Mathematical Modeling for Radial Overcut on Electrical Discharge Machining of Incoloy 800 by Response Surface Methodology

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Abstract

In the present study, Response surface methodology is applied for prediction of radial overcut in die sinking electrical discharge machining (EDM) process for Incoloy 800 superalloy with copper electrode. The current, pulse-on-time, pulse-off time and voltage are considered as input process parameters to study the ROC. The experiments were planned as per central composite design (CCD) method. After conducting 30 experiments, a mathematical model was developed to correlate the influences of these machining parameters and ROC. The significant coefficients were obtained by performing ANOVA at 5% level of significance. From the obtained results, it was found that current and voltage have significant effect on the radial overcut. The predicted results based on developed models are found to be in good agreement with the experimental results reasonably well with the coefficient of determination 0.9699 for ROC.

1 Introduction

Nickel base super alloys are widely used in high temperature and high pressure applications such as gas turbines, electric power generation equipment, nuclear reactors and high temperature chemical vessels (Hewidy et al. (2005)). Inconel 800 is a high strength, temperature resistant (HSTR) nickel-based super alloy, mainly used in aerospace.

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Keywords: Electrical discharge machining; Radial overcut; Incoloy 800 superalloy; central composite design; Response surface methodology;
Nomenclature

A  Current
B  Pulse-on-time
C  Pulse-off-time
D  Voltage
v  Volts
RSM  Response surface methodology
CCD  Central composite Design
ROC  Radial overcut
EDM  Electrical discharge machining
ANOVA  Analysis of variance
μs  Microsecond
S/N ratio  Signal-to-noise ratio
DOF  Degree of freedom
SS  Sum of squares
MS  Mean square
F  Variance ratio
P  Contribution ratio
% P  Percentage of contribution

applications, such as gas turbines, rocket motors, and spacecraft as well as in nuclear reactors, pumps and tooling. The properties of these super alloys, such as temperature strength, high hardness; low thermal diffusivity; presence of highly abrasive carbide particles and high tendency to welding to the tool and to forming built-up edge, make them extremely difficult-to-machine (Narutaki et al. (1993)). So, Traditional machining of nickel-based super alloy becomes a most challenging than those of conventional materials. To overcome these consequences, non-traditional machining methods like Electrical Discharge Machining, Electro chemical Machining, Laser beam machining and Abrasive water jet machining offers an attractive alternative.

Electrical discharge machining (EDM) is a well-established machining option for manufacturing geometrically complex or hard material parts that are extremely difficult-to-machine by conventional machining processes. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage in the manufacture of mould, die, automotive, aerospace and surgical components (Ho and Newman, (2003)). However, EDM is a very demanding process and the mechanism of the process is complex and not entirely understood yet. Therefore, it is difficult to establish an analytical model and its optimal setting that can exactly predict the performance and optimal response by correlating the process parameters (Pradhan, (2013)).

Some researchers worked on EDM of difficult-to-cut materials. Kuppan et al. (2008)] reported on an experimental investigation of small deep hole drilling of Inconel 718 using the EDM process by considering peak current, pulse on-time, duty factor and electrode speed as input machining parameters. Mathematical models were developed for the MRR and depth averaged surface roughness (DASR) responses using response surface methodology.

An attempt was made to determine the important machining parameters for performance measures like MRR, SF, and SG during WEDM of Inconel 825 material by using Taguchi grey relational analysis ((Rajyalakshmi and Venkata Ramaiah, (2013)). Muthukumar et al. (2010) have demonstrated optimization of WEDM process parameters of Incoloy800 super alloy with multiple performance characteristics such as MRR, surface roughness and Kerf based on the Grey–Taguchi Method. Mao-yong LIN et al. (2013) carried out the optimization of micro milling EDM parameters with multiple performance characteristics such as low electrode wear, high material removal rate and small working gap for the machining of Inconel 718 work material. Another attempt was made to optimize the WEDM parameters for output responses of MRR, SR and Ker width during machining of Titanium alloy (MuthuKumar et al. (2010)).
Response surface methodology (RSM) is an effective tool for developing, improving, and optimizing the processes by combining several input variables and assess how their complex interactions affect the performance of the response variables (Natarajan et al. (2011), Lin et al. (2012)). RSM uses statistical design of experiment techniques, such as the central composite design (CCD) for developing the model and the performance of the proposed model is then established by ANOVA tests. 3D Response graphs can be used to study the effect of input variables on responses. Quite a lot of researchers have used RSM technique to evaluate the performance of manufacturing processes (Djoudi et al. (2007), Asla (2008), Sohani et al. (2009), Tsao (2008), Gopalakannan and Senthilvelan (2013)).

