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Multicriteria Optimization of Surface Roughness Produced in Electro Chemical Machining using a mixed electrolyte NaNO3 and NaCl

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Abstract: Surface roughness effects on the functional properties of the work piece surface that have indirectly influenced on the quality of product. To analyze functional properties of the work piece surface such as friction, wear or lubrication, a single surface parameter is not enough. So, multiple surface parameters are required to study the functional property of the work piece surfaces. The objective of this experiment is to develop mathematical models based on central composite design under RSM to analyze the effect of controllable process parameters such as inter electrode potential, machining time and gap on surface parameters like S_q, S_{ku}, S_{sk}, S_{mmr}, S_{mvr}, S_{HTp} during machining of SG iron (pearlitic grade) by ECM and multi-criteria optimization based on Desirability Function is carried out to find the best values of the controllable parameters for minimum coefficient of friction for low wear under dry and lubricated conditions based on four surface parameters S_q, S_{sk}, S_{ku}, $S_{HTp.}$

Keywords: SG iron, surface roughness, RSM, multicriteria optimization and desirability function Introduction.

I. INTRODUCTION

Electrochemical machining, a non-traditional machining process, has an important characteristic of machining very complex features on hard and brittle materials with small tool wear and permissible accuracy. Electrochemical machining is controlled metal removal by anodic dissolution in which work piece is use as anode and tool as cathode. The electrolyte is pumped through the gap between the tool and the work piece (the machining gap); while direct current is passed through the cell at a low inter electrode potential to dissolve metal from the work piece at high efficiency. The accuracy of ECM output is mainly depends on a large number of controllable and uncontrollable process parameters such as inter electrode gap, machining feed rate, applied inter electrode potential, Flow regime, pressure, temperature, type and composition of electrolyte, pH level of electrolyte during machining and work piece material composition [1-8]. Surface roughness influences the functional properties of the work piece surface [9-11] and as a result it indirectly influences the quality of product. So to estimate surface roughness two dimensional surface parameters like R_a, $R_{q,}$ $R_{z,}$ and Rt are usually used to characterize the surface roughness. However, two dimensional parameters do not give a complete information about the machined surface so three dimensional surface parameters are used to analyze the surface feature and it is reported that these parameters more effective for surface characterization than the two dimensional one [12-14].

Functional requirement such as low wear depends on a combination of parameters. Friction and wear are reported to depend on surface roughness parameters such as R_a, R_q, R_t,R_z, R_{sk}, R_{ku}, R_{DelA},W_a [9]. Wear is reported [15] to be higher when the initial values of the amplitude parameters S_k, S_q and S_{Htp} as well as rms slope S_{Dq} are high. In case of dry wear test, coefficient of friction is low when roughness is high. In lubricated case, when roughness is low, then coefficient of friction is low [16]. It is reported [16] that increase in parameter R_{ku} led to increase in friction in lubricated case and decrease in friction in dry tests. Friction also observed to be lower when the parameter R_{sk} tends to be more negative in lubricated tests. The material chosen is SG Iron (pearlitic grade) as little information is available on machinability of this material using ECM. It is reported that as carbon percentage increases machining becomes more difficult [17].

In first sub section, regression models are developed based on Response Surface Methodology for correlating different surface roughness parameters such as S_q, S_{sk}, S_{ku}, S_{mmr}, S_{mvr}, S_{HTp} with the controllable ECM process parameters inter electrode potential, machining time and inter-electrode gap.

In second subsection, multi-criteria optimization based on Desirability Function is carried out to find the best possible values of the controllable process parameters for minimum coefficient of friction for dry and lubricated conditions.

II. MATHEMATICAL MODEL

For developing the models Central Composite Design is used for performing a series of experiments. Three important process variables namely inter electrode potential, machining time and inter-electrode gap are selected for this work. The upper and lower limits of these variables are selected based on preliminary experiments. The actual and coded values of the different variables are given in Table-1. The design matrix is shown in Table-2. The experiments are carried out as per the design matrix but in random order.

