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Experimental study of electrical discharge machine (die sinking) on stainless steel 316L using design of experiment

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Abstract

The objective of this study is to investigate the influence of Electrical Discharge Machining (EDM) input parameters on characteristics of EDM process. A combination between two advanced materials which stainless steel 316l as workpiece and copper impregnated graphite as electrode have been selected in this study. The copper impregnated graphite is considered as a hybrid material for the electrode which exponentially used in tool and mould making industry. The study was conducted using 2 levels of full factorial method in design of experiments. Analysis of variance (ANOVA) and mathematically modelling were developed for material removal rate (MRR), electrode wear rate (EWR), surface roughness (SR) and dimensional accuracy (DA). The first order model is required to fit dimensional accuracy linear model. However, second order model are required to fit MRR, EWR and SR quadratic models respectively. The result shows that the peak current was the most significant factors to all variable responses. Based on confirmation run, all the results are less than 15% error, thus, indicating the model that were developed for MRR, SR, EWR and Dimensional Accuracy are reasonable accurate.

Keywords: EDM Die Sinking; Stainless Steel;Copper Impregnated Graphite Electrode; Mathematical Modelling; Surface Roughness; Material Removal Rate; Wear; Dimensional Accuracy

1. Introduction

EDM is a non-conventional machining process which the material from work pieces is eroded by series of discharge sparks between the work pieces and tool electrode. During EDM process, the tool and the work piece are

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submerged in dielectric fluid and operated by a small gap. EDM technology is developed and is widely use in applications such as die and mild machining and micromachining. The very hard and brittle materials can be machined easily to the desired form. It removes electrically conductive materials by means of rapid, repetitive spark discharges from pulsating direct-current power supply with dielectric flow between work piece and the electrode. There are many parameters that may affect the machining results such as peak current, servo voltage, pulse on time, pulse off time, jet flushing, etc.

Hindus et al. reported that for MRR, the significant factor was pulse on time followed by peak current. Higher MRR was obtained at 15A and 30V. Tools wear increases with increase in current and decrease in voltage. For TWR the significant factor was peak current followed by pulse on time [1]. In EDM process, it is difficult to find a single optimal combination of process parameters for the performance parameters, as the process parameters influence them differently. Thus, there is a need for a multi-objective method to derive solutions to this problem [2]. Nikhil Kumar et al. conducted comparatively study for MRR on EDM using electrode of Copper and Graphite. From the results, it was found that graphite electrode is more favourable than the copper electrode for the machining of the steel work piece for MRR and tool wear rate [3]. For copper graphite electrode (EDM-C3), it can be concluded that the significant parameters that affect the MRR are the interaction between peak current and pulse on time which is the same as for EDM-3 electrode. Another significant factor that affects the MRR is the interaction between the servo voltage and pulse on time [4]. Subramaniam et al. conducted the study about effect of electrode materials on EDM of 316l and 17-4 PH stainless steel. They found that copper electrode gives the better MRR for both materials tested. Copper tungsten electrode gives low electrode wear [6]. Mehul Manoharan et al. reported that for high discharge current, copper electrodes show highest MRR, whereas brass gives good surface finish and normal MRR. The MRR could be improved by carrying out research on electrode design, process parameters, EDM variations, powder mixed dielectric and electrically insulated electrodes. Special attention must be paid to surface integrity since EDM is a thermal method. The basis of controlling and improving MRR mostly relies on empirical methods. The particle could then form an electrically conducting path between the electrode and work material, causing unwanted discharges, which become arcs and reduce the sparking efficiency [7]. Considering the above, this study investigates the influence of EDM input parameters on characteristics of EDM process. A combination between two advanced materials which stainless steel 316L as workpiece and copper impregnated graphite as electrode have been selected in this study.

2. Research methodology

The experiments in this study were performed on Sodick AM3L die sinking EDM machine. The experimental works begin with material identification, machining response parameters and machining process parameters. Copper impregnated graphite (EDM-C3) was chosen for the electrode and stainless steel 316l as the workpiece material. The EDM die sinking parameters selected were peak current, servo voltage pulse ON time and pulse OFF time. Table 1 shows the design matrix based on 2^4 full factorial experiments. The depth of machining was set to 3mm and the machining time is recorded. The response studies are material removal rate (MRR), electrode wear rate (EWR), surface roughness (SR) and dimensional accuracy (DA). Experiments were conducted based on design of experiment (DOE) approach. Design expert software version 9 was used to determine the main effects of the process parameters. The analysis of variance (ANOVA), full factorial experiment, response surface methodology (RSM) and central composite design (CCD) methods were conducted in order to discover the significant factors as well as to develop mathematical models of the various EDM die sinking responses.

