Significance of Taguchi Design compared to Response Surface Methodology in predicting optimal machining conditions for PCM process

K A V Uday Kiran1*, N Vigneshwar2, Darius Gnanaraj Solomon1 and Joseph Jeyapaul Arulraj3
1, 2 Department of Design and Automation, School of Mechanical Engineering, Vellore Institute of Technology, Vellore - 632014, INDIA
3 Department of Economics and Statistics, University of Dodoma, Tanzania
Corresponding author Email Id: ananta.udaykiran2019@vitstudent.ac.in

Abstract: Photochemical Machining (PCM) is a non-conventional machining process which produces stress free complex flat metal components. Optimization of process parameters for Photochemical machining of SS316L steel is done using Taguchi method and the results are compared with results obtained through Response surface methodology (RSM) available in literature. The objective of this work is to predict the optimal machining conditions of PCM to achieve minimum undercut for SS316L steel. The Factors affecting the response of the model are: Etching Time (Ti), Temperature (T) and Etchant Concentration (C) in PCM. This work shows that Taguchi method is faster compared to RSM in predicting the optimal conditions for minimizing defects in PCM process. Taguchi method requires only 9 experiments for finding optimal conditions whereas RSM requires 20 experiments saving about 55% of time and effort.

1. Introduction
Photochemical Machining (PCM) is a non-conventional machining process which uses the principle of metal erosion for manufacturing. This process is mostly used to fabricate sheet metal components, where the work piece is masked to differentiate the machining area with the surrounding area in order to create metal erosion using chemical etchants only in the selected area. The factors like Etching Time (Ti), Temperature (T) and Etchant Concentration (C) are significant in this process. Machining defects such as undercut arise due to change in the conditions of the factors. An experimental study has been conducted to predict minimal undercut of SS316 L steel with Photochemical Machining process (PCM) using Response Surface Methodology (RSM) [1]. The optimum conditions are found by conducting 20 experiments and by processing the data. In this work, a comparative study is done between Taguchi and RSM to find the optimal conditions to achieve minimal undercut of SS316L steel using PCM process. RSM is a statistical approach for the optimization of manufacturing processes introduced by George E. P. Box and K. B. Wilson in 1951[2]. It uses two design approaches such as Box-Behnken Design (BBD) and Central Composite Design (CCD) to find the optimal parameters affecting the response a machining process. Genichi Taguchi an engineer and statistician from Japan has introduced a method called ‘Taguchi Designs’ for the optimization problems in manufacturing industry during late 1980’s. He stated the use of Orthogonal Arrays (OA), Linear Graphs and Loss functions [3-4] in identifying the optimal conditions of a process with a less number of experiments to be carried out. This process reduces the number of experiments to be carried out for the experimentation. In recent years most of the
researchers stated that the Taguchi method is simple and efficient Design of Experiments. Optimal surface roughness of sintered PA 2200 prototypes is evaluated using Taguchi method [5], and this method showed advantages over other methods like RSM and Full Factorial Designs [FFD] in identifying the optimal conditions. Few of the works include optimizing polishing efficiency and torque evaluation in robotic polishing process [6]. Optimization of parameters for a welding unit in manufacturing sector and carbon nano tubes stiffened speaker design [7,8]. Performance evaluation of quality in PLA 3D printed parts having thin walls [9] and laser additive manufacturing in Inconel 625 [10]. The application of Taguchi design for the photochemical machining of aluminium is done in [11], where the optimal parameters are obtained with 9 experimental trials with three factor and three level interaction. The procedural steps to be followed in Taguchi approach is mentioned by Krishniah K, Shahabudeen P [3] as stated by Taguchi. This includes, finding the affecting factors and their levels in the response of the process and identifying a standard Orthogonal Array (OA) for assigning the order of the factors to be followed in experimentation using linear graphs. The optimal factors can be achieved by constructing an average response plot of the process. In this work, the optimal parameters in Photochemical Machining of SS316L steel is identified using Taguchi approach and the results are compared with the results through RSM available in literature [1]. The factors like Etching Time (Ti), Temperature (T) and Concentration (C) are considered as affecting parameters and the undercut of SS316L steel with PCM process is chosen as the response of the model. The optimal conditions are identified with only 9 experiments using Taguchi approach compared to 20 experiments required by RSM [1].