IIa. Experimentation

ECM machine model ECMAC - II, manufactured by MetaTech Industries, Pune, is used with a round shaped tool made of copper. Electrolyte used is a mixture of NaCl and $NaNO_3$ solution (125 grams of NaCl and 250 grams of $NaNO_3$ / litre of tap water). Work piece material selected is SG Iron 450/12 grade received courtesy M/s. Hindustan Malleables & Forging Ltd., Dhanbad, India. The chemical composition of the material is given in Table *3*.The material has pearlitic matrix. The microstructure as captured by using JEOL 5600 Scanning Electron Microscope (SEM) is shown in Fig.1. Hommel Tester T-8000 is used for measuring the surface parameters.

Table-1 The Actual and Coded Values of Different variables.

Variables	symbol	Low level		Medium level		Higher level	
		Actual	Coded	Actual	Coded	Actual	coded
Inter electrode potential(v)	V	15	-1	20	0	25	+1
Machining time(min)	T	2	-1	3	0	4	+1
Inter electrode gap(mm)	G	0.64	-1	0.96	0	1.28	+1

Table-2 Design matrix.

SL NO.	variables		
	V	T	G
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
18	0	0	0

Table-3 Chemical composition of SG iron

Element	C	Si	Mn	P	S	Cr	Mo	Cu	Mg	Ti	Zn	Fe	Others
%	3.365	2.393	0.238	0.072	<0.15	0.007	<0.01	0.37	0.085	0.032	0.027	90.75	2.66

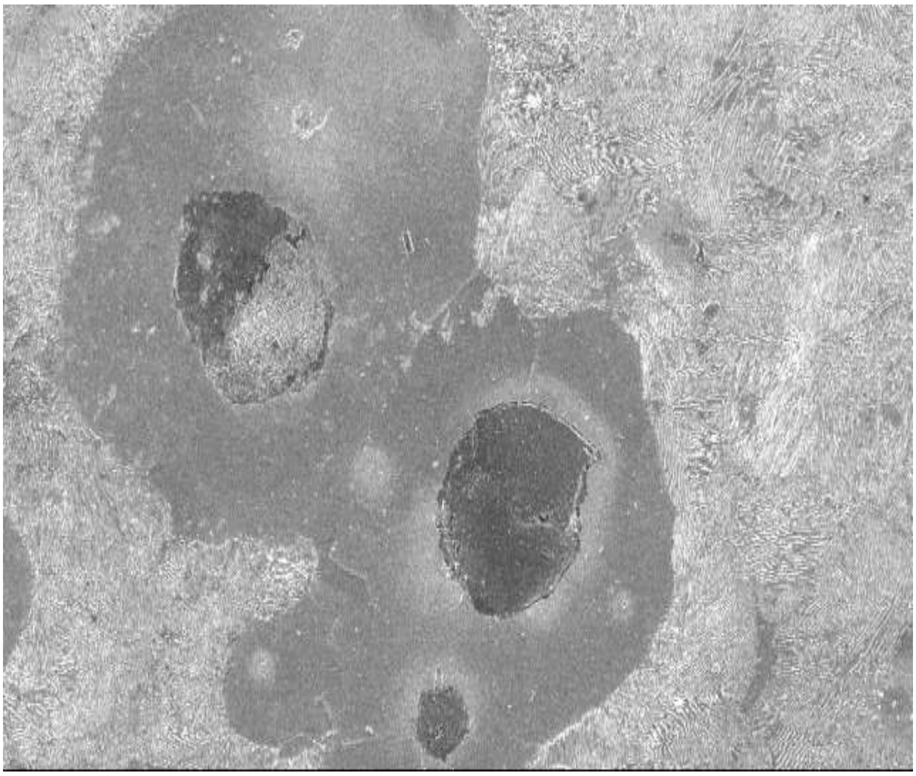

Fig.1 - Image at 5kv x500 50 m 0085 AMPRI

IIb. DEVELOPING THE MODELS

To analyze the effects of the process variables on the surface roughness parameters such as S_q, Ssk, Sku, S_{mmr}, S_{mvr}, S_{Htp}, the following second order polynomial is used.

$$Y = Bo + B1T+ B2V +B3G+ B11T^2 + B22V^2 +B33G^2 +B12TV+B13TG+B23VG \; . \; . \; . \; . \; . \; . \; . \; (1)$$

Where, B's are the regression coefficients. V, T, G are the controllable process parameters in coded form. To check the adequacy of the statistical regression models analysis of variance are carried out. 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, $R^2_{(adjusted)}$ & $R^2_{(predicted)}$. This analysis has been done using Design Expert V.9 [18]. The coefficients of the models developed and the model statistics for the models are given in Table-4.1 and Table-4.2. All the models are statistically adequate. To validate the models further one set of experiment are carried out at levels different than those of design matrix. The conditions and results are given in Table 5. The confidence interval is calculated based on the procedure given in reference [19].The calculated confidence interval with predicted response are given in Table 7. All the experimental values are within the confidence intervals. The predictions based on fitted equations are adequate only in the immediate neighbor -hood of the design.

