Advantages of Taguchi Method compared to Response Surface Methodology for achieving the Best Surface Finish in Wire Electrical Discharge Machining (WEDM)

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ABSTRACT

Design of Experiments is a method to predict the optimum conditions of a process to reduce the time and number of experiments to be conducted with limited resources. In this paper, a comparative work on design and analysis of experiments between Taguchi method and response surface methodology is carried out in predicting the set of optimal conditions for obtaining the best surface roughness of commercially pure titanium powder metallurgy component using wire electrical discharge machining process. With surface roughness of the Titanium as the response and pulse on time, pulse off time, and sintering temperature of the wire electrical discharge machining process as the affecting factors, the optimum conditions for the surface roughness of the material have been predicted and analysed. Analysis of variance is used to identify the significant factors affecting the system. Both methods gave the same results and the Taguchi approach requires less number of experiments compared to response surface methodology and the predicted surface roughness of the components with the Taguchi method is 2.4 µm, whereas it is between 2.41-3.04 µm with the Response Surface Methodology. The factor Pulse on Time (N) shows a significant effect on the response of the system.

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Introduction

Design and Analysis of experiments is a significant way to predict and analyze the optimum conditions of a manufacturing process. Titanium is one of the strongest materials with high strength and strength to weight ratio. It is used in most industries for manufacturing parts related to aeronautical, aerospace, automobiles, and biomedical applications [1, 2]. In most applications, Titanium alloys are preferred to pure Titanium components to achieve high corrosion resistance, tensile strength, and toughness. Due to the difficulty in the machining of Titanium components through conventional manufacturing methods, mostly Non-Traditional Machining Processes (NTM) are preferred to manufacture Titanium components [3]. WEDM process uses the principle of Metal erosion for machining various complex geometries such as dies, fixtures, etc. where the geometric tolerances are crucial for manufacturing [4-6]. The process parameters such as operating voltage, current, wire feed rate, etc. are significant for minor tolerances [7]. A review on the WEDM process by Balan et al. [8] stated the factors such as Pulse on Time, Pulse off Time are much crucial for machining the Titanium alloy components.

Montgomery reported that George E. P. Box and K. B. Wilson found the procedure for Response Surface Methodology in 1951 [9]. This method uses a second-order polynomial to elaborate the relation between the factors and the response of the system. It involves two design approaches namely Box-Behnken Design and Central Composite Design. RSM was used for finding optimum conditions for TIG welding, microwave radiation effect on welding, and for milling operation [10]-[12]. Even though the predicted values matched with experimental findings, 20 runs were required to optimize the parameters. The optimal conditions for CP-Ti components with the WEDM process are found by doing 15 experiments with the RSM approach based on the requirement of this method. The optimal conditions were highest sintering temperature, highest pulse off time and lowest pulse on time [13].

During the late 1980s, Genichi Taguchi an engineer and statistician from Japan had invented 'Taguchi methods' to find the optimal response of the system which requires only a limited number of experiments to be conducted. This method uses Loss Functions, Orthogonal Arrays (OA), and Linear Graphs to identify the optimal conditions [14]. Krishniah and Shahabudeen [15] presented the procedural steps involved in optimizing the process parameters which includes identifying an Orthogonal Array-based on the affecting factors and their levels that define the number of experiments to be conducted. This method made the Design of Experiments simple and reliable for every process.

The objective of this work is to find the best set of conditions for machining Commercially Pure Titanium (CP-Ti) Powder metallurgy components using Wire Electric Discharge Machining (WEDM) process using the Taguchi method and compare it with Response Surface Methodology (RSM) to find the best method among these two methods. The scope of this study is to compare RSM with the Taguchi method to find the number of experiments to be done and the effectiveness of each method. The significance of this work is to find the reduction in the number of experiments without losing the quality of results. The Methodology implemented along with the experimental design is illustrated in the following sections.

Design Procedure

The Design procedure is carried out according to the steps involved in the Taguchi Designs as described in [15] such as defining the objectives of the experiment, choosing the total number of factors affecting the response, number of levels of factors, identifying the corresponding Orthogonal Array (OA) and loss function to find the optimal response of the system. After finding the optimum response, the predicted response and confirmation experiment should be done to evaluate the optimum condition. The objective of this work is to prove that less number of experiments is enough in predicting the optimum machining conditions for achieving better surface roughness of the CP-Ti components with the Taguchi method as compared to Response Surface Methodology (RSM). The following sections describe the results through the Taguchi method and the results are compared with the results obtained with RSM.

