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RESEARCH NOTE

Mathematical Modeling and Analysis of Spark Erosion Machining Parameters of Hastelloy C-276 Using Multiple Regression Analysis

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ABSTRACT

Electrical discharge machining has the capability of machining complicated shapes in electrically conductive materials independent of hardness of the work materials. This present article details the development of multiple regression models for envisaging the material removal rate and roughness of machined surface in electrical discharge machining of Hastelloy C276. The experimental runs are devised as per Taguchi's principles and empirical relations are established using multiple regression analysis. Taguchi's methodology can be applied as a single aspects optimization technique for attaining the best set of possible process parameter for material removal rate and roughness of the machined surface. A statistical tool called analysis of variance is employed for determining the significance of input process variables that influences the desired performance measures such as material removal rate and roughness of the electrically machined surface. The developed multiple regression models are flexible, competent and precise in prediction of desired performance measures. The developed regression models were validated and the predicted results from the evolved regression models are closer with the experimental outcomes.

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1. INTRODUCTION

Superalloys are heat resistant and the mechanical and chemical properties of the materials are remains unchanged during high temperature applications [1, 2]. The properties of superalloys such as high strength and hardness, lower thermal diffusivity makes them as hard to machine materials [3-6] High strength and high hardness of these materials results in poor performance in machining and more tool wear by traditional machining processes. So there is a necessity to find a solution for machining of these super alloys which are electrically conductive hard materials by using unconventional material removal processes. Electrical Discharge Machining (EDM) is one among the available advanced machining process most commonly employed for machining the components that are used in automobile, aerospace and biomedical industries [7]. A continuous repeated electrical discharges between the tool (electrode) and the working material, results in removal of material from the workpiece in the dielectric medium [8, 9]. The tool moves towards the workpiece until the gap between the electrode and work material is close enough to ionize the dielectric fluid with the help of supplied voltage. The removal of material in workpiece happens due to the erosive action and irrespective to the material hardness. The graphical representation of EDM process is given in Figure 1.

An exploration on EDM drilling of nickel alloy detailed the importance of supplied current and same is the important process variable for obtaining the rate of material removal [10]. The plan of experiment is most important to determine the importance of the process parameters. Taguchi's experimental design method is a powerful approach for planning the experiments and to solve the single objective optimization problems. The machining performance and influence of process

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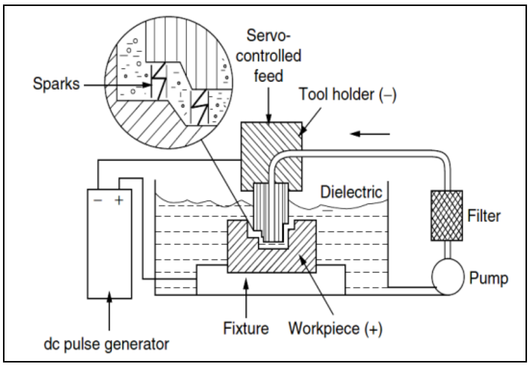

Figure 1. Schematic of Electrical Discharge Machine [11]

variables are detailed by various researchers on EDM process [12, 13]. Caydas and Hascalık [14] presented an experimental analysis to predict the roughness of machined surface in abrasive water-jet machining using an intelligent decision making tool called artificial neural network (ANN) and regression model [15].

The results demonstrated that the evolved regression model performance is comparatively better than ANN model. Sahoo and Pradhan [16] detailed an experimental analysis on machining of aluminium metal matrix composites by Taguchi's approach. Mathematical models were evolved for roughness of the machined surface and flank wear and it is make known from the analysis that the developed empirical relations are found to be significant for predicting the process parameters. Ahilan et al. [17] developed empirical relational for CNC turning process by advanced decision making methods and observed that the evolved empirical relations are consistent with estimating the various desired performance measures. It is surmised from the available literatures, that there are lack of exploration performed on development of multiple regression models for electrical discharge machining of Hastelloy C276 by considering the performance measures namely material removal rate (MRR), surface roughness (SR). Taguchi's approach is used for single objective optimization.

