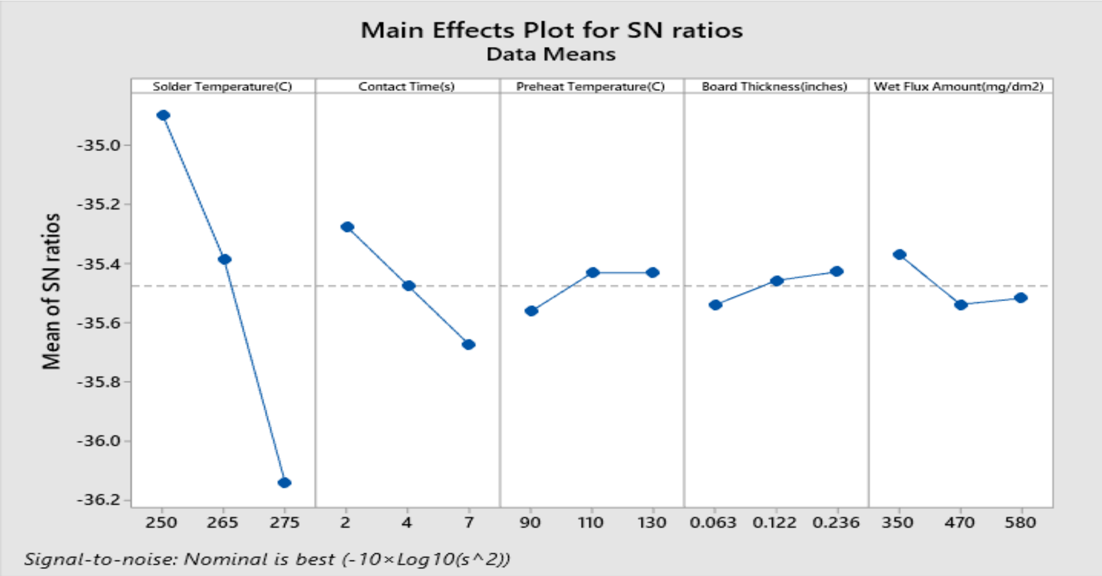


Figure-1 Main Effects Plots for SN Ratios

The main effects of independent variables (A, B, C, D and E) on the responses $R_1$ and $R_2$, of using Taguchi method, are shown in Figure 1. Figure 1 illustrates the average of S/N ratios for each variable at the three different levels and the corresponding response variables.

In case of response variables $R_1$ and $R_2$, as illustrated in Figure 1, the variables are highly dependent on solder temperature, contact time, preheat setting and wet flux amount, i.e. changing one of these settings will have the most dramatic effect on output.

### 5.1 Response Surface Regression with $R_1$:

**Coded Coefficients**

| **Term** | **Coef** | **SE Coef** | **T-Value** | **P-Value** | **VIF** |
|---|---|---|---|---|---|
| Constant | 85.068 | 0.340 | 250.01 | 0.000 | |
| Solder Temperature(C) | 6.726 | 0.508 | 13.23 | 0.000 | 1.88 |
| Contact Time(s) | 2.020 | 0.731 | 2.76 | 0.015 | 3.88 |
| Preheat Temperature(C) | -1.673 | 0.680 | -2.46 | 0.027 | 3.31 |
| Board Thickness(inches) | -2.15 | 1.06 | -2.03 | 0.062 | 8.28 |
| Wet Flux Amount(mg/dm$^2$) | 0.763 | 0.379 | 2.01 | 0.064 | 1.03 |
| Solder Temperature(C)*Contact Time(s) | -2.34 | 1.18 | -1.98 | 0.068 | 6.91 |
| Solder Temperature(C)*Preheat Temperature(C) | -0.09 | 1.26 | -0.07 | 0.946 | 7.77 |
| Solder Temperature(C)*Wet Flux | - | 0.455 | -1.06 | 0.309 | 1.0 |

