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Effect of Electrolyte Concentration on Material Removal Rate and Overcut during Machining of SG Iron

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Abstract: Electrochemical machining can be used effectively to machine SG Iron if mathematical models correlating the process parameters and the major outputs such as material removal rate (MRR) and overcut are developed. The primary objective of this work is to develop mathematical models based on design of experiments to correlate the controllable process parameters of ECM (feed rate, inter electrode potential, Inter electrode gap and electrolyte composition) with MRR and Overcut. Seventeen run Central Composite Design is used to develop mathematical models. SG Iron is selected as work piece material as very limited information is available on machining of SG iron using ECM. The functional requirement such as high MRR together with low Overcut is dependent on a number of process variables. Hence, the next objective is to use multi criteria optimization based on desirability function to find out the value of operating parameters that will ensure high rate of material removal along with low overcut. The values of operating parameters for high MRR with low overcut conditions are found. The mathematical models developed can be used effectively to select process variables to achieve desired optimum condition like high MRR with lower value of Overcut.

INTRODUCTION

Electrochemical machining is the controlled removal of metal by anodic dissolution in an electrolytic cell in which the work-piece is the anode and the tool is the cathode. ECM can be used to machine complex shapes in hard and brittle materials. ECM is used for operations as widely different as milling, drilling, turning, grinding and deburring. The material removal rate, accuracy and surface finish depend on many process parameters. Some of the basic controllable operating parameters of ECM are: initial gap between tool and work-piece, machining feed rate, inter electrode potential, concentration, temperature, pressure, flow rate, type, and pH level of inlet electrolyte. Some of the difficult or impossible to control parameters are electric field strength which depends on the shape of the electrode at any point, machining potential, flow regime, pressure, temperature and pH level of electrolyte during machining, passivation, hydrogen gas evolution and non uniform two phase flow of electrolyte, microstructure and composition (local) of work piece materials [1-8] . ECM results of only a few combinations of electrolyte and work-piece material, under specific machining conditions have been reported. It is clearly established that results reported in literature cannot be extrapolated. So for any new material - electrolyte combination and machining conditions experiments need to be conducted to predict the effects of process parameters on machined geometry.

SG Iron has emerged as an important category of engineering materials for making machine, automobile components because of the effective combination of lower cost of production compared to that of cast steel and its properties [9].

Little information is available on machining of SG Iron by electrochemical machining process. For commercial exploitation of ECM for machining SG Iron it is essential to develop models for predicting the nature of feature that will be generated. The present work is undertaken to study the material removal rate and overcut during machining of SG Iron using ECM.

Objectives: The primary objective is to develop second order regression equation for material removal rate (MRR) and Overcut for predicting and explaining their nature with respect to machining feed rate, inter electrode potential, Inter electrode gap and electrolyte composition.

The secondary objective is to utilize these mathematical models for finding the optimum combination of process variables for high MRR along with lower overcut.

Plan of Investigation

A. Following steps are followed to achieve the objectives.

1. Determining the useful limits of the variables namely machining feed rate, inter electrode potential, Inter electrode gap and electrolyte composition.
2. Selecting the design matrix to conduct the experiments.

3. Conducting the experiments as per the design matrix.
4. Developing mathematical models based on regression.
5. Checking the adequacy of the models.
6. Calculation Of desirability functions
7. Analysis of the results.

Determining the useful limits of the variables*:* Four controllable ECM parameters are selected. They are, feed rate, inter electrode potential, Inter electrode gap and electrolyte composition**.** The useful limits of the variables are chosen based on preliminary experiments conducted and information available in literature.

Selecting the Design Matrix: Central composite design [10] is selected for developing the mathematical models. The design matrix used for experimentation is a seventeen point central composite design. The matrix contains three process variables (feed rate, inter electrode potential, Inter electrode gap) at three levels. For simplifying the recording of the conditions of the experiments and processing of the experimental data, the variables are coded as +1, 0 & -1. Electrolyte composition is not included in the design matrix as it is difficult to conduct the experiments in random fashion. To circumvent the problem two sets of experiments are conducted using two electrolytes namely electrolyte 1: (NaCl 75 grams/litre of tap water + $NaNO_3$ 200 grams/litre of tap water) and electrolyte 2 (NaCl 150 grams/litre of tap water + $NaNO_3$ 200 grams/litre of tap water)

The actual and coded values of the four process variables are given in Table-1. The design matrix is shown in Table-2.