2. MATERIALS AND METHODS

Taguchi proposed a unique layout for conducting experiments called as Orthogonal Array (OA) to analyze the process variables with minimum number of experimental runs. Current (A), pulse on time (µs) and pulse off time (µs) are selected as input variables and MRR, surface roughness are considered as performance measures. Based on the selected parameters and levels, an L27 OA have been opted for EDM drilling of Hastelloy. The selected input process variables, levels and range of values are specified in Table 1. The experimental runs were performed on EDM machine (Model EMS 5030) for making through holes. The work material, Hastelloy C-276 is clamped inside of the machining chamber and Cu electrode is used as a tool.
Weight loss method is used to estimate the rate of material removal. Mitutoyo make model No. SJ 410 is used for measuring the surface roughness. Figures 2 and 3 show the experimental setup and tool used for machining, respectively. The drilled hole using EDM is shown in Figure 4. In EDM, higher MRR and lower roughness of machined surface are the indicators of better machining performance. The experiments were conducted as per L27 OA and the observations are shown in Table 2.

TABLE 1. Input process parameters and levels

Symbols	Process Variables	Levels		
		1	**2**	**3**
A	Current (A)	5	10	15
B	Pulse on Time (µs)	30	60	90
C	Pulse off time (µs)	3	6	9

Figure 2. Experimental setup for Hastelloy C-276

Figure 3. Tool used for machining of Hastelloy C-276

Figure 4. Machined hole using EDM in Hastelloy C-276

TABLE 2. Experimental Layout and measured responses

Order	Current (A)	Pulse On (μs)	Pulse Off (μs)	Material Removal Rate (g/min)	Surface Roughness (Microns)
1	5	30	3	0.0435	0.30
2	5	30	6	0.0443	0.32
3	5	30	9	0.0459	0.32
4	5	60	3	0.0481	0.32
5	5	60	6	0.0490	0.32
6	5	60	9	0.0512	0.33
7	5	90	3	0.0519	0.34
8	5	90	6	0.0523	0.34
9	5	90	9	0.0526	0.35
10	10	30	3	0.0534	0.35
11	10	30	6	0.0540	0.36
12	10	30	9	0.0546	0.40
13	10	60	3	0.0563	0.40
14	10	60	6	0.0574	0.40
15	10	60	9	0.0581	0.40
16	10	90	3	0.0620	0.41
17	10	90	6	0.0636	0.41
18	10	90	9	0.0645	0.42
19	15	30	3	0.0651	0.45
20	15	30	6	0.0655	0.49
21	15	30	9	0.0662	0.50
22	15	60	3	0.0674	0.50
23	15	60	6	0.0678	0.50
24	15	60	9	0.0685	0.50
25	15	90	3	0.0749	0.52
26	15	90	6	0.0783	0.54
27	15	90	9	0.0812	0.56

3. RESULTS AND DISCUSSION

The investigations on EDM of Hastelloy C-276 using Taguchi approach, analysis of variance and multiple regression analysis are discussed in this section. The influence of selected independent process variables on multi performance machining characteristics are detailed.

3. 1. Determination of Optimum Process Parameter for Material Removal Rate The removal rate of material is categorized under larger the better criterion. The main effect plot is obtained for the removal rate of material and it is shown in Figure 5. It shows that the MRR is increased by increase in level of current and pulse on time and pulse off time. Taguchi's analysis is performed and the outcomes are presented in Table 3. The optimum machining condition for obtaining higher material removal rate is determined as A3B3C3. It is make known from the investigation that the applied current is the important process variable which influences the material removal rate.

3. 2. Determination of Optimum Process Parameter for Surface Roughness In EDM, the surface roughness is categorized under smaller the better criterion. The main effect plot is obtained for the surface roughness and it is presented in Figure 6. It is perceived from the illustration, that the roughness of the machined surface is increased with increasing in applied current, pulse on time and pulse off time. Taguchi's analysis is performed and the results are exhibited in Table 4. The optimum machining conditions for obtaining minimized surface roughness is determined as A1B1C1.