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| | | | | | |
|---|---|---|---|---|---|
| Amount(mg/dm$^2$) | 0.480 | | | | 1 |
| Contact Time(s)*Preheat Temperature(C) | 2.452 | 0.769 | 3.19 | 0.007 | 2.88 |
| Contact Time(s)*Wet Flux Amount(mg/dm$^2$) | 0.340 | 0.455 | 0.75 | 0.466 | 1.01 |
| Preheat Temperature(C)*Wet Flux Amount(mg/dm$^2$) | 0.266 | 0.458 | 0.58 | 0.571 | 1.00 |
| Board Thickness(inches)*Wet Flux Amount(mg/dm$^2$) | 0.113 | 0.450 | 0.25 | 0.805 | 1.02 |

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 1.58552 | 95.23% | 91.14% | 81.66% |

**5.1.1 Analysis of Variance**

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 12 | 702.582 | 58.549 | 23.29 | 0.000 |
| Linear | 5 | 455.872 | 91.174 | 36.27 | 0.000 |
| Solder Temperature(C) | 1 | 440.037 | 440.037 | 175.04 | 0.000 |
| Contact Time(s) | 1 | 19.185 | 19.185 | 7.63 | 0.015 |
| Preheat Temperature(C) | 1 | 15.217 | 15.217 | 6.05 | 0.027 |
| Board Thickness(inches) | 1 | 10.384 | 10.384 | 4.13 | 0.062 |
| Wet Flux Amount(mg/dm$^2$) | 1 | 10.178 | 10.178 | 4.05 | 0.064 |
| 2-Way Interaction | 7 | 32.875 | 4.696 | 1.87 | 0.151 |
| Solder Temperature(C)*Contact Time(s) | 1 | 9.845 | 9.845 | 3.92 | 0.068 |
| Solder Temperature(C)*Preheat Temperature(C) | 1 | 0.012 | 0.012 | 0.00 | 0.946 |
| Solder Temperature(C)*Wet Flux Amount(mg/dm$^2$) | 1 | 2.799 | 2.799 | 1.11 | 0.309 |
| Contact Time(s)*Preheat Temperature(C) | 1 | 25.534 | 25.534 | 10.16 | 0.007 |
| Contact Time(s)*Wet Flux | 1 | 1.411 | 1.411 | 0.56 | 0.466 |

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| | | | | | |
|---|---|---|---|---|---|
| Amount(mg/dm$^2$) | | | | | |
| Preheat Temperature(C)*Wet Flux Amount(mg/dm$^2$) | 1 | 0.847 | 0.847 | 0.34 | 0.571 |
| Board Thickness(inches)*Wet Flux Amount(mg/dm$^2$) | 1 | 0.159 | 0.159 | 0.06 | 0.805 |
| Error | 14 | 35.194 | 2.514 | | |
| Total | 26 | 737.776 | | | |

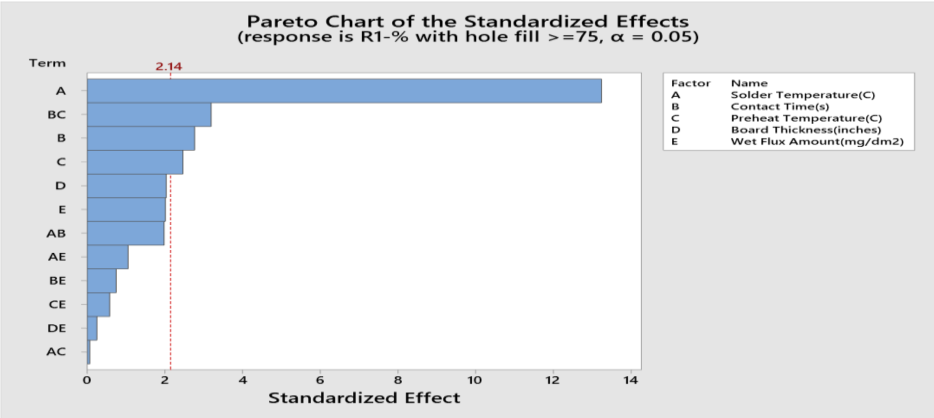


Figure-2 Pareto Chart of the Standardized Effects

**Discussion:**

For Response Surface Regression results, the factors solder temperature, contact time, preheat setting and interaction between contact time and preheat temperature are significant at 5% level of significance. Also, the model explains 91.14% of the variation in the output.