Experimentation:

For this work ECM machine model ECMAC - II, manufactured by MetaTech Industries, Pune, is used. Flat circular tool (17.203 mm diameter) made of copper is used. Work-piece material specification is given in table 3. All the experiments are conducted according to the design matrix but in random fashion to avoid any systematic error creeping into the results. MRR is calculated as: MRR = $(W_i - W_f) / \rho T$; Initial(W_i) and final (W_f) weight of specimen. ρ is the density of the material, T is the machining time. ρ is found experimentally to be 7.1 $g/cm^{3.}$. The experimental data is given in Table 4. Overcut is calculated as: OC=$(Dc - D_{tool}) / 2$.; Diameter of machined hole (Dc), diameter of tool (D_{tool}).To calculate the diameter of the tool and machined profiles, image processing software Analysis Five Pro is used. The pixel data of about 86 points on the boundary of the tool profile are measured. Then the data obtained are fitted to a circle based on the algorithms given by TaubinNTN[11] , KMvH[12], Pratt SVD[13] and PrattNTN[13]. The Matlab versions of these algorithms are given in [14]).All the algorithms gave same output. Taubin NTN algorithm is used to calculate diameter of machined profiles from 86 pixel data for each profile. The overcut values are given in Table 5.

Developing the Mathematical Model : To correlate the effects of the variables i.e. feed rate, inter electrode potential, Inter electrode gap and the response factor i.e material Removal Rate (MRR) and Overcut , the the following second order polynomial is selected.

$Y= \beta_0 + \beta_1F + \beta_2V + \beta_3G + \beta_{11}F^2 + \beta_{22}V^2 + \beta_{33}G^2 + \beta_{12}FV + \beta_{13}FG + \beta_{23}VG$, Where**, β**'s are regression coefficients and F, V and G are the ECM process parameters as mentioned in Table-1.

Checking the Adequacy of the Models: The analysis of variance (ANOVA) technique [10] is used to check the adequacy of the developed models. F-ratios of the models developed are calculated and are compared with the corresponding tabulated values for 95% level of confidence. If the calculated values of F-ratio did not exceed the corresponding tabulated value then the model is considered adequate. The goodness of fit of the models are tested by calculating R^2, $R^2_{(adjusted)}$ & $R^2_{(predicted)}$. The models are developed using the software package Design Expert [15]. The coefficients of the models developed and the model statistics for MRR are given in Table-6, and for Overcut it is mentioned in Table-7. All the models are statistically adequate.

Calculation Of Desirability Function: The Design Expert® V.9 [15] software is used for finding the optimum values of process variables for material removal rate and overcut based on desirability function[13].Each response parameter is transformed in to a desirability function using criteria larger– the -better, Smaller – the- better or target –the- best[15]. The overall desirability considering two or more response parameters are found by calculating geometric mean of the individual desirability functions. The geometric mean is then maximized over the region of interest. Normally the value of desirability function varies between 0 and 1.

Analysis of results:

For the ease of discussion machining feed, inter electrode potential, inter-electrode gap, material removal rate will be referred to as feed, potential, gap, MRR respectively. Fig.1 shows the variation of MRR with the variations in potential and gap with electrolyte 1. It is also observed that the trend shown in fig 1 does not change with change in feed. MRR is highest between 0 and 0.2 of potential and at maximum and minimum of gap. As feed increases, MRR increases. Increase in feed usually results in smaller gap between tool and work piece leading to higher current density, hence more MRR. The rate of increase in MRR is more between -1 and 0 levels of feed. Beyond that rate of increase in MRR is very small. But the trend changes when the electrolyte -2 is used. Figs2 shows that maximum MRR is obtained at a gap range of 0.4-0.5and at potential of +1 level. The rate of increase in MRR with increase in feed is more in the case of electrolyte 2 than in electrolyte 1. In case of mixed electrolytes (NaCl + $NaNO_3$) the current efficiency increases with increase in chloride to nitrate ratio [16] The current efficiency in case of NaCl is approximately independent of gap, where as for NaNO3 the current efficiency is strongly depends on the gap [17]. As the concentration of NaCl is double in electrolyte 2 compared to that of electrolyte 1, hence the increase in MRR.

