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Electrochemical Machining of SG Iron using Mixed Electrolyte (Potassium Chloride and Sodium Nitrate)

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Abstract **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. Little information is available on machining of SG Iron by electrochemical machining process. The objective is to develop mathematical models based on Box Behnken design to predict the effect of process variables such as machining time, potential, inter electrode gap and two electrolytes a) KCl + $NaNo_3$ solution-1 (125 grams of KCl + 250 grams of $NaNO_3$ /litre of tap water) and b) KCl+ $NaNO_3$ solution-2 (166.667 grams of KCl + 200 grams of $NaNO_3$ /litre of tap water) on surface roughness parameters- Sa, Sq, Sz, Ssk, Sku, Smmr, Smvr, SHtp. It is found that the chloride to nitrate ratio has a significant influence on the surface roughness parameters. A few conclusions drawn are, for E-1 electrolyte (125 grams of KCl + 250 grams of $NaNO_3$ /litre of tap water) the chloride to nitrate ratio is 0.5. The ranges of value for surface roughness parameters obtained with E-1 electrolyte are closer to that of pure $NaNO_3$ solution. The exception is for Ssk. In case of E1 the range is (-0.27 to 1.57); for pure $NaNO_3$ solution the range is (-2 to 1.0); for E-2 electrolyte (KCl+ $NaNO_3$ solution-2 (166.667 grams of KCl + 200 grams of $NaNO_3$ /litre of tap water) , the chloride to nitrate ratio is 0.83 The ranges of value for surface roughness parameters obtained with E-2 are closer to that of pure NaCl solution. The exception is for Ssk. In case of E1 the range is (-0.74 to 0.65); for pure $NaNO_3$ solution the range is (-1 to 0.49).**

Keywords— Electrochemical Machining; SG Iron; Potassium Chloride ; Sodium Nitrate; Box Behnken design; Sa, Sq, Sz, Ssk, Sku, Smmr, Smvr, SHtp

INTRODUCTION

Electrochemical machining (ECM) can be used to machine complex features in hard and difficult to machine materials with negligible tool wear, reasonable accuracy and acceptable surface finish. 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, applied potential also on type, concentration, temperature, pressure, flow rate 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 [10]. For commercial exploitation of ECM for machining SG Iron it is essential to develop models for predicting the nature of surface that will be generated. The present work is undertaken to study the surface roughness produced during machining of SG Iron using ECM.

Surface roughness influences the functional performance properties of engineering surfaces [11-13] and hence, it is treated as one of the indices of product quality. As the surfaces interact in three dimensions, rather than in two [3] hence 3D parameters or combination of different 3D parameters [3, 15-17] are found to be more effective for surface characterization than a combination of 2D parameters.

The objective is to develop mathematical models based on Box Behnken design to predict the effect of process variables on surface roughness parameters- Sa, Sq, Sz, Ssk, Sku, Smmr, Smvr, SHtp.

Statistical design of experiments is an effective tool for studying the complex effects of number of independent process variables on response factor. Box-Behnken design [18] is one such method. The three variable fifteen run Box Behnken design is a spherical design. All the design points lay on the sphere of radius . The experiments are conducted at predetermined levels and based on analysis of variance the models developed are validated.

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Plan Of Investigation

For developing the model using Box Behnken the following steps are followed:

1. Determining the useful limits of the variables namely machining time, applied potential, inter electrode gap and electrolytes.
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. Analysis of the results.

Determining the useful limits of variables: Three controllable ECM parameters are selected. They are applied potential, inter-electrode gap and machining time. All machining are done at zero tool feed rate. The useful limits of time, potential and inter electrode gap are chosen based on preliminary experiments conducted and information available in literature. Two electrolytes are chosen namely a) KCl + $NaNo_3$ solution-1 (125 grams of KCl + 250 grams of $NaNO_3$ /litre of tap water) and b) KCl+ $NaNO_3$ solution-2 (166.667 grams of KCl + 200 grams of $NaNO_3$ /litre of tap water).

For simplifying the recording of the conditions of the experiments and processing of the experimental data, the upper, lower and intermediate levels of the variables are coded as +1, -1& 0, respectively by using the following relationship:

$$X_c = \frac{2.0X - 1.0(X_{max} + X_{min})}{(X_{max} - X_{min})} \ldots\ldots\ldots\ldots(1)$$

The actual and coded values of the different variables are listed in **Table 1.**

shaped tool (10 mm side) 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. Hommel Tester T-8000 is used for measuring the surface texture parameters.