In the pareto chart of the standardized effects shown above, the interaction between contact time and preheat temperature is significant. In addition, the largest effect is due to solder temperature because it extends the farthest. Solder Temperature*Preheat Temperature (AC) is the smallest because it extends the least.

**5.2 Response Surface Regression with $R_2$:**

**Coded Coefficients**

| Term | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|
| Constant | 1.47389 | 0.00307 | 480.01 | 0.000 | |
| Solder Temperature(C) | -0.22851 | 0.00459 | -49.81 | 0.000 | 1.88 |
| Contact Time(s) | -0.02183 | 0.00660 | -3.31 | 0.005 | 3.88 |
| Preheat Temperature(C) | 0.04527 | 0.00614 | 7.38 | 0.000 | 3.31 |
| Board Thickness(inches) | 0.05685 | 0.00954 | 5.96 | 0.000 | 8.28 |

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| | | | | | |
|---|---|---|---|---|---|
| Wet Flux Amount(mg/dm²) | -0.01238 | 0.00342 | -3.62 | 0.003 | 1.03 |
| Solder Temperature(C)*Contact Time(s) | 0.0424 | 0.0106 | 3.98 | 0.001 | 6.91 |
| Solder Temperature(C)*Preheat Temperature(C) | 0.0250 | 0.0114 | 2.19 | 0.046 | 7.77 |
| Solder Temperature(C)*Wet Flux Amount(mg/ dm²) | -0.00452 | 0.00410 | -1.10 | 0.289 | 1.01 |
| Contact Time(s)*Preheat Temperature(C) | 0.00812 | 0.00694 | 1.17 | 0.262 | 2.88 |
| Contact Time(s)*Wet Flux Amount(mg/ dm²) | 0.00433 | 0.00410 | 1.06 | 0.309 | 1.01 |
| Preheat Temperature(C)*Wet Flux Amount(mg/ dm²) | 0.00420 | 0.00413 | 1.02 | 0.326 | 1.00 |
| Board Thickness(inches)*Wet Flux Amount(mg/ dm²) | 0.00369 | 0.00406 | 0.91 | 0.379 | 1.02 |

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.0143081 | 99.73% | 99.50% | 98.80% |

### 5.2.1 Analysis of Variance

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 12 | 1.06076 | 0.088397 | 431.79 | 0.000 |
| Linear | 5 | 0.52327 | 0.104655 | 511.21 | 0.000 |
| Solder Temperature(C) | 1 | 0.50791 | 0.507914 | 2481.00 | 0.000 |
| Contact Time(s) | 1 | 0.00224 | 0.002240 | 10.94 | 0.005 |
| Preheat Temperature(C) | 1 | 0.01114 | 0.011141 | 54.42 | 0.000 |
| Board Thickness(inches) | 1 | 0.00726 | 0.007264 | 35.48 | 0.000 |
| Wet Flux Amount(mg/ dm²) | 1 | 0.00268 | 0.002680 | 13.09 | 0.003 |
| 2-Way Interaction | 7 | 0.00752 | 0.001074 | 5.25 | 0.004 |


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| | | | | | |
|---|---|---|---|---|---|
| Solder Temperature(C)*Contact Time(s) | 1 | 0.00324 | 0.003239 | 15.82 | 0.001 |
| Solder Temperature(C)*Preheat Temperature(C) | 1 | 0.00098 | 0.000983 | 4.80 | 0.046 |
| Solder Temperature(C)*Wet Flux Amount(mg/dm$^2$) | 1 | 0.00025 | 0.000249 | 1.22 | 0.289 |
| Contact Time(s)*Preheat Temperature(C) | 1 | 0.00028 | 0.000280 | 1.37 | 0.262 |
| Contact Time(s)*Wet Flux Amount(mg/dm$^2$) | 1 | 0.00023 | 0.000228 | 1.12 | 0.309 |
| Preheat Temperature(C)*Wet Flux Amount(mg/dm$^2$) | 1 | 0.00021 | 0.000212 | 1.03 | 0.326 |
| Board Thickness(inches)*Wet Flux Amount(mg/dm$^2$) | 1 | 0.00017 | 0.000169 | 0.83 | 0.379 |
| Error | 14 | 0.00287 | 0.000205 | | |
| Total | 26 | 1.06363 | | | |

