Journal of Engineering Science and Technology
Vol. 10, No. 6 (2015) 780 - 789
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OPTIMIZATION OF PROCESSING PARAMETERS IN ELECTROCHEMICAL MACHINING OF AISI 202 USING RESPONSE SURFACE METHODOLOGY

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Abstract

This paper attempts to optimize the predominated machining parameters in Electro Chemical Machining (ECM) of AISI 202 Austenitic stainless steel using Response Surface Methodology (RSM). The chosen material has been used in railway rolling stock. The selected influencing parameters are applied voltage, electrolyte discharge rate with three levels and tool feed rate with four levels. Thirty six experiments were conducted through design of experiments and central composite design in RSM was applied to identify the optimum conditions which turn into the best Material Removal Rate (MRR) and Surface roughness (SR). The experimental analyses reveal that applied voltage of 16 V, tool feed rate of 0.54 mm/min and electrolyte discharge rate of 10 L/min would be the optimum values in ECM of AISI 202 under the selected conditions. For checking the optimality of the developed equation, MRR of 298.276 mm^3/min and surface roughness Ra of 2.05 μm were predicted at applied voltage of 12.5 V, tool feed rate of 0.54 mm/min and electrolyte discharge rate of 11.8 L/min with composite desirability of 98.05%. Confirmatory tests showed that the actual performance at the optimum conditions were 291.351 mm^3/min and 2.17 μm. The deviation from the predicted performance is less than 6% which proves the composite desirability of the developed models for MRR and surface roughness.

Keywords: Electrochemical machining, Material removal rate, Surface roughness, Response surface methodology, Optimization.

Nomenclatures

F	The ratio of the model SS/residual SS
NaCl	Sodium chloride
P	Stepwise regression function
X_1	Voltage, V
X_2	Federate, mm/min
X_3	Electrolyte discharge rate. L/min
Y_u (MRR)	Response of MRR

Abbreviations

ANOVA	Analysis Of Variance
DOF	Degrees Of Freedom
ECM	Electrochemical machine
IEG	Inter Electrode Gap
MRR	Material Removal Rate
MS	Mean Square
RSM	Response Surface Methodology
SS	Sum of Squares

1. Introduction

Advanced materials have a high importance especially for applications in the automobile, metal forming and aerospace industries. The ECM process offers an excellent solution to machine precisely those kinds of materials. There is an extremely low generation of thermal energy between the tool-electrode and workpiece being machined during the ECM-machining. It does not affect material microstructure and does not create cavities in metallic materials [1].

ECM technology is preferred in the field of machining steels due to low thermal energy and complete absence of tool wear [2]. These advantages lead ECM technology to be applied in non- machinable or poor machinable or hard materials such as AISI 202 Austenitic stainless steel, High carbon high chromium (HCHC) die steel and super alloys [3, 4]. The value consistency of an inter electrode gap (IEG) in ECM depends on various factors namely electrolyte temperature, thickness of the generated passive layer and the effectiveness in removal of residues from IEG. These factors play a vital role in promoting a constant current density at the IEG which results in obtaining a better Material removal rate (MRR) and surface roughness [5]. Hence, the optimal use of ECM demands consistent current density in ECM through the selection of optimum parameters [6]. Since the ECM process needs high initial investment, tooling and maintenance costs, the optimum selection of process parameters is demanded in achieving better results [7].

The present research paper attempts to develop a mathematical model using Response surface methodology (RSM) for correlating the interactive and higher-order influences of the machining parameters namely applied voltage, tool feed rate and electrolyte discharge rate on the most dominant machining criteria; MRR and surface roughness.

2. Experimental Setup

Figure 1 shows the ECM used for experiments which consists of machining unit, control panel and electrolyte tank. The workpiece and tool are the anode and cathode respectively which is separated by an electrolyte solution with a controlled electrical conductivity. The copper tool and the aqua solution of 15% NaCl were selected for the experimentation. It was completely analyzed using water testing kit and electrolyte temperature was continuously monitored for maintaining the range between 27^{o}C – 30^{o}C in order to control the properties of electrolyte. Surface roughness (*Ra*) value was computed by the average of measurements taken in three different positions. A digital flow meter with two digit accuracy was employed to adjust the volumetric flow of electrolyte to the ECM process. The electrolyte was passed from the reservoir to the tool which is tubular in form and laterally insulated by polymers in order to avoid stray current effects on the machined workpiece. IEG was set as 0.1 mm and maintained throughout the experimentation.