Identifying the factors and levels

In this work, the Pulse on Time (N), Pulse off Time (F) of the WEDM process are taken as effecting factors along with the Sintering Temperature (T) during the manufacturing of powder metallurgy components. The experimentation data is taken from Das et al. [13] by considering these factors at three levels and the factors are assigned with symbols such as N, F, T, and the levels with -1, 0, 1 as shown in Table 1. The objective of the work is to minimize the surface roughness of the CP-Ti components such that the loss function, ‘Smaller the Better’ criterion is chosen for optimal response.

Table 1: The number of factors and their levels [13]

Parameters	Unit	Symbol	Low (-1)	Medium (0)	High (1)
Pulse on Time	µs	N	6	8	10
Pulse off Time	µs	F	9	11	13
Sintering Temperature	°C	T	1350	1400	1450

Selecting the orthogonal array

To select an Orthogonal Array, the total number of experiments to be conducted should be identified using the formula mentioned in Equation (1) [15].

$$N = 1+N_f\,(L-1) \tag{1}$$

where,
N = Total Number of Experiments to be conducted
N_f = Total Number of Factors
L = Number of Levels of Factors

Therefore, the Taguchi approach suggests seven experiments to be conducted to identify the optimal parameters. Krishniah and Shahabudeen [15] suggested that, when the number of experiments is less than the standard number for choosing an Orthogonal Array, the nearby OA is greater than the obtained number along with required factors and levels should be chosen. By following this rule, an L_9 (3^4) Orthogonal Array is chosen for the model and the factors are assigned according to the linear graph of L_9 OA as illustrated in Figure 1. The Orthogonal Array with the assigned factors is shown in Table 2.

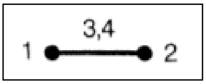


Figure 1: Shows the Linear Graph for L_9 OA [15].

Table 2: Assignment of factors for L_9 OA

Trial No.	Pulse on Time(N)	Pulse off Time (F)	Dummy (e)	Sintering Temperature (T)
1	-1	-1	-1	-1
2	-1	0	0	0
3	-1	1	1	1
4	0	-1	0	1
5	0	0	1	-1
6	0	1	-1	0
7	1	-1	1	0
8	1	0	-1	1
9	1	1	0	-1

Predicting the responses

The responses are predicted using the regression equation [13] and the values are tabulated in Table 3.

$$R_a = 2.66 + 0.156N - 0.053F - 0.106T + 0.106N^2 - 0.046F^2 + 0.021T^2 - 0.155NF + 0.023NT - 0.075FT \quad (2)$$

Table 3: The predicted responses of the Taguchi model

Trial No.	Pulse on Time (N)	Pulse off time (F)	Sintering Temperature (T)	Predicted Surface Roughness (R_a)
1	-1	-1	-1	2.53
2	-1	0	0	2.61
3	-1	1	1	2.48
4	0	-1	1	2.65
5	0	0	-1	2.78
6	0	1	0	2.56
7	1	-1	0	3.08
8	1	0	1	2.86
9	1	1	-1	2.84

Response totals and the average responses of the factors have been evaluated and the optimal ranking of the factors is assigned as shown in Table 4 and Table 5.

Table 4: The response totals of the factors at each level

Levels	Pulse on Time (N)	Pulse off Time (F)	Sintering Temperature (T)
Low (-1)	7.62	8.26	8.15
Medium (0)	7.99	8.25	8.25
High (1)	8.78	7.88	7.99

Table 5: The average response values and ranking of the factors

Levels	Pulse on Time (N)	Pulse off Time (F)	Sintering Temperature (T)
Low (-1)	2.54	2.75	2.71
Medium (0)	2.66	2.75	2.75
High (1)	2.92	2.62	2.66
Difference	3.04	2.62	2.7
Ranking	1	3	2

Optimal conditions of the factors

As the objective of the experiment is to identify the machining conditions for achieving minimal surface roughness of CP-Ti components, the minimum average values of factors should be considered at each level. From Tables 4 and 5, it is clear that the minimal surface roughness condition is Low Pulse on Time (N_{-1}), High Pulse off Time (F_1), and High Sintering Temperature (T_1). The ranking of the factors in Table 5 shows the order of priority to be considered that affects the response of the system. The average response plot of the model is shown in Figures 2, 3, and 4. It is seen that the best machining conditions for achieving the better surface finish of CP-Ti components are Low Pulse on Time (N), High Pulse off Time (F), and High Sintering Temperature (T). For evaluating the optimum surface roughness, the average response prediction Equation (3) is considered as mentioned below [15].