From the literature study, it was understood that no research work has been reported in Electric Discharge Machining of INCOLOY 800 material. So, In this study, response surface methodology is used for the development of a mathematical of ROC with peak current, pulse on time, pulse off time and voltage as input parameters. The adequacy of the developed model has been evaluated by ANOVA test and the effect of machining parameters on ROC has been investigated through 3D response graphs.

2 Experimental details

The experiments were carried out on Roboform-40 die-sinking EDM machine manufactured by Charmilles technologies, Switzerland. The commercial grade EDM oil was used as a dielectric fluid and impulse jet flushing system was employed to flush away the eroded material from the sparking area. The workpiece material used for the experiments was Incoloy 800. Table 1 depicts the chemical composition of Incoloy 800. The copper electrode with a diameter of 9.4 mm is selected for the purpose of this study.

| Element | C  | Cr   | Mn | Al | Ni   | Fe  | Ti | Si |
|---------|----|------|----|----|------|-----|----|----|
| Wt %    | 0.081 | 22.463 | 0.300 | 0.228 | 34.462 | 41.004 | 0.308 | 0.488 |

The diameter of holes produced in the work material has been measured by using Video Measuring System(VMS 2010F) as shown in Figure 1. The Radial overcut is defined as half the difference of diameter of the hole produced to the diameter of tool (Veenaraja et al. (2013)), that is,

\[ \text{ROC} = \frac{d_t - d_{\mu}}{2} \]  

Here \( d_t \) is the diameter of the tool and \( d_{\mu} \) is the diameter of the hole produced by the tool on the work piece.

3 Experimental design and parameter selection

Response surface methodology (RSM) is an effective tool for developing, improving, and optimizing the processes by combining several input variables and assess how their complex interactions affect the performance of the response variables. In general case, the response surface is described by an equation of the form (Sameh, S.Habib (2009)):

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i^2 x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \]  

(2)
Table 2 selected machining parameters and its levels

| Factors       | Notation | Unit | Levels |
|---------------|----------|------|--------|
| Current       | A        |      | -1 8   |
| Pulse-on-time | B        | μs   | 0.2 0.9|
| Pulse off time| C        | μs   | 0.2 0.9|
| Gap voltage   | D        | v    | 30 115 200 |

RSM uses statistical design of experiment techniques, such as the central composite design (CCD) for developing the model and the performance of the proposed model is then established by ANOVA tests. Experiments were designed on the basis of the experimental design technique called a CCD approach. The coefficients of regression model can be found out from the experimental results by using the Design Expert 8.0 statistical software. Based on literatures on EDM research and the working characteristics of the selected machine, the machining parameters chosen for this work are discharge current, pulse on-time, pulse-off time and voltage. The selected machining parameters and its levels are presented in Table 2.