2) *Developing the Mathematical Model : To correlate the effects of the variables and the response factor i.e. the surface roughness parameters Sa, Sq, Ssk, Sku, Smmr, Smvr and SHtp the following second order polynomial is selected.*

$$Y = B_o + B_1T + B_2V + B_3G + B_{11}T^2 + B_{22}V^2 + B_{33}G^2 + B_{12}TV + B_{13}TG + B_{23}VG$$

where, B's are the regression coefficients. The controllable ECM parameters T, V, G and their combinations are in coded values.

Table 2. Design Matrix

Sl.No.	Variables		
	T	V	G
1	-1	-1	0
2	+1	-1	0
3	-1	+1	0
4	+1	+1	0
5	-1	0	-1
6	+1	0	-1
7	-1	0	+1
8	+1	0	+1
9	0	-1	-1
10	0	+1	-1
11	0	-1	+1
12	0	+1	+1
13	0	0	0
14	0	0	0
15	0	0	0

Checking the Adequacy of the Models: The analysis of variance (ANOVA) technique [18] is used to check the adequacy of the developed models at 95% confidence level. 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.

Table 1. The Actual And Coded Values of Different Variables

Variables	Symbol	Low Level		Intermediate Level		High Level	
		Actual	Coded	Actual	Coded	Actual	Coded
TIME (minutes)	T	2	-1.0	3	0	4	+1.0
POTENTIAL (volt)	V	15	-1.0	20	0	25	+1.0
INTER ELECTRODE GAP (mm)	G	0.64	-1.0	0.96	0	1.28	+1.0

Selecting the Design Matrix: The three variable design matrix is shown in Table 2. Electrolyte is not taken as one of the design matrix variable as it is difficult to conduct the experiments in a random order. Hence, two sets of experiments are conducted using the electrolytes to assess their effects on surface texture parameters.

1) Experimentation: For carrying out the experiments ECM machine model ECMAC - II, manufactured by MetaTech Industries, Pune, India, is used. Flat hexagon

The goodness of fit of the models are tested by calculating R^2, $R^2_{(adjusted)}$ & $R^2_{(predicted)}$. The coefficients of the models developed and model statistics are given in Table 4 – 6. Table 5 shows that by using reduced quadratic models $R^2_{(predicted)}$ can be improved. This analysis has been done using Design Expert [19].For a few cases the experimental data are transformed to improve normality. All the models are statistically adequate.

To validate the models further experiments were carried out at levels different than those of design matrix. The conditions and results are given in Table 7a. The confidence interval is

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calculated based on the procedure given in reference [20].The calculated confidence interval with predicted response are given in Table 7b. The predictions based on fitted equations are adequate only in the immediate neighbor -hood of the design [18].

Table 3. Work-piece material specification (SG Iron):

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

*Nodularity measured using Analysis^{TM} five pro.

Table 4: The Coefficients of the Models Developed and the Statistical Model Parameters for $KCl+NaNO_3$ -1 electrolyte.

Coefficients Of The Models Developed		Surface Texture Parameters							
		Sa	Sq	Sz	S*sk	Sku	S#mmr	S#mvr	SHtp
	B_o	3.86667	5.04667	26.13335	2.07030	3.87334	0.12682	0.13172	7.37667
	B_1	0.37500	0.61500	4.95000	-0.13574	0.82500	0.00290	0.01335	0.66375
	B_2	1.49000	1.93625	6.42500	0.20494	-0.14125	0.03068	0.00322	3.02750
	B_3	-1.17250	-1.27125	0.67500	-0.05644	-0.21875	-0.01659	-0.01279	-2.50125
	B_{11}	-0.60208	-0.90083	-5.67917	-0.25287	0.66208	-0.02791	-0.00773	-1.56209
	B_{22}	0.75792	0.90167	2.97083	-0.01111	-1.42042	0.01041	0.00406	2.59541
	B_{33}	0.56792	0.72667	1.97083	-0.13269	0.19458	0.00711	0.01193	2.31291
	B_{12}	0.31250	0.28750	2.02500	0.05096	-0.25500	-0.00078	-0.00259	0.91000
	B_{13}	0.10250	-0.02750	5.42500	0.27832	-1.39500	0.00772	-0.01469	0.33250
	B_{23}	-1.48750	-1.51500	-0.17500	-0.02679	0.11750	-0.03495	-0.03182	-5.51500
	F_{RATIO}	0.71343	0.76820	0.17591	0.05602	0.04638	0.05153	0.28039	0.89869
	σ^2	0.30823	0.48203	22.36334	0.02295	0.79723	0.00033	0.000127	1.40423
	R^2	97.18542	96.85638	93.72179	95.73463	93.35975	96.37896	95.98708	97.90006
	$R^2_{(adj)}$	92.11916	91.19787	82.42100	88.05698	81.40730	89.86110	88.76382	94.12018
	$R^2_{(pred)}$	73.66158	69.78322	67.84574	85.84431	79.12079	88.27924	74.62453	78.69841