2. Design Methodology
The procedure of Taguchi design is followed as described by Krishniah K and Shahabudeen [3]. Genichi Taguchi has introduced few procedural steps to be followed during the experimentation. Initially the factors affecting the undercut (response) in the Photo Chemical Machining (PCM) is chosen at three different levels. The Orthogonal Array (OA) was chosen based on factors and levels to identify the total number of experiments to be conducted to predict the optimal response. Then, factors are assigned accordingly with the aid of linear graph which suggest the sequential order of levels to be used for the experiment. The Response graphs and ANOVA have been carried out to identify the optimal and significant factors in the experiment. The step by step analysis of experiment is illustrated in the following sections.

2.1. Factors and Levels
Photo Chemical Machining (PCM) is a machining process that utilizes chemical reaction for etching of the material. In this process, the etching time, etchant temperature and concentration are the significant parameters affecting the unmasked area exposed to the chemical. Any abrupt change in the process parameters may result in the material defect called ‘Undercut’. So, the optimal conditions of factors should be chosen to minimize the effect on to the material. In this work these factors are considered at three different levels taken from [1] with notations of factors as Ti, T, C along with coded values -1, 0, 1 as shown in the table 1 below.

| Factor              | Notation | Low (-1) | Medium (0) | High (1) |
|---------------------|----------|----------|------------|----------|
| Time (min)          | Ti       | 30       | 45         | 60       |
| Temperature (°C)    | T        | 50       | 65         | 80       |
| Concentration (gm /lit) | C     | 600      | 750        | 900      |

Table 1. Factors and their Levels [1]
2.2. Identifying an Orthogonal Array (OA)

The Orthogonal Array (OA) defines the standard order of experimentation to be carried out. An OA is chosen by the number of experiments to be conducted on to the process selected. The formula mentioned below is used to identify the number of experiments to be used in Taguchi method.

\[ N = 1 + N_f (L - 1) \]  

Where,

- \( N \) = Number of total Experiments to be conducted
- \( N_f \) = Number of input Factors
- \( L \) = Number of Levels of Factors

As the experiment is a combination of three factors and three levels, a three level standard orthogonal array must be chosen, where the total number of experiments to be conducted as per the above equation are seven, based on the required number of experiments, the nearby OA \( L_9 (3^4) \) is chosen as per the guidelines given in [3]. Now the factors are assigned to the chosen \( L_9 (3^4) \) OA by following the standard linear graph of \( L_9 \) OA as shown in the below figure1.

**Figure 1. Linear Graph for \( L_9 \) OA**

The assignment of the factors in OA is analyzed and is done accordingly by fixing a dummy factor at column 4. The results obtained with this assignment are similar with fixing the dummy factor at column 3 of the OA. The standard orthogonal array with the assigned factors is shown in the table2.

**Table 2. Assigned Factors \( L_9 (3^4) \) OA**

| Experiment No | Time (Ti) | Temperature (T) | Concentration (C) |
|---------------|-----------|-----------------|-------------------|
| 1             | -1        | -1              | -1                |
| 2             | -1        | 0               | 0                 |
| 3             | -1        | 1               | 1                 |
| 4             | 0         | -1              | 0                 |
| 5             | 0         | 0               | 1                 |
| 6             | 0         | 1               | -1                |
| 7             | 1         | -1              | 1                 |
| 8             | 1         | 0               | -1                |
| 9             | 1         | 1               | 0                 |

2.3. Response Analysis

The responses of the Taguchi model are predicted using the regression equation 2 shown below and the values obtained are tabulated in table 3.

\[ U_d = 0.09139 + 0.06062 (Ti) + 0.0583 (T) + 0.0041 (C) - 0.00985 (Ti^2) + 0.02955 (T^2) - 0.00545 (C^2) + 0.024875 (Ti \times T) - 0.000875 (Ti \times C) + 0.001625 (T \times C) \]
Table 3. Predicted Responses of the Taguchi Model

| Experiment No | Time (Ti) | Temperature (T) | Concentration (C) | Predicted Response |
|---------------|-----------|-----------------|-------------------|-------------------|
| 1             | -1        | -1              | -1                | 0.008             |
| 2             | -1        | 0               | 0                 | 0.021             |
| 3             | -1        | 1               | 1                 | 0.085             |
| 4             | 0         | -1              | 0                 | 0.063             |
| 5             | 0         | 0               | 1                 | 0.090             |
| 6             | 0         | 1               | -1                | 0.168             |
| 7             | 1         | -1              | 1                 | 0.085             |
| 8             | 1         | 0               | -1                | 0.133             |
| 9             | 1         | 1               | 0                 | 0.255             |