Table 3 CCD Design layout and experimental results

| Exp. Run | A  | B  | C  | D  | ROC  |
|----------|----|----|----|----|------|
|          | Current | Pulse-on time | Pulse-off time | Voltage | Radial over cut |
| 1        | 16  | 0.9 | 0.9 | 30  | 0.235 |
| 2        | 16  | 0.9 | 0.9 | 115 | 0.2611 |
| 3        | 24  | 1.6 | 1.6 | 200 | 0.2154 |
| 4        | 8   | 1.6 | 0.2 | 30  | 0.277 |
| 5        | 24  | 0.2 | 1.6 | 200 | 0.1846 |
| 6        | 24  | 1.6 | 0.2 | 200 | 0.195 |
| 7        | 24  | 0.2 | 0.2 | 30  | 0.1385 |
| 8        | 24  | 0.2 | 0.2 | 200 | 0.1722 |
| 9        | 16  | 0.9 | 0.2 | 115 | 0.185 |
| 10       | 8   | 0.2 | 1.6 | 200 | 0.188 |
| 11       | 8   | 1.6 | 1.6 | 30  | 0.1863 |
| 12       | 16  | 0.9 | 0.9 | 115 | 0.1895 |
| 13       | 16  | 0.9 | 0.9 | 115 | 0.1935 |
| 14       | 16  | 1.6 | 0.9 | 115 | 0.2498 |
| 15       | 16  | 0.2 | 0.9 | 115 | 0.2375 |
| 16       | 16  | 0.9 | 0.9 | 115 | 0.1936 |
| 17       | 8   | 1.6 | 0.2 | 200 | 0.1972 |
| 18       | 24  | 0.9 | 0.9 | 115 | 0.2198 |
| 19       | 24  | 0.2 | 1.6 | 30  | 0.1286 |
| 20       | 8   | 0.9 | 0.9 | 115 | 0.1767 |
| 21       | 8   | 1.6 | 1.6 | 200 | 0.1214 |
| 22       | 16  | 0.9 | 0.9 | 200 | 0.1885 |
| 23       | 8   | 0.2 | 1.6 | 30  | 0.2295 |
| 24       | 16  | 0.9 | 0.9 | 115 | 0.1824 |
| 25       | 8   | 0.2 | 0.2 | 30  | 0.1982 |
| 26       | 16  | 0.9 | 1.6 | 115 | 0.2218 |
| 27       | 24  | 1.6 | 1.6 | 30  | 0.255 |
| 28       | 16  | 0.9 | 0.9 | 115 | 0.261 |
| 29       | 8   | 0.2 | 0.2 | 200 | 0.2154 |
| 30       | 24  | 1.6 | 0.2 | 30  | 0.277 |
4 Experimental results and discussion

A total number of 30 experimental runs for the CCD were conducted as per input data in Table 3. Fig.1 illustrates the measurement of diameter of EDMachined holes on work material by using Video Measurement System. Then output response, ROC is calculated by using the Eqn. (1) for each run and is tabulated in Table 3.

Fig.1 Measuring diameter of EDMachined holes on work material by Video Measurement System

4.1 Development of Mathematical model for ROC and Analysis of variance

The mathematical model has been developed to correlate the effects of the machining parameters on the magnitude of ROC by using Design Expert software and utilizing the relevant experimental data from Table 3. The checking of goodness of fit of the model is very much essential for data analysis. The model adequacy checking comprises the test for significance of the regression model, test for significance on model coefficients, and test for lack of fit. For this purpose, analysis of variance (ANOVA) is performed. The fit summary recommended that the quadratic model is statistically significant for analysis of ROC. The results of quadratic model for ROC are given in ANOVA Table 4.

The Model F-value of 34.51 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The values of "Prob > F" in Table 3 for the term of models less than 0.05 (95% confidence) indicate model terms are significant. In this case A, D, AD, A² are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Lack of Fit F-value" of 2.24 implies the Lack of Fit is not significant relative to the pure error. There is a 19.33% chance that a "Lack of Fit F-value" this large could occur due to noise.
It also shows the R-Squared and adjusted R-Squared values for the model. When the R\(^2\) approaches unity, the better the response model fits the experimental data. Here, obtained value of 0.9699 R-Squared infers that the model explains approximately 96.99% of the variability in ROC. The "Pred R-Squared" of 0.8816 is in reasonable agreement with the "Adj R-Squared" of 0.9418. Further, the value of "Adeq Precision" in this model is greater than 4 and is desirable and this value of 21.246 indicates an adequate signal. This model can be used to navigate the design space.

Table 4 Analysis of variance for ROC model

| Source          | Sum of Squares | DOF  | Mean Square | F value | P value |
|-----------------|---------------|------|-------------|---------|---------|
| Model           | 0.048         | 14   | 3.430E-003  | 34.51   | < 0.0001|
| A-Current       | 0.030         | 1    | 0.030       | 298.83  | < 0.0001|
| B-Pulse-on time | 5.689E-007    | 1    | 5.689E-007  | 5.725E-003 | 0.9407 |
| C-Pulse-off time| 1.217E-004    | 1    | 1.217E-004  | 1.22    | 0.2859  |
| D-Gap voltage   | 0.013         | 1    | 0.013       | 133.74  | < 0.0001|
| AB              | 4.516E-006    | 1    | 4.516E-006  | 0.043   | 0.8341  |
| AC              | 8.266E-006    | 1    | 8.266E-006  | 0.083   | 0.7770  |
| AD              | 8.776E-004    | 1    | 8.776E-004  | 8.83    | 0.0095  |
| BC              | 7.526E-005    | 1    | 7.526E-005  | 0.76    | 0.3979  |
| BD              | 6.631E-006    | 1    | 6.631E-006  | 0.067   | 0.7997  |
| CD              | 3.071E-004    | 1    | 3.071E-004  | 3.09    | 0.0991  |
| A\(^2\)         | 2.236E-003    | 1    | 2.236E-003  | 22.50   | 0.0003  |
| B\(^2\)         | 6.928E-005    | 1    | 6.928E-005  | 0.70    | 0.4168  |
| C\(^2\)         | 8.629E-005    | 1    | 8.629E-005  | 0.87    | 0.3662  |
| D\(^2\)         | 1.615E-008    | 1    | 1.615E-008  | 1.623E-004 | 0.9900 |
| Residual        | 1.491E-003    | 15   | 9.937E-005  |         |         |
| Lack of Fit     | 1.219E-003    | 10   | 1.219E-004  | 2.24    | 0.1933  |
| Pure error      | 2.720E-004    | 5    | 5.441E-005  |         |         |
| Corr. Total     | 0.050         | 29   |             |         |         |