* (1/(1.0+A)**0.5)*2 , # A**0.5 - transformation formula used.

Table 5: ANOVA for response surface reduced quadratic model (backward, α to exit 0.1) ¢ neglected

Coefficients Of The Models Developed		Sa	Sq
	B_o	3.86667	5.04667
	B_1	0.37500	0.61500
	B_2	1.49000	1.93625
	B_3	-1.17250	-1.27125
	B_{11}	-0.60208	-0.90083
	B_{22}	0.75792	0.90167
	B_{33}	0.56792	0.72667
	B_{12}	¢	¢
	B_{13}	¢	¢
	B_{23}	-1.48750	-1.51500
	F_{RATIO}	0.71343	0.7214
	σ^2	0.30823	0.48203
	R^2	96.23	96.35
	$R^2_{(adj)}$	92.46	92.70
	$R^2_{(pred)}$	85.32	80.70

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Table 6: The Coefficients of the Models Developed and the Statistical Model Parameters for KCl+NaNO3_2 electrolyte.

		Surface Texture Parameters							
		Sa*	Sq*	Sz	Ssk#	Sku	Smmr	Smvr&	SHtp$
Coefficients Of The Models Developed	B_o	1.86922	2.09525	21.53335	0.84453	2.90333	0.01570	27.64998	2.70401
	B_1	0.05033	0.06238	0.67500	0.02292	-0.19500	0.00051	-1.27413	0.07465
	B_2	0.21157	0.19503	4.33750	-0.00818	-0.20625	0.00166	0.63724	0.35954
	B_3	-0.35025	-0.37533	-7.61250	0.00726	0.20125	-0.00467	3.59614	-0.55764
	B_{11}	0.02853	0.03559	3.00833	0.08826	0.20083	-0.00100	-3.74319	0.01112
	B_{22}	0.12207	0.13251	2.18333	0.09586	0.34333	-0.00025	-2.82147	0.22123
	B_{33}	0.18694	0.19725	0.68333	0.06200	-0.37667	0.00032	-1.52207	0.30820
	B_{12}	0.18018	0.15588	2.22500	0.00394	-0.84250	0.00170	1.36862	0.33190
	B_{13}	0.01410	0.02420	0.42500	0.00740	-0.10250	0.00027	-0.93907	0.04933
	B_{23}	-0.48888	-0.53218	-6.90000	-0.02324	0.05000	-0.00472	7.84095	-0.77704
	F_{RATIO}	0.1908088	0.2344974	0.2775899	0.1989946	0.06003	0.28699	0.13611	0.2158639
	σ^2	0.0389926	0.0449179	15.623330 1	0.0015012	0.08413	0.00001	13.87407	0.1024783
	R^2	96.31093	95.96771	95.19419	95.04249	96.49705	95.37846	93.17770	96.23249
	$R^2_{(adj)}$	89.67061	88.70959	86.54373	86.11897	90.19174	87.05971	80.89758	89.45098
	$R^2_{(pred)}$	80.40591	76.49837	69.75772	73.16990	88.13236	70.47863	68.74218	78.84940

*(A)**0.5 # (1+A)**0.125 & (1.0/a)**0.75 $ (A)**0.5

Table 7a. Model Validation for KCl+$NaNO_3$ -1: experimental details and measured values roughness parameters

Sl .no		T	V	G	Sa	Sq	Sz	Ssk	Sku	Smmr	Smvr	SHtp
1	Coded	-1.0	-0.4	-0.34375	3.42	4.26	20.2	-0.108	2.65	0.0115	0.0107	7.33
	Actual	2.0min	18V	0.85mm								
Confidence interval (±)												
2	Coded	0.0	0.2	0.3125	3.57	4.47	26.4	0.314	3.22	0.0133	0.0153	7.69
	Actual	3.0min	21V	1.06mm								
Confidence interval (±)												
3	Coded	1.0	0.4	0.65625	3.9	4.91	22.3	-0.0683	3.04	0.0164	0.0157	8.29
	Actual	4.0min	22V	1.17mm								
Confidence interval (±)												