Table 1.Two level full factorial experiments with four factors

Std	Run	Factor 1	Factor 2	Factor 3	Factor 4
		A:Peak Current (Ampere)	**B:Servo Voltage (Volt)**	**C:Pulse On Time (µs)**	**D:Pulse Off Time (µs)**
1	11	5.00	20.00	20.00	60.00
2	13	45.00	20.00	20.00	60.00
3	4	5.00	60.00	20.00	60.00

4	17	45.00	60.00	20.00	60.00
5	9	5.00	20.00	160.00	60.00
6	7	45.00	20.00	160.00	60.00
7	14	5.00	60.00	160.00	60.00
8	15	45.00	60.00	160.00	60.00
9	2	5.00	20.00	20.00	260.00
10	6	45.00	20.00	20.00	260.00
11	3	5.00	60.00	20.00	260.00
12	8	45.00	60.00	20.00	260.00
13	1	5.00	20.00	160.00	260.00
14	5	45.00	20.00	160.00	260.00
15	10	5.00	60.00	160.00	260.00
16	18	45.00	60.00	160.00	260.00
17	16	25.00	40.00	90.00	160.00
18	19	25.00	40.00	90.00	160.00
19	20	25.00	40.00	90.00	160.00
20	12	25.00	40.00	90.00	160.00

3. Results and analysis

The full factorial experimental design of 2^4 experiments with 4 centre points had been conducted. The Design Expert version 9 software was employed to perform all the data analysis. From ANOVA, due to curvature is significant, thus, response surface methodology with type of central composite design (CCD) is required to fit the second order model. The "face-centered CCD" involves 28 experimental observation with corresponds to an α value of 1 which consist of four central points.

The responses of MRR, EWR, SR and DA were evaluated by F-test of ANOVA to determine the significant effects. Based on analysis done by the Design Expert software, if the value of probability (Prob > F) is less than 0.05, it indicates that the factors are significant to the response parameters. The results of fit summary revealed that the model was statistically significant and valid for quadratic regression. Regression models are statistical models which used for studying how changes in one or more variables will change the value of another variable. The models are used to determine the optimum setting for best response value. Predicted equation can be developed using Equation (1) and (2):

$$\hat{y} = \widehat{\beta_0} + \widehat{\beta_1}X_1 + \widehat{\beta_2}X_2 + \cdots + \widehat{\beta_n}X_n \tag{1}$$

If there is curvature in the system, then a polynomial of higher degree must be used, such as the second-order model.

$$\hat{y} = \widehat{\beta_0} + \Sigma\widehat{\beta_i}X_i + \Sigma\,\Sigma\widehat{\beta_{ii}}X^2{}_i + \Sigma\Sigma\widehat{\beta_{ij}}X_iX_j + \varepsilon \tag{2}$$

Regression models in term of coded value are shown in Eqs. 3 to 6. A quadratic transformation recommended by Box-Cox plot need to be performed specifically for MRR and EWR. This is to ensure that the quadratic models are statistically significant.

$$\text{Ln(MRR)} = -1.73 + 1.16*A + 0.85*C - 0.31*D - 0.91*A^2 - 0.61*C^2 \tag{3}$$

$$\text{Ln(EWR)} = -4.11 + 0.61*A + 0.81*C - 0.47*D - 1.11*A^2 \tag{4}$$

$$\text{Surface Roughness} = 9.31 + 2.35*A + 1.94*C + 0.83*AC - 2.48*A^2 \tag{5}$$

$$\text{Dimensional Accuracy} = 0.04 + 0.015*A + 0.019*C + 0.0046*D + 0.0062*AC \tag{6}$$

Regression model obtained from CCD analysis are given in Eqs. 7 to 10 below, where three of the first models fit the quadratic model and the dimensional accuracy model satisfies for a linear model.

$$Ln(MRR) = -6.2145 + 0.17148 Peak\ Current + 0.0345 * Pulse\ On\ Time - 0.00305 * Pulse\ Off\ Time - 0.00227 * Peak\ Current^2 - 0.00012 * Pulse\ On\ Time^2 \quad (7)$$

$$Ln(EWR) = -6.8823 + 0.1688 * Peak\ Current + 0.0115 * Pulse\ On\ Time - 4.69259E003 * Pulse\ Off\ Time - 2.76847E\text{-}003 * Peak\ Current^2 \quad (8)$$

$$SR = 1.34024 + 0.3740 * Peak\ Current + 0.01288 * Pulse\ On\ Time + 0.0005 * Peak\ Current * Pulse\ On\ Time - 0.006196 * Peak\ Current^2 \quad (9)$$

$$DA = 0.00064 + 0.000339 * Peak\ Current + 0.000153 * Pulse\ On\ Time + 4.6292e\text{-}005 * Pulse\ Off\ Time + 4.46352e\text{-}006 * Peak\ Current * Pulse\ On\ Time \quad (10)$$

3.1 Confirmation Run

Confirmation runs were conducted in order to evaluate margin error between theoretically prediction and confirmation test results. Basically the objective of confirmation runs is to evaluate whether the optimum parameters predicted were in allowable range. The margin error should be less than 15%.