R\(^2\) = 0.9699 \quad \text{Adeq. Precision} = 21.246 \quad \text{Pred.R}^2 = 0.8816

In order to adjust the fitted quadratic model for ROC the non-significant terms are eliminated by backward elimination process. The final quadratic model of ROC is determined as follows:

\[
\text{ROC} = 0.19 + 0.041A + 0.027D - 7.406 \times 10^{-3} AD - 4.381 \times 10^{-3} CD + 0.029A^2 + 7.895 \times 10^{-3} D^2
\]
Then test of the normality assumptions of the data is conducted and it can be seen in Fig. 2 that all the points on the normal plot come close to forming a straight line. This indicates that the data are fairly normal and there is no deviation from the normality. Further, each experimental data is compared with the predicted data calculated from the model and is represented in the Fig. 3. It is clear that predicted values match the experimental values reasonably well for ROC of Incoloy 800 material in EDM.

4.2 Effect of EDM parameters on the ROC

Radial overcut is the inherent parameter to the EDM process which is unavoidable though suitable compensations are provided at the tool design. In order to achieve the greater accuracy in EDM process overcut should be minimum. Therefore, parameters affecting the overcut are essential to recognize.
can be seen that minimum overcut occurs for a minimum level pulse-off time and near to minimum level of current, but the influence of current is larger than that of pulse-off time.

Fig. 6 Response surface plot for ROC Vs pulse-on time and pulse-off time

Fig. 7 Response graph for ROC Vs voltage and current

Fig. 6 shows the effect of pulse-on time and pulse off-time on ROC. It is clear that lower ROC occurs for a lower pulse off-time and lower value of pulse-on time and also note that the middle level of both factors are not a good condition for lower overcut but the extreme levels are good. Fig. 7 shows the influence of both voltage and current on ROC. It can be seen that minimum ROC occurs for a minimum level of voltage and current and also it is cleared that ROC depends more on current than on voltage.

Fig. 8 Response surface plot for ROC Vs voltage and pulse-on time

Fig. 9 Response graph for ROC Vs voltage and pulse-off time

Fig. 8 shows the influence of voltage and pulse-on time on ROC. A minor ROC occurs for the lower values of voltage and pulse-on time. It is cleared that ROC depends more on voltage than pulse-on time. Fig. 9 shows the effect of voltage and pulse-off time on ROC. A minimum ROC occurs for minimum levels of voltage and pulse-off time. It can be seen that the influence of voltage is larger than that of pulse-off time.

5. Conclusions

In this study, an attempt was made to apply response surface methodology for prediction of ROC in electrical discharge machining of Incoloy 800 with copper electrode. Thirty experiments were conducted successfully for four input parameters at three levels as per central composite design (CCD) method. The mathematical model for ROC has been developed on the basis of RSM by utilizing the experimental results. ANOVA results show that current and voltage are highly significant parameters, while pulse-on time and pulse-off time are non-significant parameters by considering ROC response. The predicted values match the experimental results reasonably well with the coefficient of determination of 0.9699 for ROC. From the response surface plots, it is cleared that lower level of current and voltage minimizes the ROC considerably. This study demonstrates that response surface methodology can be successfully used to model input machining parameters of
EDM process for Incoloy 800 super alloy. In future the study can be extended for developing models for other responses like MRR, TWR and SR.

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