Table 7b: Model Validation for KCl+$NaNO_3$ -1: experimental details and measured values roughness parameters

ECM parameters					From model							
Sl .no		T	V	G	Sa	Sq	Sz	Ssk	Sku	Smmr	Smvr	SHtp
1	coded	-1.0	-0.4	-0.34375	2.6805	3.2152	16.0611	UL:0.420224 LL: -0.23908	3.07247	UL:0.0158 6 LL:0.00282	UL:0.0172 8 LL:0.00627	5.2082
	actual	2.0min	18V	0.85mm								
Confidnce interval (±)					1.3995	1.6615	10.3565		1.79883			3.53725
2	coded	0.0	0.2	0.3125	3.7911	5.0490	27.9296	UL:0.25515 LL:-0.289075	3.74626	UL:0.0268 LL:0.00845	UL:0.0233 1 LL:0.01055	7.18553
	actual	3.0min	21V	1.06mm								
Confidnce interval (±)					1.3369	1.5867	9.8898		1.71778			3.37786
3	coded	1.0	0.4	0.65625	3.4415	4.7606	34.0655	UL:0.670856 LL:-0.15844	4.03027	UL:0.0198 9 LL:0.00435	UL:0.0207 1 LL:0.00811	6.59375
	actual	4.0min	22V	1.17mm								
Confidence interval (±)					1.4418	1.7112	10.666		1.85260			3.64297

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RESULTS AND DISCUSSIONS

For the ease of discussion applied potential, inter-electrode gap, machining time, KCl + $NaNo_3$ solution-1, KCl+ $NaNO_3$ solution-2 will be referred to as potential, gap, time, E-1 & E-2 respectively. The trends of Sa, Sq are quite similar. It is in conformity with the results reported by Nowicki [13] that a strong correlation exists between Sa, Sq.

The trends of Sq obtained with E-1 and E-2 for machining time (Figs.1&2) are quite different. For E-1 electrolyte as the time changes from -1 to +1 the minimum value of Sq increases steadily up to time level 0 and then starts decreasing. However, as machining time changes from -1 to +1 level minimum value of Sq increases steadily for E-2.electrolyte The value of Sq is in the range of 2.5 – 11.4um in case of E-1 and from 2.6 - 12.6 um in case of E-2.

For E-1 electrolyte the chloride to nitrate ratio is 0.5. The ranges of value for surface roughness parameters obtained with E-1 electrolyte are closer to that of pure $NaNO_3$ solution [21]. The exception is for Ssk. In case of E1 the range is (-0.27 to 1.57); for pure $NaNO_3$ solution the range is (-2 to 1.0)[21]. For E-2, the chloride to nitrate ratio is 0.83 The ranges of value for surface roughness parameters obtained with E-2 are closer to that of pure NaCl solution [21]. The exception is for Ssk. In case of E2 the range is (-0.74 to 0.65); for pure $NaNO_3$ solution the range is (-1 to 0.49)[21].

The mechanism of material removal depends on the ratio of chloride /nitrate[22,23] . The chloride anaions cause only a localized attack of passive film formed in the presence of nitrate ions on the steel surface. The chloride ions lowers oxidation powers of nitrate anaions and that prevents the formation of strongly adherent films [24]. It is reported that that where Cl^- ion is present the anodic current is large in the active region. The presence of Cl^- in mixed electrolyte leads to the formation of porous surface films. [24]. In mixed electrolyte as the concentration ratio of chloride/nitrate increases the metal removal rate and current efficiency increases[24].

Sku is the kurtosis of topography height distribution. This is a measure of the peakedness or sharpness of the surface height distribution. A Gaussian surface has Sku value of 3.0. Fig. 3&4 show the variation of Sku in E-1 &E-2 electrolytes at machining time +1 level. In case of E-1 and E-2 Sku varies in the ranges of 1.72 to 7.17 and 1.93 to 4.3 respectively. High value of Sku signifies sharp peak. The variation of Sku with E-2 electrolyte is quite small which means a surface with lower undulations. Ssk signifies skewness of surface height distribution. A surface with predominantly deep valleys will tend to have a negative skew, whereas a surface comprised predominantly of peaks will have positive skew. Negative skew is the criteria for good bearing surface. In case E-1 and E-2 electrolytes the parameter Ssk varies in the ranges of -0.27 to 1.57 and -0.74 to 0.65 respectively. The surface obtained with E-2 electrolyte has more valleys than peaks. Fig. 5&6 show the variation of Ssk in E-1 &E-2 electrolytes at machining time +1 level.