3.1.1 Single Objective Confirmation Run

Single objective confirmation runs for each response were performed and final results obtained are exhibited in Tables 2, 3, 4 and 5, respectively. Individual response desirability must be defined according to the ultimate goal. The goal of MRR is high, EWR is low, SR is low and Dimensional Accuracy is low.

Table 2.Analysis of confirmation experiments for MRR in EDM process

No	Peak Current	Servo Voltage	Pulse On	Pulse Off	Predicted MRR	Actual MRR	Residual	%Error
	A	V	µs	µs	g/min	g/min		
1	37.7	40	139.06	60	0.49439	0.43271	-0.06168	-14.25

Table 3.Analysis of confirmation experiments for EWR in EDM process

No	Peak Current	Servo Voltage	Pulse On	Pulse Off	Predicted EWR	Actual EWR	Residual	%Error
	A	V	µs	µs	g/min	g/min		
1	5	40	90	260	0.00211	0.00235	0.00024	10.2

Table 4.Analysis of confirmation experiments for SR in EDM process

No	Peak Current	Servo Voltage	Pulse On	Pulse Off	Predicted SR	Actual SR	Residual	%Error
	A	V	μs	μs	(μm)	(μm)		
1	5	20	20	160	3.3726	3.3700	-0.0026	-0.1

Table 5.Analysis of confirmation experiments for Dimensional Accuracy in EDM process

No	Peak Current	Servo Voltage	Pulse On	Pulse Off	Predicted Dimensional Accuracy	Actual Dimensional Accuracy	Residual	%Error
	A	V	μs	μs	%	%		
1	5	40	20	60	0.008633	0.007531	-0.0011	-14.6

3.1.2 Multiple Objective Confirmation Run

Multiple objective confirmation run was performed and final result is obtained as exhibited in Table 6.

Table 6.Analysis of confirmation experiments for multiple objectives confirmation run in EDM process

<table>
<tr><th rowspan="2">No</th><th rowspan="2">Peak Current (Amp)</th><th rowspan="2">Servo Voltage (Volt)</th><th rowspan="2">Pulse On (μs)</th><th rowspan="2">Pulse Off (μs)</th><th>Response</th><th>Predicted</th><th>Actual</th><th>Residual</th><th>%Error</th></tr>
<tr><td>MRR (gram/min)</td><td>0.31296</td><td>0.331</td><td>0.0177</td><td>5.3</td></tr>
<tr><td rowspan="3">1</td><td rowspan="3">24</td><td rowspan="3">20</td><td rowspan="3">50</td><td rowspan="3">50</td><td>EWR (gram/min)</td><td>0.0214</td><td>0.0243</td><td>0.0029</td><td>11.93</td></tr>
<tr><td>SR (μm)</td><td>9.24</td><td>9.01</td><td>-0.23</td><td>-2.55</td></tr>
<tr><td>Dimensional Accuracy (%)</td><td>0.0442</td><td>0.0436</td><td>-0.0006</td><td>-1.3</td></tr>
</table>

Based on confirmation runs, all the results are less than 15%, thus, indicating the developed models for MRR, SR, EWR and Dimensional Accuracy are reasonable accurate. All the actual values are within 95% prediction interval (PI). Therefore, no prejudice on the model developed for each response.

5. Conclusion

- Feasibility of EDM process for stainless steel 316l by using cooper impregnated graphite electrode has been proven.
- All parameter selected for this experiment, peak current, pulse on time and pulse off time are significant factors. The servo voltage does not have significant effects to the machining responses in RSM.

- Mathematical models developed to predict the various machining characteristics are statistically valid. The quadratic models were obtained and significant for MRR, EWR and SR. However, the Dimensional Accuracy response only fitted for first order model or linear equation.
- The margin error obtained from all responses studied in this research work were all accepted as the results within prediction interval (PI) and below than 15%.

6. Recommendation

- Depth of cut should set at least 5mm instead of 3mm prior to get more precise data especially for electrode weight.
- Workpiece surface integrity such as recast layer, heat affected zone (HAZ), microstructure and micro cracks should be investigated also for better understanding of EDM phenomenon.
- In order to get optimum settings for EWR and SR, it is suggested that proper screening of range of parameters should be carried out.
- Others factors influencing EDM machining responses such as jet flushing, dielectric fluid, etc should be investigated.

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