The selected workpiece material AISI 202 Austenitic stainless steel is one of the highest corrosion resistant and poor machinability materials with hardness of 88 in HR_b scale [8]. The complete chemical composition is presented in Table 1. Material removal (MR) is the difference in weight between before and after machining. The accuracy of weight difference measurement was ensured by Sartorius electronic weighing machine with three digit accuracy. Mitutoyo surface tester with a range of 0-150 μm was used for measuring surface roughness (*Ra*). The process parameters used in the experiment is presented in Table 2.

Fig. 1. ECM Setup.

Table 1. Chemical Composition of AISI 202.

Element	C	Cr	Mn	Ni	P	Mo	Co	S	Fe
Wt %	0.107	13.98	9.75	0.189	0.052	0.0162	0.033	0.005	73.7

Table 2. Process Parameters.

Applied voltage (V)	12, 15 and 18
Inter electrode gap (mm)	0.1
Tool feed rate (mm/min)	0.1, 0.21, 0.32 and 0.54
Electrolyte discharge rate (L/min)	8, 10 and 12
Selected electrolyte	15 % NaCl aqua solution
Tool-electrode condition	Stationary
Electrolyte temperature range (^{o}C)	27^{o}- 30^{0}
Workpiece material with its hardness	AISI 202 - 88 HR_B
Machining time (min)	3

3. Experimental Design and Response Surface Modeling

Design of Experiment (DoE) is applied to determine the relationship among the selected influencing variables namely tool feed rate, applied voltage and electrolyte discharge rate using MINITAB software. Three levels of experimentation on influencing parameters; applied voltage and electrolyte discharge rate and four levels of experimentation on tool feed rate were considered. It is possible to assess the main and interaction effects of different process parameters using the developed L_{36} array. A first-order experiment was performed to determine the magnitudes of the relative changes to the process variables that would result in a better MRR and surface roughness [9, 10]. Subsequently, a second-order central composite design was selected to identify the optimum conditions which turn into the optimum MRR and surface roughness. The RSM contour locates the optimum range of influencing parameters in obtaining the optimum MRR and surface roughness.

The general second –order polynomial mathematical model used for optimization of process parameters is shown below.

$$Yu = b_0 + \sum_{i=1}^{n} b_i x_{iu} + \sum_{i=1}^{n} b_{ii} x^2_{iu2} + \sum_{i<j}^{n} b_{ij} x_{iu} x_{ju} \tag{1}$$

where *Yu* is the response like MRR, surface roughness, etc., The terms b_0, b_i, etc., are the second-order regression coefficients. The results could be obtained by conducting a series of experiments for various sets of parametric combinations.

3.1. Mathematical model of MRR

The mathematical models that influence the selected objectives are evaluated using MINITAB. Equation (2) shows the developed mathematical model for MRR.

$$Yu(MRR) = -272.013 + 39.78X_1 + 52.021X_2 - 1.997X_3 + 1.131X_1^2 + 12.554X_2^2 + 10.805X_3^2 + 5.641X_1X_2 + 9.071X_1X_3 - 1.802X_2X_3 \quad (2)$$

where X_1, X_2 and X_3 represent the applied voltage, tool feed rate and electrolyte discharge rate respectively.

The degree of fitness of the developed mathematical model was confirmed through ANOVA and presented in Table 3. The value of R^2 is found to be 96.8% which confirms the accuracy of fitness of the mathematical model.

Table 3. ANOVA Results for MRR of AISI 202 Austenitic Stainless Steel.