$$\mu_{Pred} = \bar{Y} + (N_{-1} - \bar{Y}) + (F_1 - \bar{Y}) + (T_1 - \bar{Y}) \quad (3)$$

where,

N_{-1}, F_1, T_1 = Response Totals of factors at respective levels.

$$\bar{Y} = \text{Grand Average Mean} = \frac{GrandTotalofallObservations}{TotalNoofObservations}$$

Therefore, the predicted surface roughness of CP-Ti components with the obtained optimal condition is:

$$\mu_{Pred} = 2.4$$

From the results available in Das et al. [13], it is clear that the surface roughness of the CP-Ti components using RSM is in the range of 2.41-3.04 µm. We can see that the surface roughness obtained using the Taguchi approach is the same as that of the Response Surface Methodology (RSM).

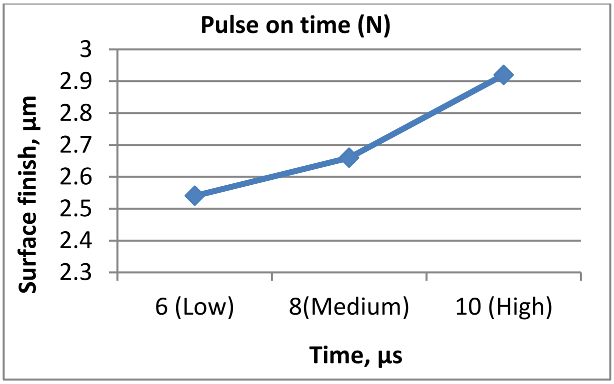


Figure 2: The average response plot of pulse on time (N).

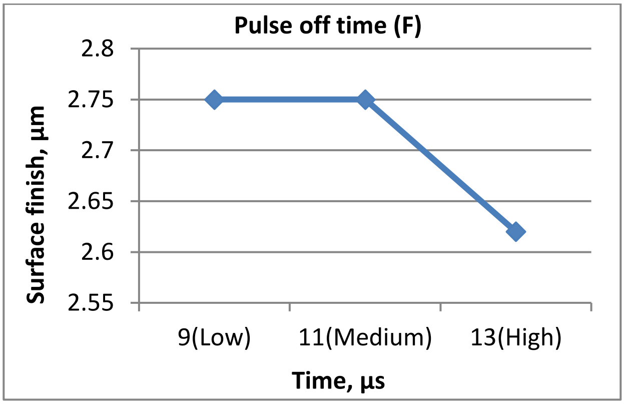


Figure 3: The average response plot of pulse off time (F).

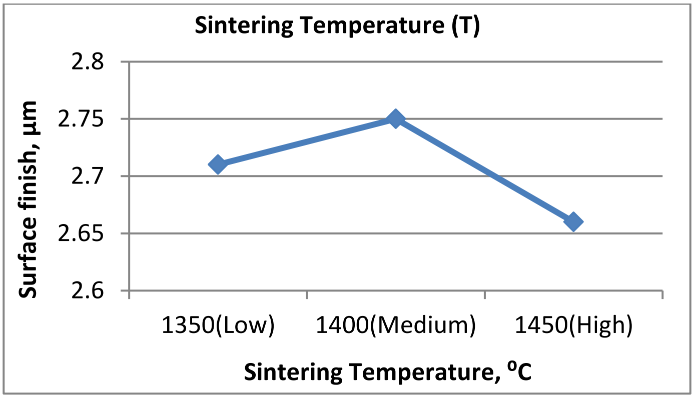


Figure 4: The average response plot of sintering temperature (T).

Analysis of Variance (ANOVA)

Analysis of Variance is performed to verify the significant factors affecting the model, the correction factor is measured and the sum of squares of each factor is evaluated. ANOVA helps in testing the significance of factors by comparing the mean squares against experimental errors at specific confidence levels. F-test is a statistical tool to find the parameters which have significant effects on the quality characteristics. In this table, for a 5% significance, degree of freedom 2, error degree of freedom 3, $F_{0.05,2,3} = 9.55$. Table 6 shows the ANOVA of the model, the value of pulse on time is 13.6087 which is more than the F value of 9.55, which is significant. The P-value reports the significant levels of parameters. If $P < 0.05$, it is significant. Since the value of pulse on time is 0.031 which is less than 0.05, it is significant. Hence, the Pulse on Time (N) is the most significant factor affecting the surface roughness of the CP-Ti components in the WEDM process compared to the pulse off time and sintering temperature.