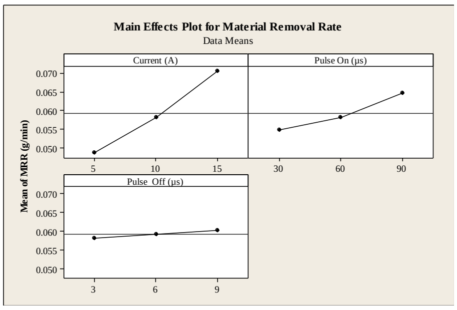

Figure 5. Main effect plot for Material removal rate

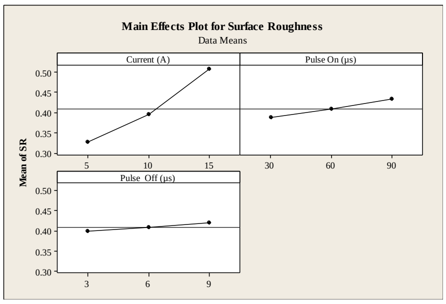

Figure 6. Main effect plot for surface roughness.

TABLE 3. Optimum level selection for MRR – EDM of Hastelloy

Level	Current (A)	Pulse on time (μs)	Pulse off time (μs)
1	0.04876	0.05472	0.05807
2	0.05821	0.05820	0.05913
3	0.07055	0.06459	0.06031
Delta	0.02179	0.00987	0.00224
Rank	1	2	3

TABLE 4. Optimum level selection for Surface Roughness – EDM of Hastelloy

Level	Current (A)	Pulse on time (μs)	Pulse off time (μs)
1	0.3267	0.3878	0.3989
2	0.3944	0.4078	0.4089
3	0.5067	0.4322	0.4200
Delta	0.18	0.0444	0.0211
Rank	1	2	3

3. 3. Analysis of Variance for Desired Performance Measures

ANOVA is used to determine the significance of process parameters on the performance measures at 95% confidence level and it is computed using statistical software Minitab 16.0. The ANOVA analysis for rate of removal of materials, roughness of machined surface in electrical discharge drilling of Hastelloy C276 are presented in Table 5.

From the 'P' values, it is witnessed from the analysis that the applied current is the significant process variable for rate of material removal, roughness of machined surface in electrical discharge drilling of Hastelloy C276.

TABLE 5. ANOVA for EDM of Hastelloy C276

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Material Removal Rate (g/min)						
Current (A)	2	0.002149	0.002149	0.001075	388.93	0
Pulse On (μs)	2	0.000451	0.000451	0.000226	81.6	0
Pulse Off (μs)	2	2.27E-05	2.27E-05	1.13E-05	4.1	0.032
Error	20	5.53E-05	5.53E-05	2.8E-06	---	---
Total	26	0.002678	---	---	---	---
Surface Roughness (Ra) (microns)						
Current (A)	2	0.148763	0.148763	0.074381	480.45	0
Pulse On (μs)	2	0.008919	0.008919	0.004459	28.8	0
Pulse Off(μs)	2	0.002007	0.002007	0.001004	6.48	0.007
Error	20	0.003096	0.003096	0.000155	---	---
Total	26	0.162785	---	---	---	---

3. 4. Development of Multiple Regression Models

Multiple regressions technique is employed to ascertain the relationship among the process variables. Regression equations have linear model, quadratic model, interaction model and full model and are as shown in Equations (1)-(4) (for three input parameters).

$$y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 \quad (1)$$

$$y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4(X_1)^2 + \beta_5(X_2)^2 + \beta_6(X_3)^2 \quad (2)$$

$$y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4 X_1 X_2 + \beta_5X_1 X_3 + \beta_6 X_2X_3 \quad (3)$$

$$y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4(X_1)^2 + \beta_5(X_2)^2 + \beta_6(X_3)^2 \; \beta_4 X_1 X_2 + \beta_5X_1 X_3 + \beta_6 X_2X_3 \quad (4)$$

MRR = 0.0423052 + 0.000467444 Current (A) - 0.000136907 Pulse On (μs) - 9.42593e-005 Pulse Off (μs) + 5.75778e-005 Current (A)*Current (A) + 8.06111e-006 Current (A)*Pulse On (μs) + 1.27222e-005 Current (A)*Pulse Off (μs) + 1.6179e-006 Pulse On (μs)*Pulse On (μs) + 4.43519e-006 Pulse On (μs)*Pulse Off (μs) + 6.23457e-006 Pulse Off (μs)*Pulse Off (μs) (5)