The parameters Smmr and Smvr for all the electrolytes vary predominantly within 0.004 to 0.04 and 0.003 to 0.04 respectively. The high value of Smmr (>3$\mu m^3/\mu m^2$ i.e. 0.003 mm^3/mm^2) indicates that the material volume will be subjected to higher wear [25]. Smmr and Smvr are numerically equal to Sp/1000 and Sv/1000 where Sp and Sv are maximum height of peaks and maximum height of valleys.

High value of the SHtp indicates a steep bearing ratio curve and a lower value indicates a flatter one. For higher bearing loads, a flat curve is desirable Depending on the functional requirement it is possible to select the process variables to maintain SHtp in a specified range. The overall range of SHtp for E-1 electrolyte is 3.7 – 23.3 and for E-2 electrolyte is 4.1-24.6. There is little difference in the distribution of SHtp obtained with E-1 and E-2 electrolytes. Fig. 7&8 show the variation of SHtp in E-1 &E-2 electrolytes at machining time +1 level.

In general, from literature [1,2,22-25] it is found that as the inter electrode potential increases the current density increase. With increase in inter electrode gap resistance of the electrolyte increases and the current density decreases. The flow pattern also changes with the gap as well as the local surface condition of the work piece. This also affects the current density. For example if the graphite particles are removed or a film is formed on the surface then the current density changes. The active electrolyte and passive electrolytes affect the machining rate and surface finish in more way than one. The concentration of chloride, nitrate anions and their ratios together with current density change material removal mechanism.

All the roughness amplitude parameters observed in the study are in high range. It [24] is suggested that Cl^- ions does not remove the anodic film uniformly. The attack is relatively localized and that may lead to non-uniform material removal. Another possible reason is the microstructure of SG Iron. The matrix is ferritic. Most of the electrolytes preferentially attack ferrite-graphite interface because of the difference in electrical conductivity. The different electrical conductivities of iron and graphite lead to change in the intensity of local electricity field. That in turn leads to inhomogeneous oxidation of microstructure leading to a rough surface finish [26]. It is reported that at low current level current density, the current efficiency is very low in case of pure $NaNO_3$ electrolyte because of oxygen evolution but as the current density increases the current density also increase rapidly [22]. In case of pure NaCl electrolyte current efficiency varies slightly with change in current density and hydrogen evolution takes place at cathode [22]. In case of mixed electrolytes (NaCl + $NaNO_3$) the current efficiency increases with increase in chloride to nitrate ratio [24].

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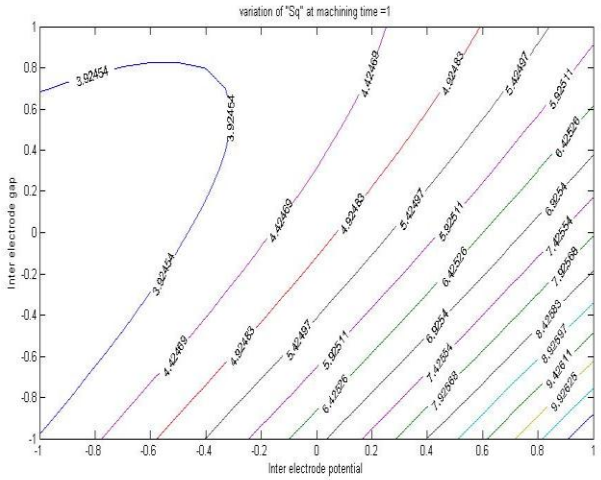

Fig.1 Variation of Sq at machining time +1 (E1 electrolyte)