The response totals and the average response of the model are evaluated by summing up the responses of the factors at each level and dividing by the number of levels of the respective factor. The response totals and the average response values are shown in the tables 4 and 5.

Table 4. Response Totals of the Model

| Levels | Time (Ti) | Temperature (T) | Concentration (C) |
|--------|-----------|-----------------|-------------------|
| -1     | 0.1141    | 0.1553          | 0.3096            |
| 0      | 0.3206    | 0.2443          | 0.3383            |
| 1      | 0.4727    | 0.5078          | 0.2595            |

Table 5. Average Response Values of the Model

| Levels      | Time (Ti) | Temperature (T) | Concentration (C) |
|-------------|-----------|-----------------|-------------------|
| Low (-1)    | 0.0380    | 0.0517          | 0.1032            |
| Medium (0)  | 0.1068    | 0.0814          | 0.1127            |
| High (1)    | 0.1575    | 0.1692          | 0.0865            |
| Difference  | 0.2260    | 0.1980          | 0.0961            |
| Ranking     | 1         | 2               | 3                 |

The Response plot is plotted between the average responses of the factors and their levels as shown in figure 2 which illustrates the optimal conditions obtained from the experiment as Low Time (Ti₁), Low Temperature (T₁) and High Concentration (C₁).
2.4. ANOVA
The Analysis of Variance (ANOVA) is conducted using the correction factor and sum of squares of the factors. The Mean Square error of the factors is calculated by dividing the Sum of Squares by the Degree of Freedom (DOF) of each factor. The F-value and p-value obtained showed that, Etching time (Ti) and Temperature (T) are significant parameters affecting the response of the model. The table 6 below shows the ANOVA of the Model.

**Table 6. ANOVA of the Model**

| Source of Error     | Sum of Squares | DOF | Mean Square Error | F-Value | p-value |
|---------------------|----------------|-----|-------------------|---------|---------|
| Etching Time (Ti)   | 0.0215         | 2   | 0.01075           | 26.875  | 0.0121  |
| Temperature (T)     | 0.0224         | 2   | 0.0112            | 28      | 0.0114  |
| Concentration (C)   | 0.001          | 2   | 0.0005            | 1.25    | 0.4028  |
| Error               | 0.0012         | 3   | 0.0004            |         |         |

Figure 2. Average Response plot
The table 6 shows that the F-Value is greater than the standard F-Value i.e. 9.55 and the calculated P-values of the factors Etching Time (Ti) and the Temperature (T) are less than 0.05. It is observed that the factors Etching Time (Ti) and Temperature (T) are showing significant effect on undercut of the material with Photochemical Machining process.

3. Signal to Noise (S/N) Analysis

Signal to Noise (S/N) ratios are calculated to find the effects of noise factors on the responses of the model. The analysis is done using ‘smaller the better’ quality characteristic approach. The S/N response of the model is calculated by using the equation 3 mentioned below.

\[
\eta = -10 \log \left[ \frac{1}{n} \sum Y_i^2 \right]
\]

(3)

In S/N analysis, the maximum response is chosen as the optimal response irrespective of minimization or maximization condition. The responses of the model are calculated and tabulated in Table 7 and the Average Responses of the model are plotted as shown in figure 3. The tables 8 and 9 illustrate the total and average response values of the model.