SR = 0.273704 - 0.00444444 Current (A) + 0.000277778 Pulse On (μs) +0.00333333 Pulse Off (μs) + 0.000888889 Current (A)*Current (A) + 5e-005 Current (A)*Pulse On (μs) + 0.000277778 Current (A)*Pulse Off (μs) + 2.46914e-006 Pulse On (μs)*Pulse On (μs) - 5.55556e-005 Pulse On (μs)*Pulse Off (μs) + 6.17284e-005 Pulse Off (μs)*Pulse Off (μs) (6)

where, 'y' is criterion variable and 'X1', 'X2' and 'X3' are predictor variables. 'β1', 'β2', 'β3'…… 'βn' are regression coefficients.

Regression model for MRR: The empirical equations for associating the relationship among the desired performance measure and the considered process variables has been obtained. The R^2 values of various regression models for material removal rate is tabulated in Table 6 and the desired full model is shown in Equation (5).

Regression model for Surface Roughness: The mathematical relationship, attained to analyze the influences of the dominant machining parameters on the surface roughness is given by full model Equation (6). The R^2 values of various regression models for surface roughness is shown in Table 7.

TABLE 6. R^2 values of various regression models for MRR in EDM of Hastelloy

Regression Model	R^2 value (%)
Linear	97.00
Linear + square	97.94
Linear + interaction	97.74
Full model (linear + square + interaction)	98.68

TABLE 7. R^2 values of various regression models for Surface Roughness in EDM of Hastelloy

Regression model	R^2 value
Linear	96.26 %
Linear + square	98.10 %
Linear + interaction	96.99 %
Full model (linear + square + interaction)	98.82 %

3. 5. Comparative Analysis of Experimental Values and Predicted Values by Multiple Regression Equation A comparison has been made for the measured values from the conducted trials and the values obtained from the prediction by developed regression equations. The values predicted from the multiple regression equations are presented in Table 8. The Comparisons between the experimental observations and the values predicted by the developed multiple regression model are shown in Figure 7 for rate of material removal and Figure 8 for the surface roughness, respectively. From the comparative analysis, it is shown that the values predicted from the developed regression models were closer with the experimental observations.

The SEM microgrph of the spark erosion machined Hastelloy C-276 is shown in Figure 9. The micrograph illustrates the machined surface did not encountered with any adverse change.

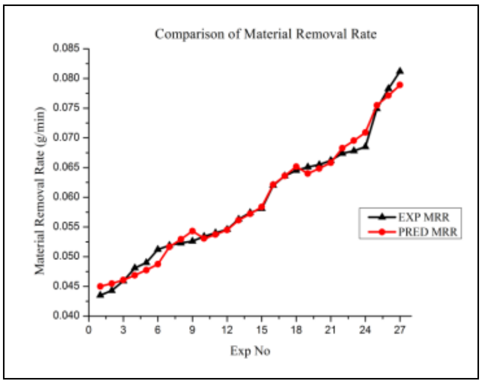

Figure 7. Comparison of material removal rate

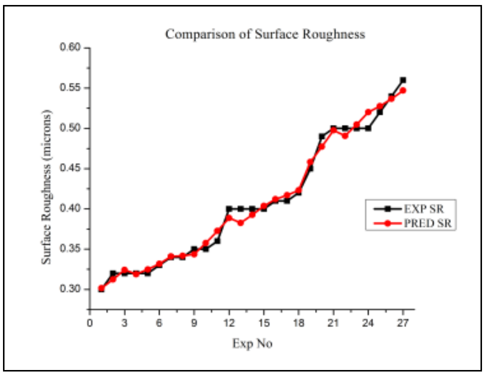

Figure 8. Comparison of material removal rate

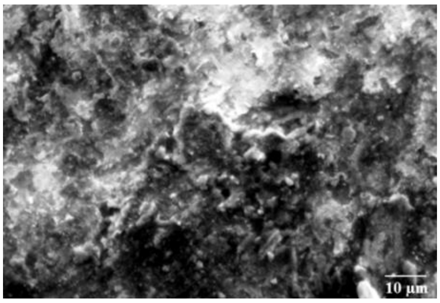

Figure 9. SEM image of the spark erosion machined Hasetlloy C-276 work surface

TABLE 8. Strouhal number for different geometric c Results from multiple regression analysis