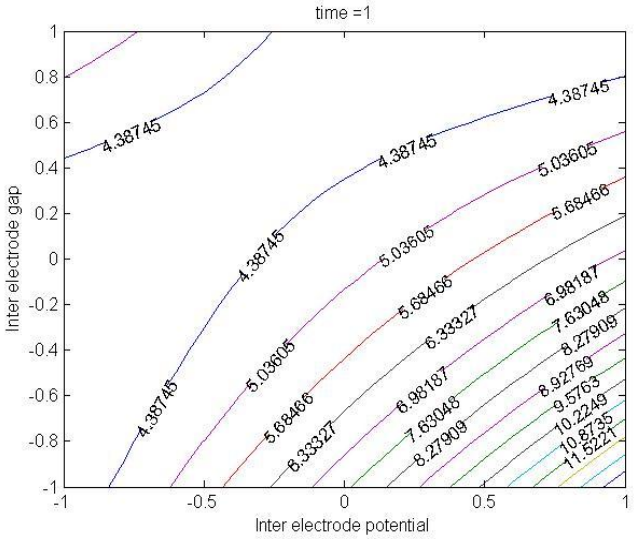

Fig.2 Variation of Sq at machining time +1 (E2 electrolyte)

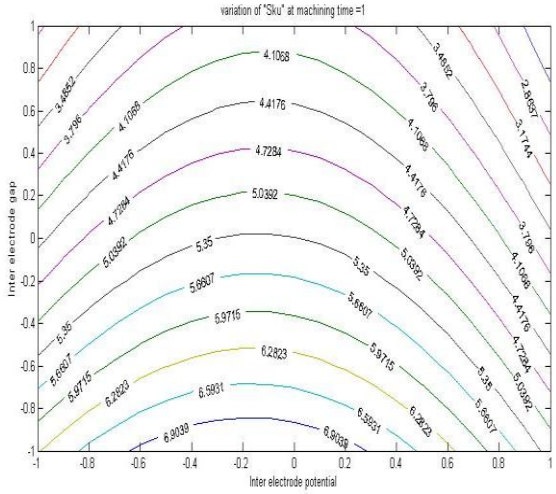

Fig.3 Variation of Sku at machining time +1 (E1 electrolyte)

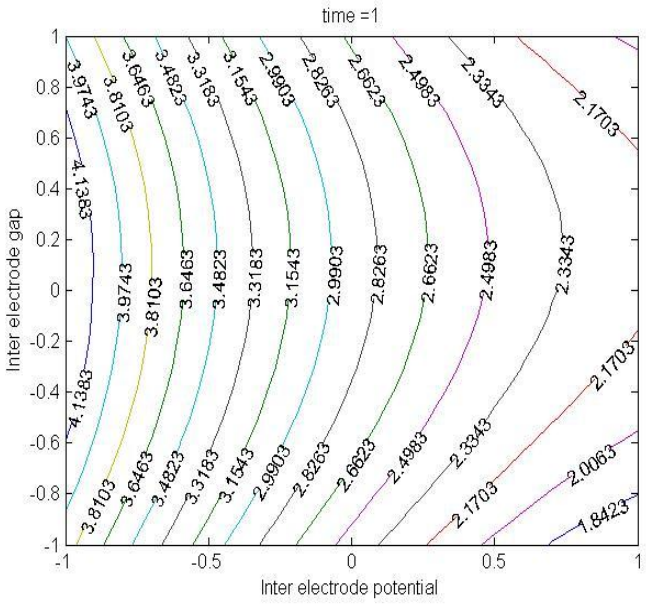

Fig.4 Variation of Sku at machining time +1 (E2 electrolyte)

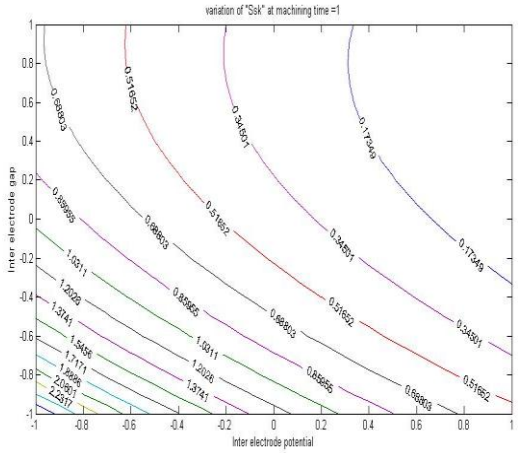

Fig.5 Variation of Ssk at machining time +1 (E1 electrolyte)