Table 6: The ANOVA of the model

Source of Error	Sum of Squares	Degrees of Freedom	Mean Square Error	F	P
Pulse on Time (N)	0.23407	2	0.11704	13.6087	0.031
Pulse off Time (F)	0.03127	2	0.01564	1.81802	0.303
Sintering Temperature (T)	0.01147	2	0.00574	0.66686	0.575
Error	0.0258	3	0.0086		
Total	0.3026	8			

Signal to Noise Ratio (S/N)

Signal factors are significant in optimization problems to identify the variation between the target value and the affecting factors. This predicts the effect of noise factors in the response of the model. Generally, the signal to noise ratio depends on the quality characteristic of the model which depends on the objective of the experiment. In this work, the objective is to minimize the surface roughness of the CP-Ti components, such that the 'Smaller the Better' type quality characteristic function is chosen.

Table 7**:** Noise factors for each combination of trials

N	F	T	R_a	η
-1	-1	-1	2.53	-8.06
-1	0	0	2.61	-8.33
-1	1	1	2.48	-7.88
0	-1	1	2.65	-8.46
0	0	-1	2.78	-8.88
0	1	0	2.56	-8.16
1	-1	0	3.08	-9.77
1	0	1	2.86	-9.12
1	1	-1	2.84	-9.06

The noise factor for each combination of trials is calculated by using Equation (4) for combinations shown in Table 7.

$$\eta = -10 \log\left[\frac{1}{n}\sum Y_i^2\right] \tag{4}$$

S/N ratio analysis

The effect of the signal-to-noise ratio is measured by analysing the total and average noise responses of the model. The total and average noise responses are shown in Tables 8 and 9. From Table 9 it is clear that the optimum noise factors are Low Pulse on Time (N_{-1}), High Pulse off Time (F_1), and High Sintering Temperature (T_1). The Optimum response in terms of the S/N ratio is:

$$\eta_{Opt} = \bar{\eta} + (N_{-1} - \bar{\eta}) + (F_1 - \bar{\eta}) + (T_1 - \bar{\eta})$$

where,

N_{-1}, F_1, T_1 = Response Totals of factors at respective levels

$$\bar{\eta} = \text{Grand Average Mean} = \frac{GrandTotalofallObservations}{TotalNoofObservations}$$

Therefore,

$\eta_{Opt} = -7.69$

The obtained optimal value is nearly similar to the maximum experimental trial value in Table 7, which confirms that the optimal condition is satisfactory.

Table 8: Total Noise factors at each level

Factor	N	F	T
Low (-1)	-24.28	-26.29	-26.00
Medium (0)	-25.51	-26.34	-26.26
High (1)	-27.96	-25.12	-25.48

Table 9: Average Noise factors at each level

Factor	N	F	T
Low (-1)	-8.09	-8.76	-8.66
Medium (0)	-8.50	-8.78	-8.75
High (1)	-9.32	-8.37	-8.49
Difference	9.73	8.39	8.58
Ranking	1	3	2

ANOVA

From Table10, the factor Pulse on Time (N) is significant in the response of the system, which is verified with the ANOVA in Table 6. By this, we can say that the factor Pulse on Time (N) has a significant effect on the surface roughness of the CP-Ti powder metallurgy components with the WEDM process.

Table 10: ANOVA of S/N ratio

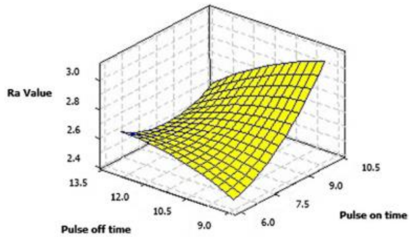
Source of Error	Sum of Squares	Degrees of Freedom	Mean Square Error	F	P
Pulse on Time (N)	2.341	2	1.1705	14.879	0.027
Pulse off Time (F)	0.32	2	0.16	2.033	0.276
Sintering Temperature (T)	0.107	2	0.0535	0.68	0.570
Error	0.236	3	0.0786		
Total	3	8			