For electrolyte 1, as feed increases the overcut decreases (fig. 3). Minimum overcut is at -1 level of voltage and at +1 level of gap. For electrolyte 2, feed has negligible effect on overcut. Minimum overcut is at -1 level of voltage and at -1 level of gap (fig.4). As voltage increases, current increases and that leads to larger overcut [17].

3. Multi-Optimization using Desirability Function.

The conditions for multi-criteria optimization for electrolyte 1&2 are given in tables 7&9 .The process variables are given in their coded values and the responses (MRR and overcut) are in their actual values. The highest desirability value obtained for maximum MRR and Minimum Overcut for electrolyte 1 is 0.867 (table 8) corresponding to the coded process parameter values of feed= 1.00 , inter electrode potential =-0.486, inter electrode gap=1.000.The optimum values of the responses are **MRR= 0.052** cm^3/min and **Overcut =0.818** mm. Similarly, The highest desirability value obtained for maximum MRR and Minimum Overcut for electrolyte 2 is 0.871 (table 10)

Conclusions:

1. Mathematical models based on Central composite design have been developed to predict the effect of feed rate, inter electrode potential, Inter electrode gap and electrolyte composition on Material removal rate and Overcut.

2. As feed increases, MRR increases. In the case of electrolyte1, the rate of increase in MRR is more between -1 and 0 levels of feed. Beyond that rate of increase in MRR is very small. The rate of increase in MRR with increase in feed is more in the case of electrolyte 2 than in electrolyte 1 as the current efficiency is more with NaCl solution than with $NaNO_3$ solution.

3. For electrolyte 1, as feed increases the overcut decreases. Minimum overcut is at -1 level of voltage and at +1 level of gap.

4. For electrolyte 2, feed has negligible effect on overcut. Minimum overcut is at -1 level of voltage and at -1 level of gap.

5. The highest desirability value obtained for maximum MRR and Minimum Overcut with electrolyte 1 is 0.867 and for electrolyte 2 it is 0.871. The corresponding conditions for feed, inter electrode potential and inter electrode gap have been found.

Table 1. **The Actual and Coded Values of Different Variables**

Variables	Symbols	Levels			Unit
		-1	0	+1	
Machining Feed	F	0.1	0.21	0.32	mm/ min
Inter electrode potential	V	12	16	20	Volts
Inter electrode gap	G	1.0	2.1	3.2	mm

Table.2 : Three level face centered composite design matrix.

Experiment no.	Time (min)	Voltage(volts)	Gap(mm)
1	+1	+1	+1
2	-1	+1	+1
3	+1	-1	+1
4	-1	-1	+1
5	+1	+1	-1
6	-1	+1	-1
7	+1	-1	-1
8	-1	-1	-1
9	+1	0	0
10	-1	0	0
11	0	+1	0
12	0	-1	0
13	0	0	+1
14	0	0	-1
15	0	0	0
16	0	0	0
17	0	0	0

Table 3. Specification of work-piece material.

Chemical composition					BHN	Nodularity	Matrix
%C	%Si	%Mn	%S	%P			
3.60-3.63	2.30-2.38	0.35-0.36	0.014-0.013	0.083-0.080	179	58.24	Ferritic

Table 4. Material removal rate (MRR) gm/cm^3

Experiment no.	MRR for electrolyte1	MRR for electrolyte 2
1	0.0364	0.0252
2	0.0262	0.0157
3	0.0416	0.0144
4	0.0112	0.0106
5	0.0447	0.0502
6	0.0282	0.0269
7	0.0525	0.0431
8	0.0184	0.0234
9	0.0450	0.0521
10	0.0247	0.0302
11	0.0324	0.0428
12	0.0209	0.0292
13	0.0512	0.0163
14	0.0563	0.0346
15	0.0516	0.0286
16	0.0548	0.0317
17	0.0432	0.0383