Source	Regression	Linear	Square	Interaction	Residual Error	Total
DOF	9	3	3	3	26	35
SS	95685.0	91849.7	2058.6	1776.7	3198.4	98883.4
MS	10631.7	29849.4	686.2	592.2	123.0	--
F	86.43	242.65	5.58	4.81	--	--
P	0.000	0.000	0.004	0.008	--	--

3.2. Mathematical modeling of the surface roughness

Equation (3) is mathematical model of surface roughness in which X_1, X_2 and X3 represent applied voltage; tool feed rate and electrolyte discharge rate respectively.

$$Yu(Surface\ roughness) = 2.84 - 0.05X_1 - 0.529X_2 - 0.014X_3 - 0.145X_1^2 + 0.1X_2^2 + 0.064X_3^2 + 0.074X_1X_2 + 0.14X_1X_3 + 0.025X_2X_3 \quad (3)$$

The result of goodness fit obtained from ANNOVA is tabulated in Table 4. The value of R^2 is found to be 92% which confirms the fitness of the mathematical model.

Table 4. ANOVA Results for Surface Roughness of AISI 202 Austenitic Stainless Steel.

Source	Regression	Linear	Square	Interaction	Residual Error	Total
DOF	9	3	3	3	26	35
SS	6.41547	5.75169	0.27063	0.39316	1.67142	8.08689
MS	0.71283	1.83219	0.09021	0.13105	0.06429	--
F	11.09	28.50	1.40	2.04	--	--
P	0.000	0.000	0.264	0.133	--	--

4. Results and Discussion

4.1. Analysis of the influencing parameters on MRR

The experimental studies were carried out to analyze the effects of the various process variables on MRR using the developed mathematical model.

Response surface plot for MRR was generated and shown in Fig. 2. It shows the effects of applied voltage and tool feed rate on MRR for AISI 202 Austenitic stainless steel at 10 L/min electrolyte discharge rate. The value of R^2 is more than 95% which means that regression model provides an excellent relationship between independent variables and response. Associated p-value for model is less than 0.05 which represents that the linear effect of applied voltage and non-linear effect of tool feed rate on the MRR are significant.

The contour plots have significantly strengthened the relationship between the influencing parameters and MRR. At higher voltages, MRR increases with the increase of tool feed rate. The increase in electrolyte discharge rate improves the ECM performance at higher feed rates and voltages. It is due to effective flushing of the residues and gases from the IEG and results in an improved current intensity yielding an improved MRR. A maximum MRR of 410.214 mm^3/min is achieved under tool feed rate of 0.54 mm/min, electrolyte discharge rate of 12 L/min and applied voltage of 18 V conditions.

From Fig. 3, it is observed that the MRR pattern rapidly changed at 10 L/min for all tool feed rate conditions. The current density is apparently lower at lower voltages. 10 L/min electrolyte discharge rate helps to distribute current density uniformly across over the IEG which results better MRR. However the removal rate would be higher due to high current density at higher voltages, hence it does not need higher electrolyte discharge rate in obtaining better MRR. This is apparently shown by contour plots shown in Figs. 3(a), (b) and (c).

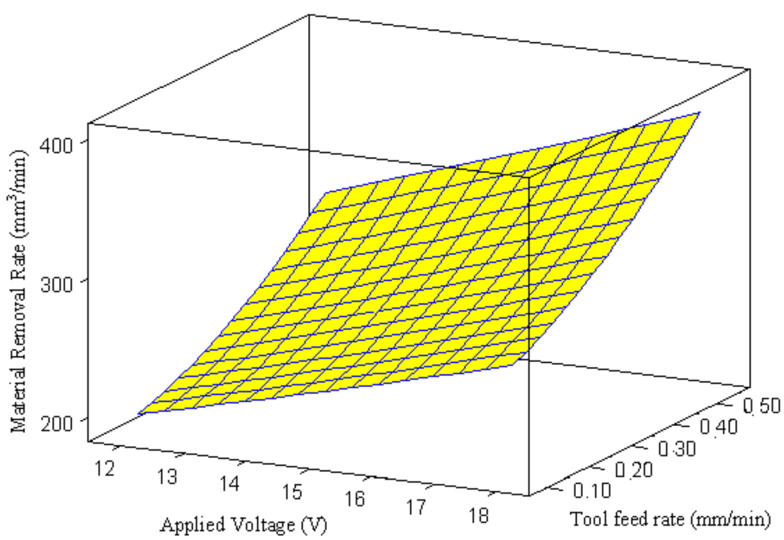

Fig. 2. Surface Plot for MRR with Applied Voltage and Tool Feed Rate at 10 L/min Electrolyte Discharge Rate.