Results and Discussions

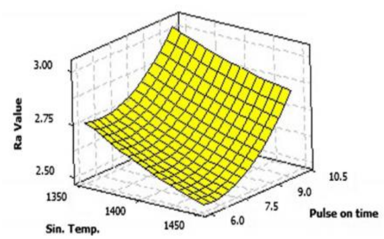
The optimal conditions for achieving the surface roughness characteristic of CP-Ti powder metallurgy components with the WEDM process have been identified using the Taguchi approach. The Signal-to-Noise ratios of factors at each level are measured and the optimal conditions are verified with the 'Smaller the Better' quality characteristic. Both Orthogonal Array and Loss function had predicted the same optimal conditions such as 'Low Pulse on Time (N_{-1})', 'High Pulse off Time (F_1)', and 'High Sintering Temperature (T_1)'. The obtained optimum conditions are verified with 'Response Surface Methodology (RSM)', where the conditions are assuring the best surface roughness characteristic for the CP-Ti components. The Surface plots obtained with Response Surface Methodology (RSM) by Das et.al [13] between the factors are shown in Figure 5. Effects of sintering time, pulse on time on the surface roughness are indicated in Figures 5(a), 5(b), and 5(c). In Figure 5(a), surface roughness increase with an increase in pulse time and a decrease in pulse-off time. In Figure 5(b), the surface roughness decrease with an increase in sintering temperature and a decrease in pulse on time for a fixed value of pulse-off time. In Figure 5(c), the surface roughness decrease with an increase in pulse-off time and an increase in sintering temperature for a fixed pulse on time. Hence the best surface finish is found to be related to the highest sintering temperature, the highest pulse off time, and the lowest pulse on time.

In the past years, many researchers have proved the efficiency of using the Taguchi approach in the Design and Analysis of Experiments. Taguchi method is used for optimizing operating parameters in laser additive manufacturing, production of activated carbon from rubber seed shell, inclined plane classifier used for segregating particles of different sizes, and for producing a strong electro-fusion joint [16]-[19]. Several works showed that the implementation of the Taguchi method to various processes resulted in a limited number of experiments to be conducted to obtain the optimal conditions for various manufacturing processes like electrical discharge machining and abrasive water jet machining [20, 21].

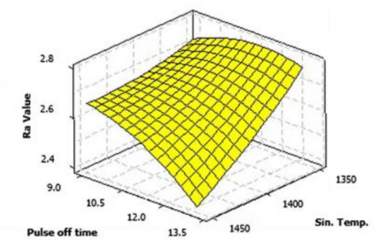
Figure 5 shows the optimum condition using Response Surface Methodology (RSM) and Figures 2, 3 and 4 show the optimum conditions obtained using the Taguchi method for achieving a better surface finish. We can see from both the approaches that the best machining conditions for achieving the better surface finish of CP-Ti components are Low Pulse on Time (N), High Pulse off Time (F), and High Sintering Temperature (T). The approach using RSM requires 15 runs as reported by Das et al. [13] and it requires only 9 runs when we use the Taguchi method used in this work. Since the Taguchi method requires 6 runs lesser than RSM, the number of runs is reduced by 40% (6/15). Hence, we can conclude that the Taguchi method helps researchers to find the optimum conditions by performing 40% fewer experiments. However, the following are some limitations in this study: (1) The number of factors and their levels are assumed to be the same for both methods, (2) A dummy column was assumed to suit the requirement of L_9 orthogonal array as per the procedure of Taguchi method and (3) based on one comparison and a few pieces of evidence from the literature, the conclusion drawn not applicable to all cases.



(a)



(b)



(c)

Figure 5: Shows the plot between (a) Pulse off time and pulse on time, (b) Sintering temperature and pulse on Time, (c) Pulse off time and sintering temperature [13].

Conclusion

In this work, the optimum machining conditions for achieving a better surface finish of Commercially Pure Titanium (CP-Ti) powder metallurgy components are evaluated using the Taguchi method. The results obtained are compared with the optimum conditions found through Response Surface Methodology (RSM) available in the literature. The significance of the study is to compare RSM with the Taguchi method to find which method is fast and accurate.

i. Taguchi Method gave the same optimal machining conditions for achieving the better surface finish of the CP-Ti components similar to the optimal conditions obtained through Response Surface Methodology (RSM), available in the literature.
ii. The number of experiments conducted using the Taguchi approach is only 9 which is less than Response Surface Methodology (RSM) which requires 15 experiments. It is confirmed that the Taguchi method is quick and efficient than RSM. However, this statement cannot be generalized to all cases owing to a few limitations in this study.
iii. The predicted surface roughness of the components with the Taguchi method is 2.4 µm, whereas it is between 2.41-3.04 µm with the Response Surface Methodology
iv. Both Signal to Noise ratio analysis and Orthogonal Array (OA) analysis predicted the same optimal conditions and from the ANOVA evaluated, the factor Pulse on Time (N) shows a significant effect on the response of the system.

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