Electrochemical Machining of SG Iron: Effect of Process Variables on Surface Roughness Parameters

Bishnu.M.Jha[*#] and A.Mandal**

** Deptt. of Manufacturing Engineering,NIFFT,Hatia,Ranchi, India,*
#Corresponding author

Abstract

For commercial exploitation of ECM for machining SG Iron it is essential to develop mathematical models for predicting the nature of surface that will be generated. Fifteen run Box Behnken Design is used to develop mathematical models to predict the effect of process variables - applied potential, inter-electrode gap and machining time on surface roughness parameters- Sa, Sq, Sz, Ssk, Sku, Smmr, Smvr, SHtp. Two electrolytes are used namely KCl solution (250 grams/litre of tap water) and $NaNo_3$ solution (400 grams/litre of tap water).

It is observed that for the parameters Sa,Sq ,Sz,SHtp at any machining time level, the range of variation of a roughness parameter is wider and lower bound of the range of predicted value is smaller in case of $NaNO_3$ compared to that of in KCl. The mathematical models developed can be used effectively to select process variables to achieve desired surface roughness characteristics.

1. Introduction

The ability to machine very complex features in hard and difficult to machine materials with negligible tool wear, reasonable accuracy and acceptable surface finish has made electrochemical machining (ECM) an important non-traditional machining process. ECM is based on anodic dissolution of work-piece material under operating conditions such as low inter-electrode potential, high current density and high flow rate of electrolyte through a small inter-electrode gap. Industrial applications of ECM include die sinking, profiling and contouring, deburring, polishing, grinding, drilling[1-5].

However, there are many parameters both controllable and uncontrollable that dictate the material removal rate, accuracy and surface texture. Some of the basic controllable operating parameters of ECM are: initial gap between tool and work-piece, machining feed rate, applied potential, electrolyte parameters such as type, concentration, temperature, pressure, flow rate and pH level at inlet.

Some of the difficult or impossible to control parameters that influence the machined feature are: electric field strength which depends on the shape of the electrode at any point, machining potential, electrolyte parameters such as flow regime, pressure, temperature and pH level during machining, passivation, hydrogen gas evolution and non uniform two phase flow of electrolyte, microstructure (crystallographic defects, grain size & boundaries, crystal structures and orientations), localized surface oxide films and composition (local) of work piece materials [1,2,6-14]

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, models based on experiments need to be developed to predict the effects of process parameters on machined geometry.

1.1 Analyses of surface roughness of machined surfaces.

Surface roughness influences the functional performance of engineering surfaces [15, 16] and hence, it is treated as an index of product quality [17]. Estimation of roughness with a single two dimensional parameter such as Ra, Rq, Rz, Rt is not sufficient to characterize the machined surface. Hence, a multi-parameter roughness approach is recommended [18,19]. Though two-dimensional surface roughness parameters are being used extensively but limited information can be extracted, as far as, surface characterization is concerned. The reason being, surfaces interact in three dimensions, rather than in two [20]. 3D parameters or combination of different 3D parameters [16,20-22] are found to be more effective for surface characterization than a combination of 2D parameters.

SG Iron has emerged as an important class 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 desirable properties [23].

Little information is available on machining of SG Iron by electrochemical machining process [24]. 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. As discussed before there are a number of independent variables that influence the characteristics of machined surface. Statistical design of experiments has proved to be an effective tool for studying the complex effects of a number of independent process variables on response factor. Box-Behnken design [25] is one such method. The three variables, fifteen run Box Behnken design is a spherical design. All the design points lay on the sphere of radius √2. The experiments are conducted at predetermined levels and based on analysis of variance the models developed are validated

The objective of this study 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.

2. Plan of Investigation

For developing the model using Box Behnken design 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.

2.1. Determining the useful limits of variables.

The three controllable ECM parameters selected for this study are applied potential, inter-electrode gap and machining time. All machining are done at zero tool feed rate. The useful limits of machining time, applied potential and inter electrode gap are chosen based on preliminary experiments conducted and information available in literature. Two electrolytes are chosen namely KCl solution (250 grams/litre of tap water) and $NaNO_3$ solution (400 grams/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:

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

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

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

2.2. Selecting the Design Matrix.

The matrix selected is a fifteen point design [25]. The fifteen experiments allow estimation of the linear, quadratic and two-way interaction effects of the variables on the surface parameters. The 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 two electrolytes to assess their effects on surface texture parameters.