### Table 7. S/N responses of the model

| Ti  | T  | C  | Rₐ  | η   |
|-----|----|----|-----|-----|
| -1  | -1 | -1 | 0.008 | 41.72 |
| -1  | 0  | 0  | 0.021 | 33.59 |
| -1  | 1  | 1  | 0.085 | 21.41 |
| 0   | -1 | 0  | 0.063 | 24.06 |
| 0   | 0  | 1  | 0.090 | 20.91 |
| 0   | 1  | -1 | 0.168 | 15.49 |
| 1   | -1 | 1  | 0.085 | 21.46 |
| 1   | 0  | -1 | 0.133 | 17.49 |
| 1   | 1  | 0  | 0.255 | 11.87 |

### Table 8. S/N response totals of the model

| Factor   | Ti  | T  | C  |
|----------|-----|----|----|
| Low (-1) | 96.73 | 87.25 | 74.71 |
| Medium (0) | 60.47 | 72.00 | 69.54 |
| High (1)  | 50.83 | 48.78 | 63.78 |
Table 9. Average response totals of the model

| Factor     | Ti  | T   | C   |
|------------|-----|-----|-----|
| Low (-1)   | 32.24 | 29.08 | 24.90 |
| Medium (0) | 20.15 | 24.00 | 23.18 |
| High (1)   | 16.94 | 16.26 | 21.26 |
| Difference | 4.860 | 11.17 | 19.53 |
| Ranking    | 3   | 2   | 1   |

From the table 9 it is clear that the optimum noise factors are Low Time (Ti), Low Temperature (T) and Low Concentration (C) and the Optimum response in terms of S/N ratio is evaluated from the equation 4 below.

\[ \eta_{opt} = \bar{\eta} + (Ti - \bar{\eta}) + (T - \bar{\eta}) + (C - \bar{\eta}) \] (4)

Where,

\( Ti, T, C \) = Response Totals of factors at respective levels

\( \bar{\eta} = \) Grand Average Mean = \( \frac{\text{Grand Total of all Observations}}{\text{Total No of Observations}} \)

Therefore,

\[ \eta_{opt} = 40.01 \]

The optimal factors obtained with S/N analysis are Low Time (Ti), Low Temperature (T) and Low Concentration (C) and the predicted response is 40.01 is close to the value 41.72 as reported in table 7. From this, we can conclude that the optimal conditions obtained through S/N analysis are satisfactory. The optimal conditions with raw data analysis reported in table 5 are Low Time (Ti), Low Temperature (T) and High Concentration (C). The predicted optimal factors found through RSM [1] satisfy all these conditions.

![Time Graph](a)

![Temperature Graph](b)
4. Results and Discussion

The optimal conditions obtained and the significant factors with the Taguchi experiments are compared with the results obtained through RSM available in literature. The number of experiments required by Taguchi method is equal to 9 which are considerably less compared to 20 experiments required by RSM approach. This shows that Taguchi is better approach than RSM in predicting the optimal machining conditions of Photo Chemical Machining (PCM) process. The results of Taguchi method through raw data analysis gives the following optimum conditions for achieving the minimum undercut are Low Etching Time (Ti), Low Temperature (T) and Low Concentration (C) levels. The S/N ratio analysis gives the following set of conditions such as Low Etching Time (Ti), Low Temperature (T) and High Concentration (C) levels. The analysis of variance (ANOVA) shows the Etching Time (Ti), Temperature (T) as the significant factors affecting the response of the model in both the cases. Since the concentration is not significant and also both high and low concentrations give the minimum values of undercut as per figure 4 (c), it can be concluded that the use of Taguchi method saves 55% of the effort and time required for finding the optimum conditions.
Figure 4. Surface Plots obtained using Response Surface Methodology (RSM) between (a) Etching Time and Temperature, (b) Etching Time and Concentration and (c) Temperature and Concentration [1]

5. Conclusion
In this work, the optimal etching conditions of Photo Chemical Machining (PCM) process on SS316L Steel is predicted using Taguchi method. The results are compared with the results obtained by Response Surface Methodology (RSM) available in literature.

- The etching conditions obtained by Taguchi method are similar to the results obtained through RSM and the number of experiments with TAGUCHI method is less than RSM which shows about 55% reduction.
- The Etching time (Ti) and Temperature (T) showed significant effect on the Undercut of the SS316L steel with PCM and the concentration of etchant is not significant.
- Optimal conditions for achieving optimum undercut are: Low etching time (30 min.), Low temperature (50⁰C) and low concentration (600 gm/lit) or high concentration (900 gm/lit).
- Taguchi method is better than RSM approach in predicting the optimal machining conditions of PCM to achieve minimal undercut.

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