Table-4.1 The Coefficients for surface roughness parameter

Co-efficient	S_q	S_{ku}	S_{sk}
B_0	11.55988095	2.75464	-0.317550952
B_1	2.562	0.165	0.16968
B_2	0.932	-0.227	-0.21158
B_3	-2.017	0.045	-0.038599
B_{12}	2.4775	-0.11125	0.080125
B_{13}	0.05	-0.04125	0.013675
B_{23}	0.355	-0.39125	-0.229375
B_{11}	3.067738095	-0.306786	0.005351905
B_{22}	-0.382261905	0.573214	0.182851905
B_{33}	-2.997261905	-0.336786	0.280946905
F ratio	0.0517719	0.747067	0.068447
σ^2	1.840866	0.13	0.145454
R^2	0.8819079	0.9573	0.921507
R^2 (adj)	0.7490542	0.9092	0.833203
R^2 (pred)	0.7613867	0.8242	0.819541

Table-4.2 The Coefficients for surface roughness parameter

Co-efficient	S_{mmr}	S_{mvr}	S_{HTp}
B_0	0.026391667	0.029440476	20.00880952
B_1	0.00109	0.00799	6.042
B_2	0.00236	0.00246	1.198
B_3	-0.00455	-0.00447	-4.892
B_{12}	0.0060875	0.0069625	5.3025
B_{13}	0.0026125	-0.0006125	0.7525
B_{23}	0.0017125	-0.0029375	2.1225
B_{11}	0.009191667	- 0.004280952	8.357380952
B_{22}	- 0.002858333	0.014469048	-3.742619048
B_{33}	- 0.008708333	- 0.007880952	-3.192619048
F ratio	0.14454	0.326888	0.156004
σ^2	0.003775	0.004111	3.387263
R^2	0.897658	0.935211	0.921485
R^2(adj)	0.782523	0.862323	0.833155
R^2(pred)	0.744925	0.758827	0.783204

CALCULATION OF DESIRABILITY FUNCTION: Based on the literature survey it is decided to locate optimal process parameters for ECM based on low coefficient of friction for two cases i.e. dry and lubricated conditions. The conditions are:

1. Dry case-Max S_q, S_{HTp} and Miminum S_{sk}, S_{ku}

2. Lubricated case- Minimum S_q, S_{sk}, S_{HTp} and Maximum S_{ku}

The Design Expert® V.9 [18] software is used for finding the optimum values of process variables for material removal rate and overcut based on desirability function.Each response parameter is transformed in to a desirability function using criteria larger– the -better, Smaller – the- better or target –the- best. 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.

Table 5: - confidence interval of surface parameter

process parameter	coded	actual	responses	from experiment	from model	confidence interval
voltage (v)	-0.6	17	s_q	10	10.4460	4.3387
			s_{ku}	2.79	2.8144	0.3396
			s_{sk}	-0.207	-0.2006	0.3655
time (min)	-0.5	2.5	s_{mmr}	0.0274	0.0263	0.0095
			s_{mvr}	0.0258	0.0257	0.0104
			s_{htp}	17	17.3945	7.6421
gap (mm)	0.28125	1.05				

III. MULTIPLE OPTIMIZATIONS

The conditions for multi-factor optimization are given in tables 6&8.The process variables are given in their coded values and the responses (surface texture parameters) are in their actual values. The desirability value obtained for minimum wear in dry condition is 0.822 corresponding to the coded process parameter values of inter electrode potential= 1, electrode gap=0.248 and machining time=0.639.The optimum values of the surface parameters are S_q=18.59, S_{sk}= -0.177, S_{ku}=2.55 and S_{HTp}=36.14 (table7).Fig.2 shows the distribution of desirability value for dry condition. The desirability value obtained for minimum wear in lubricant condition is 0.73 corresponding to the coded process parameter values of inter electrode potential= -0.553, electrode gap=0.280 and machining time=1.The optimum values of the surface parameters are S_q=9.55, S_{sk}= -0.538, S_{ku}=2.86 and S_{HTp}=12.6 (table 9). Fig.3 shows the distribution of desirability value for lubricated condition.