S.No	Experimental Values		Predicted Values	
	Material Removal Rate (g/min)	Surface Roughness (microns)	Material Removal Rate (g/min)	Surface Roughness (microns)
1	0.0435	0.30	0.0450	0.30
2	0.0443	0.32	0.0455	0.32
3	0.0459	0.32	0.0461	0.32
4	0.0481	0.32	0.0469	0.32
5	0.0490	0.32	0.0477	0.32
6	0.0512	0.33	0.0487	0.33
7	0.0519	0.34	0.0517	0.34
8	0.0523	0.34	0.0529	0.34
9	0.0526	0.35	0.0543	0.35
10	0.0534	0.35	0.0531	0.35
11	0.0540	0.36	0.0537	0.36
12	0.0546	0.40	0.0545	0.40
13	0.0563	0.40	0.0561	0.40
14	0.0574	0.40	0.0572	0.40
15	0.0581	0.40	0.0584	0.40
16	0.0620	0.41	0.0621	0.41
17	0.0636	0.41	0.0636	0.41
18	0.0645	0.42	0.0652	0.42
19	0.0651	0.45	0.0640	0.45
20	0.0655	0.49	0.0649	0.49
21	0.0662	0.50	0.0658	0.50
22	0.0674	0.50	0.0683	0.50
23	0.0678	0.50	0.0695	0.50
24	0.0685	0.50	0.0709	0.50
25	0.0749	0.52	0.0755	0.52
26	0.0783	0.54	0.0771	0.54
27	0.0812	0.56	0.0789	0.56

4. CONCLUSIONS

The following are the conclusions obtained from the present exploration: ANOVA has been used for identifying the significance of the independent process variables on desired performance measures. From the analysis, it is clear that the current (A) is most significant parameter for desired performance measures such as rate of material removal rate and surface roughness. The empirical models were developed using multiple regression analysis to correlate the relationship among the independent process variables and dependent process variables and also based on the R^2 values the developed equations are used for further predictions.

It is observed from the comparative analysis, that the predicted values from the developed regression models were closer with the experimental observations. Taguchi's approach is established its capability to be an effectual tool to investigate the influence of process parameters for various machining processes.

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RESEARCH NOTE

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چکیده

EDM توانایی پردازش اشکال پیچیده را در مواد هدایت الکتریکی مستقل از سختی مواد کار دارد. در این مقاله حاضر، توسعه مدل های رگرسیون چندگانه برای پیش بینی میزان حذف مواد و زبری سطح ماشین کاری در 276EDM Hastelloy C. آزمایشهای انجام شده بر اساس اصول Taguchi طراحی شده و روابط تجربی با استفاده از تجزیه و تحلیل رگرسیون چندگانه ایجاد شده است. روش Taguchi می تواند به عنوان تکنیک بهینه سازی تک جنبه برای دستیابی به بهترین مجموعه ای از پارامترهای فرایند ممکن برای میزان حذف مواد و زبری سطح ماشین کاری مورد استفاده قرار گیرد. یک ابزار آماری به نام تجزیه و تحلیل واریانس برای تعیین اهمیت متغیرهای فرآیند ورودی که بر اندازه گیری های مورد نظر از قبیل میزان حذف مواد و زبری سطح ماشین کاری الکتریکی تأثیر می گذارد، استفاده می شود. مدل های رگرسیون چندگانه توسعه یافته در پیش بینی ضوابط عملکرد مطلوب، انعطاف پذیر، صحیح و دقیق هستند. مدل های رگرسیون توسعه یافته اعتبار یافته و نتایج پیش بینی شده از مدل های رگرسیون تکامل یافته با نتایج تجربی نزدیک تر است.

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