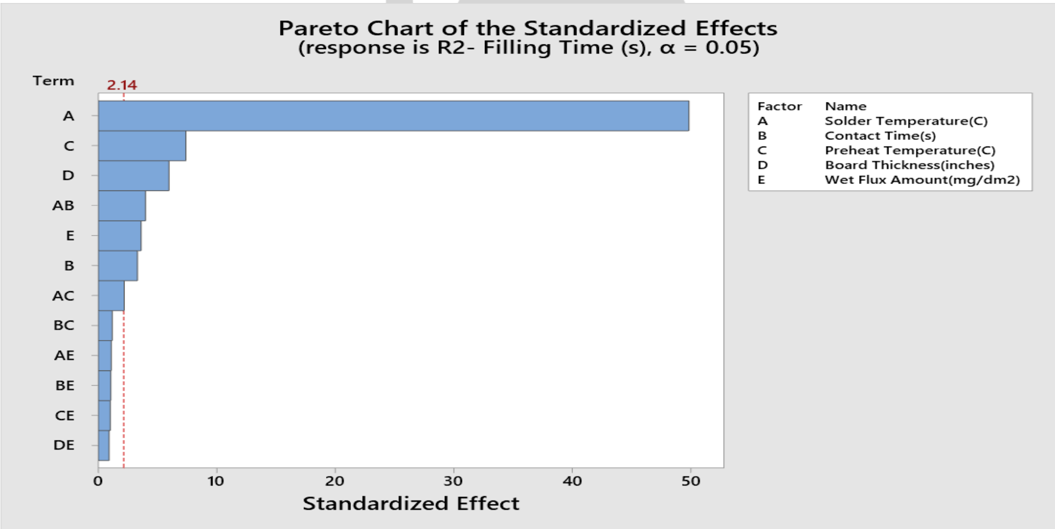


Figure-3 Pareto Chart of the Standardized Effects

**Discussion:**

For Response Surface Regression results, the factors solder temperature, contact time, preheat setting and interaction between contact time, preheat temperature, board thickness and wet flux amount are significant at 5% level of significance. Interactions solder temperature*contact time and solder temperature*preheat temperature is also significant. The adjusted R-square values in the response surface regression are observed to be 91.14% and 99.5%, respectively indicating that the model parameters can explain variation in the response variables $R_1$ (% with hole fill >=75) and $R_2$ (filling time (s)) very well.

In the pareto chart of the standardized effects shown above, the interaction between contact time and solder temperature is significant. In addition, the largest effect is due to solder temperature because it extends the farthest. Board Thickness*Wet Flux Amount (DE) is the smallest because it extends the least.

**5.3 Prediction with $R_1$ -% with hole fill >=75%:**

**Setting-1**

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| Variable | Setting |
|---|---|
| Solder Temperature(C) | 250 |
| Contact Time(s) | 2 |
| Preheat Temperature(C) | 90 |
| Board Thickness(inches) | 0.063 |
| Wet Flux Amount(mg/dm$^2$) | 350 |

**Prediction**

| Fit | SE Fit | 95% CI | 95% PI |
|---|---|---|---|
| 79.6516 | 1.33361 | (76.7913, 82.5120) | (75.2081, 84.0952) |

**Setting-2**

| Variable | Setting |
|---|---|
| Solder Temperature(C) | 265 |
| Contact Time(s) | 4 |
| Preheat Temperature(C) | 110 |
| Board Thickness(inches) | 0.122 |
| Wet Flux Amount(mg/dm$^2$) | 470 |

**Prediction**

| Fit | SE Fit | 95% CI | 95% PI |
|---|---|---|---|
| 86.8100 | 0.442823 | (85.8602, 87.7597) | (83.2792, 90.3407) |

**Setting-3**

| Variable | Setting |
|---|---|
| Solder Temperature(C) | 275 |
| Contact Time(s) | 7 |
| Preheat Temperature(C) | 130 |
| Board Thickness(inches) | 0.236 |
| Wet Flux Amount(mg/dm$^2$) | 580 |