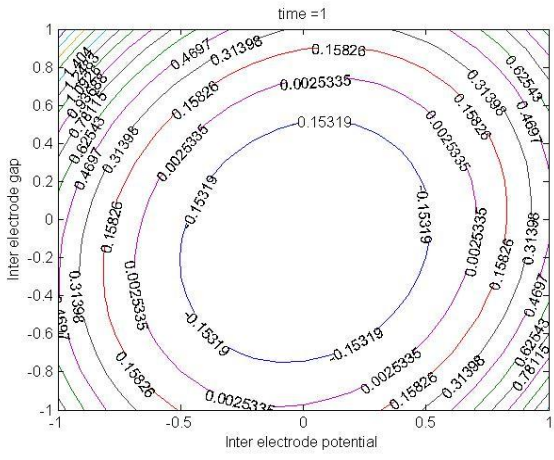

Fig.6 Variation of Ssk at machining time +1 (E2 electrolyte)

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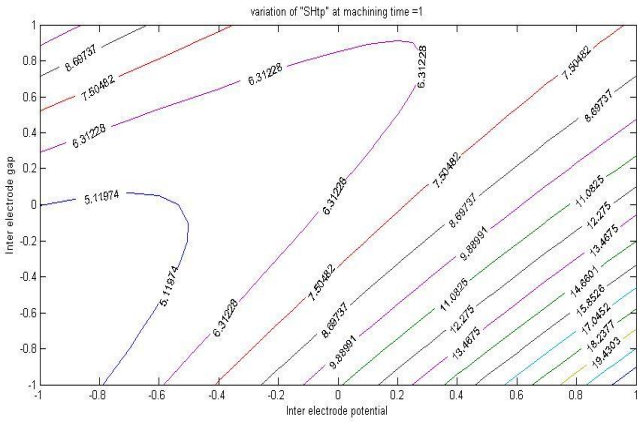

Fig.7 Variation of SHtp at machining time +1 (E1 electrolyte)

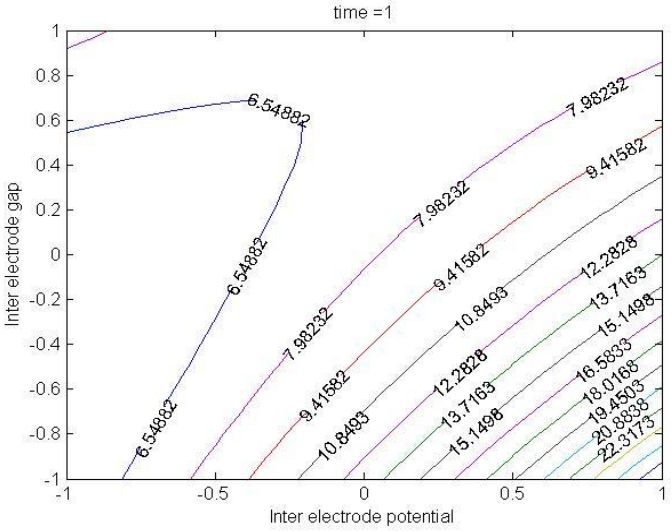

Fig.8 Variation of SHtp at machining time +1 (E2 electrolyte)

CONCLUSIONS

1. By using Box Behnken experimental design regression equations are developed to correlate ECM process variables operating voltage, work piece – tool gap and machining time with surface roughness parameters Sa, Sq , Sz, Ssk, Sku, Smmr, Smvr and SHtp.
2. It is found that the chloride to nitrate ratio has a significant influence on the surface roughness parameters.
3. For E-1 electrolyte (KCl + $NaNo_3$ solution-1 (125 grams of KCl + 250 grams of $NaNO_3$ /litre of tap water) the chloride to nitrate ratio is 0.5. The ranges of value for surface roughness parameters obtained with E-1 electrolyte are closer to that of pure $NaNO_3$ solution. The exception is for Ssk. In case of E1 the range is (-0.27 to 1.57); for pure $NaNO_3$ solution the range is (-2 to 1.0)[21].
4. For E-2 electrolyte (KCl+ $NaNO_3$ solution-2 (166.667 grams of KCl + 200 grams of $NaNO_3$ /litre of tap water) , the chloride to nitrate ratio is 0.83 The ranges of value for surface roughness parameters obtained with E-2 are closer to that of pure NaCl solution. The exception is for Ssk. In case of E1 the range is (-0.74 to 0.65); for pure $NaNO_3$ solution the range is (-1 to 0.49)[21].
5. There is little variation in the range of values in SHtp for both the cases (E-1 and E-2 electrolytes).
6. The regression equations may be used to select machining time, applied potential, inter electrode gap for producing surface roughness within a desired range.

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