Table 6: - Condition for dry case

		Lower	Upper	Lower	Upper	
Name	Goal	Limit	Limit	Weight	Weight	importance
voltage	In range	-1	1	1	1	3
machining time	In range	-1	1	1	1	3
gap	In range	-1	1	1	1	3
Sku	minimize	2.09	3.69	1	1	3
Sq	maximize	5.39	18.7	1	1	3
Ssk	minimize	-0.589	0.675	1	1	3
SHTp	maximize	8.98	37.1	1	1	3

Table 7: - optimum value process parameter corresponding their optimize responses at dry condition

VOLTAGE	MACHINING TME	GAP	Sku
1	0.639998	0.248647	2.555463
Sq	Ssk	SHTp	Desirability
18.59721	-0.17708	36.14663	0.822757

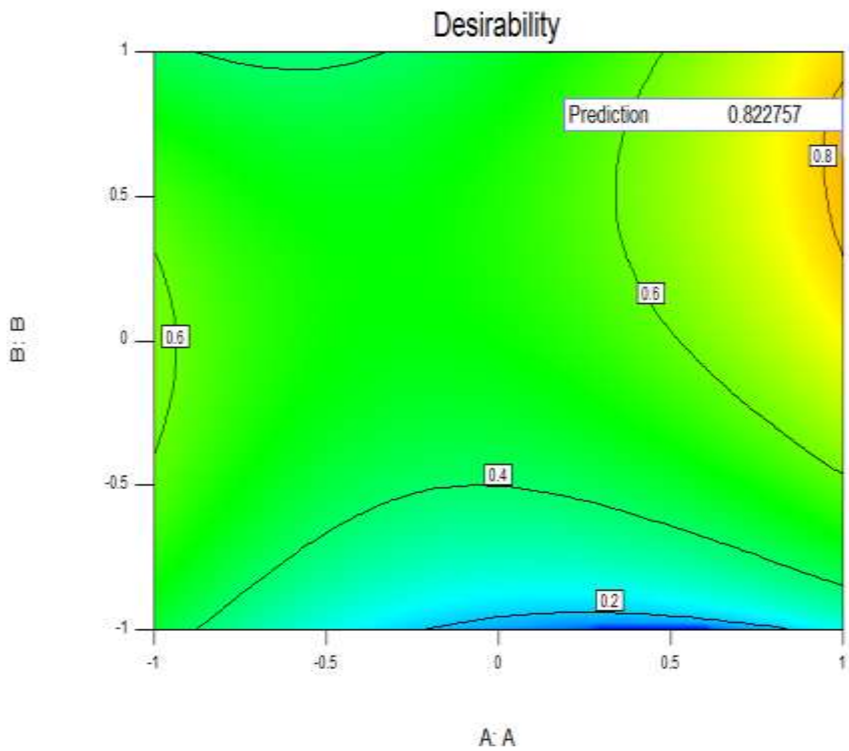

Fig.2 Contour graph showing desirability function values dry condition

Table 8: - Condition for lubricant case

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	importance
voltage	In range	-1	1	1	1	3
machining time	In range	-1	1	1	1	3
gap	In range	-1	1	1	1	3
Sku	maximize	2.09	3.69	1	1	3
Sq	minimize	5.39	18.7	1	1	3
Ssk	minimize	-0.589	0.675	1	1	3
SHTp	minimize	8.98	37.1	1	1	3

Table 9: - optimum value process parameter corresponding their optimize responses at lubricant condition

VOLTAGE	MACHINING TME	GAP	Sku
-0.553	1	0.280	2.861
Sq	Ssk	SHTp	Desirability
9.551	-0.538	12.601	0.725482