Table 5. Overcut (mm)

Ex no.	Overcut for electrolyte1	Overcut for electrolyte 2
1	1.12175	2.1119
2	1.93895	2.17415
3	0.60235	1.508
4	1.4745	1.49065
5	1.11315	1.37445
6	1.35815	1.91784
7	1.007	1.0978
8	1.6865	1.1684
9	1.25585	2.2838
10	1.9019	2.24065
11	1.43265	1.8249
12	1.20785	1.1768
13	1.3059	1.773
14	1.3499	1.93345
15	1.62865	1.9536
16	1.3121	2.2244
17	1.8454	1.8914

Table 6: The Coefficients of the Models Developed and the Statistical Model Parameters

		MRR for electrolyte 1	MRR for electrolyte 2	Overcut for electrolyte1#	Overcut for electrolyte &
Coefficients Of The Models Developed	Bo	0.04606	0.03527	1.23964	0.49365
	B1	0.01115	0.00782	-0.14355	*
	B2	0.00233	0.00401	0.047741	-0.12201
	B3	-0.0035	-0.00960	-0.00997045	-0.070153
	B11	-0.00836	0.00407	0.025521	*
	B22	-0.01656	-0.00108	-0.076371	0.17445
	B33	0.01054	-0.01163	-0.072043	*
	B12	-0.00472	0.00116	0.036208	*
	B13	-0.00125	-0.00371	-0.045752	*
	B23	0.00098	0.00066	0.067860	*
	FRATIO	0.72735	0.68092	0.9912	0.2638
	σ^2	0.00004	0.00002	0.012	0.0021739
	R^2	93.59	94.50	0.9279	0.8343
	R^2 (adj)	85.35	87.44	0.8351	0.7961
	R^2 (pred)	75.64	75.27	0.8183	0.6786

*dropped, Transformation used # A**0.5, & 1.0/A

Table 7. The conditions for multi criteria optimization for electrolyte 1.

		Constraints				
		Lower	**Upper**	**Lower**	**Upper**	
Name	**Goal**	**Limit**	**Limit**	**Weight**	**Weight**	**Importance**
A:A	is in range	-1	1	1	1	3
B:B	is in range	-1	1	1	1	3
C:C	is in range	-1	1	1	1	3
MRR1	maximize	0.0112	0.0563	1	1	3
Overcut	minimize	0.60235	1.93895	1	1	3

Table 8. Optimized Condition for electrolyte 1.

Machining Feed	Inter Electrode Potential	Inter Electrode Gap	MRR1	Overcut	Desirability
1.000	-0.486	1.000	0.052	0.818	0.867

Table 9. The conditions for multi criteria optimization for electrolyte 2.

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:A	is in range	-1	1	1	1	3
B:B	is in range	-1	1	1	1	3
C:C	is in range	-1	1	1	1	3
MRR2	maximize	0.0106	0.0521	1	1	3
overcut	minimize	1.0978	2.2838	1	1	3

Table 10. Optimized Condition for electrolyte 2.

Machining Feed	Inter Electrode Potential	Inter Electrode Gap	MRR1	Overcut	Desirability
1.000	-1.000	-0.737	0.045	1.196	0.871