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**Prediction**

| Fit | SE Fit | 95% CI | 95% PI |
|---|---|---|---|
| 91.0244 | 3.90133 | (82.6569, 99.3919) | (81.9923, 100.057) |

**5.4 Prediction with $R_2$- Filling Time (s):**

**Setting-1**

| Variable | Setting |
|---|---|
| Solder Temperature(C) | 250 |
| Contact Time(s) | 2 |
| Preheat Temperature(C) | 90 |
| Board Thickness(inches) | 0.063 |
| Wet Flux Amount(mg/dm$^2$) | 350 |

**Prediction**

| Fit | SE Fit | 95% CI | 95% PI |
|---|---|---|---|
| 1.71762 | 0.0120348 | (1.69181, 1.74344) | (1.67752, 1.75772) |

**Setting-2**

| Variable | Setting |
|---|---|
| Solder Temperature(C) | 265 |
| Contact Time(s) | 4 |
| Preheat Temperature(C) | 110 |
| Board Thickness(inches) | 0.122 |
| Wet Flux Amount(mg/dm$^2$) | 470 |

**Prediction**

| Fit | SE Fit | 95% CI | 95% PI |
|---|---|---|---|
| 1.41212 | 0.0039961 | (1.40355, 1.42069) | (1.38026, 1.44398) |

**Setting-3**

| Variable | Setting |
|---|---|
| Solder Temperature(C) | 275 |

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| | |
|---|---|
| Contact Time(s) | 7 |
| Preheat Temperature(C) | 130 |
| Board Thickness(inches) | 0.236 |
| Wet Flux Amount(mg/dm$^2$) | 580 |

**Prediction**

| Fit | SE Fit | 95% CI | 95% PI |
|---|---|---|---|
| 1.39644 | 0.0352065 | (1.32093, 1.47195) | (1.31493, 1.47795) |

**Discussion:**

After conducting the experiment, the overall optimum settings for the outputs based on experimental data were determined to be A2, B2, C2, and E2 because the combination of these settings gives the smallest standard error fit. The optimum settings for the process are as under:

A. Solder temperature= 265$^0$C ; B. Contact time = 4s; C. Preheat temperature = 110$^0$C;

D. Wet flux volume = 470 mg/dm$^2$.

It is important to mention here that the Solder temperature of 265$^0$C causes least damage (in terms of thermal shock) to components and board material.

**6. Findings and Suggestions**

In this study, an orthogonal Taguchi **L27 (3$^5$)** array was employed for optimization of wave soldering process parameters. For this purpose, five variables including solder temperature, contact time, preheat temperature, board thickness and wet flux amount were examined at three levels. According to the ANOVA results, solder temperature and contact time were the most significant variables among others and preheat temperature was the least significant variable.

The coefficient of determination, the adjusted R-square values in the response surface regression were observed to be 91.14% and 99.5% respectively indicating that the model parameters can explain variation in the response variables $R_1$(% with hole fill >=75) and $R_2$ (filling time (s)) very well. Therefore, the model has good practical significance.

The optimum conditions for solder temperature, contact time, preheat temperature and wet flux amount were equal to 265$^0$C, 4s, 110$^0$C and 470 mg/dm$^2$, respectively. Thus, Taguchi's design of experiments would enable the process engineer to conduct the study with only a small number of test-runs to achieve minimum variation in the newly-developed process.

**7.Conclusion**

As a result of this study, the factors solder temperature, contact time, preheat temperature and wet flux amount are found significant. The aim of the completed optimization was to decrease the number of defects. The interactions solder temperature*contact time and solder temperature*preheat temperature and contact time*preheat temperature have also been found significant. It was observed that for reducing insufficient solder fill defects and filling time, a higher solder temperature was better. Moderate contact times and preheat temperature with a setting of 110$^0$C yielded better results for this experiment.

The present study would enable the process engineers to reach a practical understanding of what will be required in their own specific application with only a small number of experimental runs. Many of the above points can be

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applied in situations where hole fill is not adequate and can be used to determine the best set of parameters to achieve maximum wetting and hole fill.

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