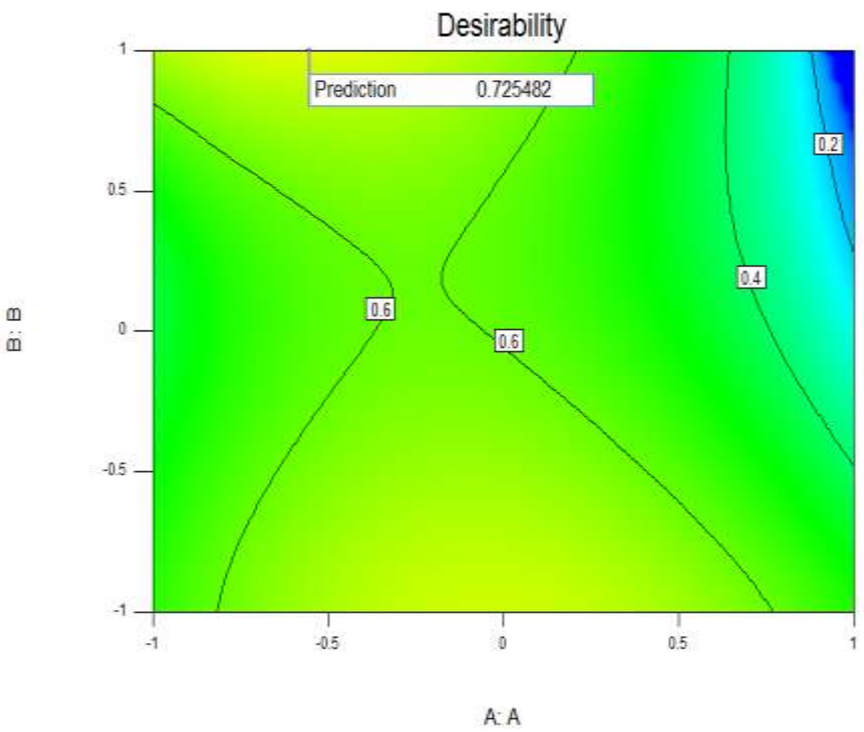

Fig.3 Contour graph showing desirability function values lubricant condition

As the results of validation runs are within the predicted range of 95% confidence level (Table5&10), it can be assumed that the optimum values obtained using desirability function should be within the predicted levels.

Table 10: - validation run to check the value of process parameter corresponding their optimize responses at lubricant condition

VOLTAGE	MACHINING TME	GAP	Sku
-0.553	1	0.280	2.69
Sq	Ssk	SHTp	Desirability
7.53	-0.253	11.6	0.725482

CONCLUSION

1. For simultaneous optimization of several response parameters, Overall desirability function is used in this study. Here four surface roughness parameters Sq, Ssk, Sku and SHTp have been optimized based on constraints selected to minimize the coefficient of friction. As the results of validation runs are within the predicted range of 95% confidence level, it can be assumed that the optimum values obtained using desirability function should be within the predicted levels.
2. Design-Expert is used to locate the optimum values of ECM process variables - applied potential, inter-electrode gap and machining time based on constraint applied to four surface roughness parameters Sq,Ssk,Sku and SHTp during dry and lubricant conditons.
3. The desirability value obtained for minimum wear in dry condition is 0.822 corresponding to the coded process parameter values of inter electrode potential= 1, electrode gap=0.248 and machining time=0.639.The optimum values of the surface parameters are S_q=18.59, S_{sk}= -0.177, S_{ku}=2.55 and S_{HTp}=36.14.
4. The desirability value obtained for minimum wear in lubricant condition is 0.73 corresponding to the coded process parameter values of inter electrode potential= -0.553, electrode gap=0.280 and machining time=1.The optimum values of the surface parameters are S_q=9.55, S_{sk}= -0.538, S_{ku}=2.86 and S_{Htp}=12.6.

ABBREVIATIONS

All parameters with S are3D extension of R roughness profile parameter: for example S_q is the 3D extension of R_q

R_{DelA} : Average Slope of the Profile.
R_t : Maximum Height of Profile.
S_a: Arithmetic Mean Deviation of the Surface ,µm
S_{Dq} : Root mean square gradient of the surface
S_{ku}: Kurtosis of the Topography Height Distribution.
S_q: Root-Mean-Square (RMS) Deviation of the Surface,µm
S_{Htp}: Surface section height difference (20% - 80%)

S_{mmr}: Mean Material Volume Ratio,

S_{mvr}: Mean Void Volume Ratio,

S_{sk}: Skewness of the Topography Height Distribution.
S_z: Ten Point Height of the Surface,µm.
W_a : Mean Value of the Waviness of the Unfiltered Profile.

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