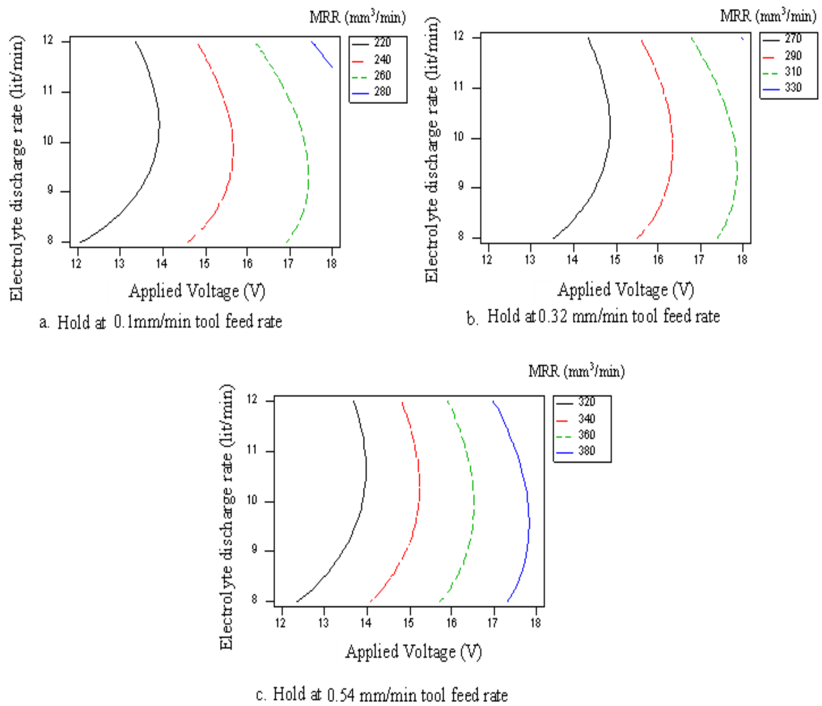

Fig. 3. Contour Plots for MRR on AISI 202 Austenitic Stainless Steel.

4.2. Analysis of the influencing parameters on the surface roughness

Figure 4 shows a mini-max response surface plot. The decrease in surface roughness is observed from the stationary point (saddle point) near the center of the design with the increase of applied voltage and tool feed rate at 16V. The effective removal rate of residues and gases from the IEG would be the deciding factors in obtaining a better surface roughness. Figure 5 shows the relationship between the influencing factors namely applied voltage, electrolyte discharge rate and the surface roughness in various feed rate conditions.

Surface roughness decreases with increase in feed rate which is confirmed through the surface roughness pattern line at 2.1 µm in Fig. 5(c). The significant effect of electrolyte discharge rate on surface roughness is clearly noticed at 10 L/min. A minimum value of surface roughness of 1.85 µm is observed under 15 V, 0.54 mm/min and 12 L/min conditions. The corresponding MRR is 342.22 mm^3/min which is 20% lower compared than obtained maximum MRR of 410.214 mm^3/min at the same working condition. But 34 % improved surface roughness is achieved at the compromise of some % of MRR.

Other influencing variables in the effect of surface finish may be gas layer at IEG, variation in temperature, concentration, conductivity of electrolyte, electrochemical equivalent of material, valance electron, etc.

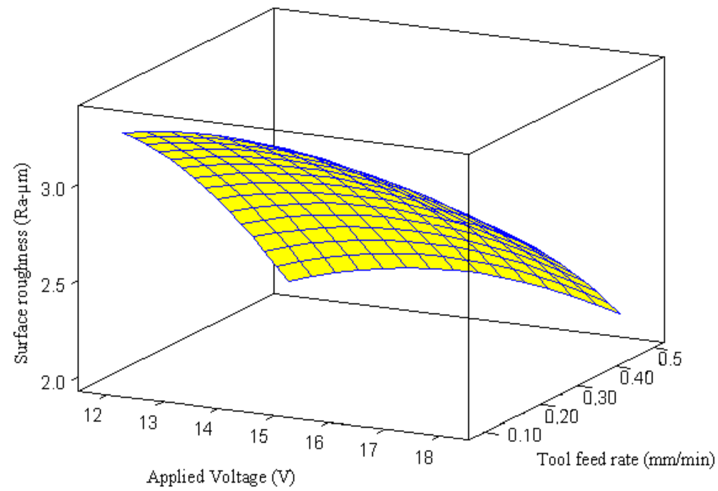

Fig. 4. Surface Plots for Surface Roughness with Applied Voltage and Tool Feed Rate at 10 L/min Electrolyte Discharge Rate.