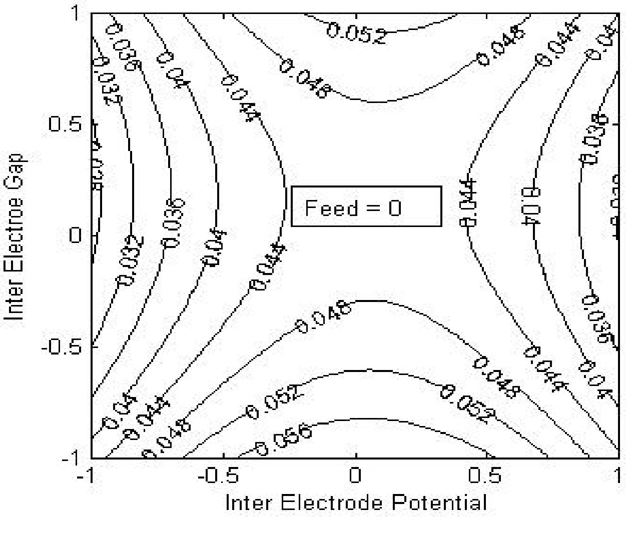

Fig.1 Variation in overcut with electrolyte 1

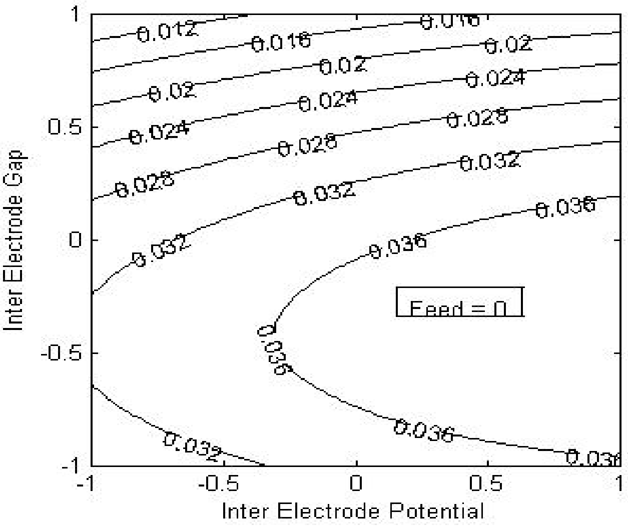

Fig.2 Variation in MRR with electrolyte 2

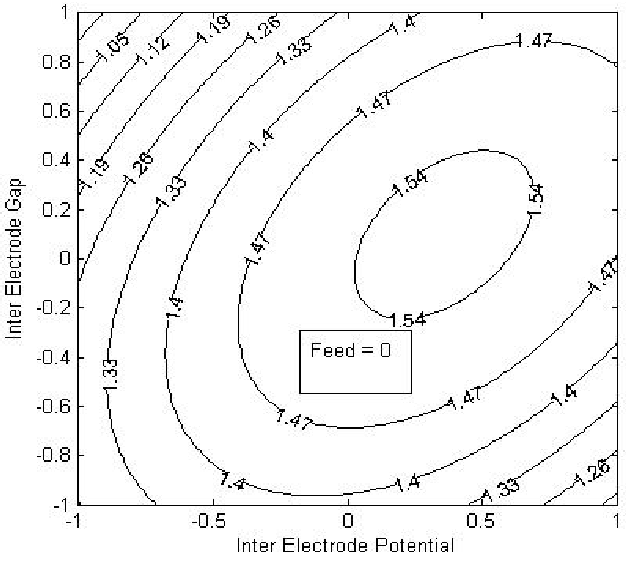

Fig.3. Variation in overcut with electrolyte 1

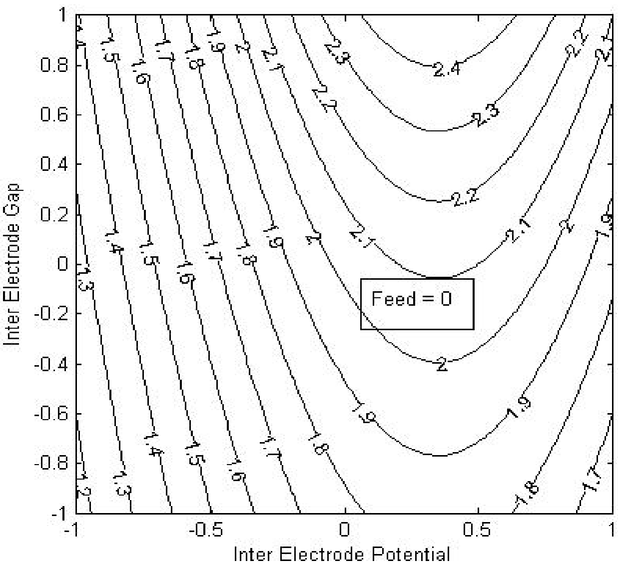

Fig. 4 Variation in overcut with electrolyte 2

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