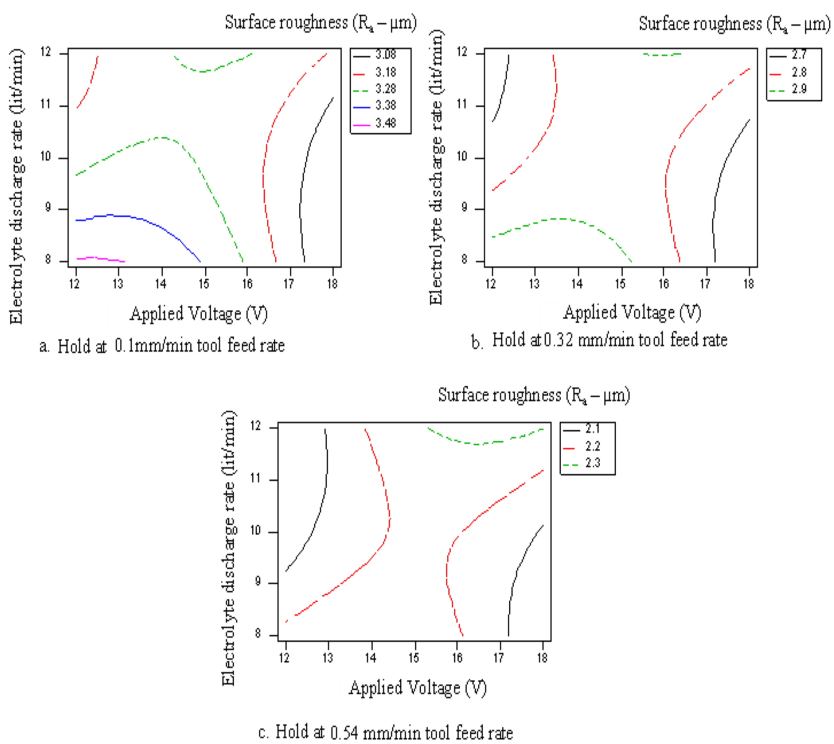

Fig. 5. Contour Plots for Surface Roughness on AISI 202 Austenitic Stainless Steel.

5. Analysis for Optimality Search

Optimality search test was carried out based on the developed second-order response, surface equations. This was carried out to determine the optimal combination of the machining parameters and their effects on the desired response criteria. It is known from the experiments that MRR of 298.276 mm^3 /min and surface roughness Ra of 2.05 µm were predicted at applied voltage of 12.5 V, tool feed rate of 0.54 mm/min and electrolyte discharge rate of 11.8 L/min with composite desirability of 98.05 %. The confirmatory tests showed that the actual performances at the optimum conditions are 294.351 mm^3/min and 2.17 µm. A deviation of less than 5% is noticed between them proves the composite desirability of the developed models for MRR and surface roughness and good and fit.

6. Conclusions

The analysis of the experimental observations shows that MRR and surface roughness in ECM is greatly influenced by the various process parameters. Based on the experimental results, the following conclusions are drawn.

- Material removal rate increases linearly with applied voltage and non-linearly increases with tool feed rate.
- Surface roughness decreases with increase in the applied voltage and electrolyte discharge irrespective of tool feed rates.
- The optimum range of influencing parameters in obtaining a better MRR and surface roughness is observed from RSM contours.
- The results reveal that applied voltage of 16 V, tool feed rate of 0.54 mm/min and electrolyte discharge rate of 10 L/min would be the optimum values in ECM of AISI 202 under the selected conditions.
- Only a deviation of less than 5% is noticed in confirmatory test which prove the composite desirability of the developed models for MRR and surface roughness.

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