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

2.3. Experimentation

For this work ECM machine model ECMAC - II, manufactured by MetaTech Industries, Pune, is used. Flat hexagon shaped tool (12 mm side) made of copper is used. Work-piece material specifications are given in Table 3. Courtesy of M/S HINDUSTAN MALLEABLES &FORGING ltd.

Table 3. Work-piece material specification:

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

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 roughness parameters.

2.4. Developing the Mathematical Model

To correlate the effects of the process 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.

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

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

2.5. Checking the Adequacy of the Models

The analysis of variance (ANOVA) technique 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. The goodness of fit of the models are tested by calculating R^2, $R^2_{(adjusted)}$ & $R^2_{(predicted)}$.

2.6. Results and Discussions.

The coefficients of the models developed and model's statistics are given in Table 4, 5. All the models are statistically adequate. The variance for the mean predicted values can be calculated using equation 3 [27].

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

		Surface Texture Parameters							
		S_a	**S_q**	**S_z**	**S^*_{sk}**	**S_{ku}**	**$S^\#_{mmr}$**	**$S^\#_{mvr}$**	**SH_{tp}**
Coefficients Of The Models Developed	B_o	5.9	6.7	23.6	10.5	3.16	7.30	9.41	12.60
	B_1	0.30	0.38	1.88	0.36	-0.44	-0.93	-1.10	0.32
	B_2	-0.26	0.12	1.60	0.45	1.95	-1.05	-0.27	-0.64
	B_3	-1.59	-1.62	-6.71	0.11	0.49	3.31	2.39	-3.39
	B_{11}	-0.24	-0.42	1.09	-0.67	-0.34	1.38	-1.85	-0.48
	B_{22}	-3.46	-3.50	-11.5	0.49	1.68	2.40	2.35	-7.93
	B_{33}	0.70	1.15	6.79	0.34	-0.03	1.22	0.96	2.74
	B_{12}	0.50	0.69	1.20	0.47	-0.92	-1.39	0.19	0.58
	B_{13}	2.60	3.02	12.5	0.18	-0.52	-1.68	-1.77	6.59
	B_{23}	1.28	2.03	5.15	0.38	0.30	-1.72	-0.98	3.39
	F_{RATIO}	1.36	9.44	0.23	0.64	0.33	1.65	0.29	0.23
	σ^2	0.28	0.05	10.3	0.09	0.27	0.43	1.31	3.87
	R^2	98.3	98.8	98.57	95.55	95.37	98.16	96.75	98.25
	$R^2_{(adj)}$	95.3	96.6	95.8	87.5	87.1	94.9	90.77	95.12
	$R^2_{(pred)}$	81.02	81.87	91.38	59.88	68.37	78.14	78.5	89.80

Table 5: The Coefficients of the Models Developed and the Statistical Model Parameters for KCl electrolyte.

		Surface Texture Parameters							
		S_a	S_q	S_z	S_{sk}	S_{ku}	S_{mmr}	S_{mvr}	SH_{tp}
Coefficients Of The Models Developed	B_o	6.66	8.30	39.6	-0.18	2.84	0.02	0.02	13.4
	B_1	0.49	0.44	2.65	0.06	0.18	0.001	0.00	2.14
	B_2	0.93	1.12	1.95	-0.22	-0.23	-0.0	-0.00	2.11
	B_3	0.08	0.08	1.07	-0.19	0.22	-0.000	-0.0	0.44
	B_{11}	-0.02	0.01	-2.60	-0.28	0.19	0.001	-0.00	-0.30
	B_{22}	1.80	2.06	7.19	0.15	0.31	-0.00	0.00	4.57
	B_{33}	-2.48	-3.08	-13.5	-0.00	-0.33	-0.008	-0.008	-4.83
	B_{12}	-0.93	-1.25	-3.10	0.36	0.68	-0.007	0.001	-1.6
	B_{13}	0.33	0.55	3.0	-0.29	0.12	0.003	0.002	0.002
	B_{23}	1.01	1.29	7.10	0.09	0.30	0.001	0.00	2.03
	F_{RATIO}	0.31	0.82	0.12	0.05	0.50	2.87	0.00	0.35
	σ^2	0.27	0.27	9.50	0.08	0.02	0.000	0.00	2.94
	R^2	98.53	98.50	98.3	91.5	98.2	98.1	93.5	96.8
	$R^2_{(adj)}$	95.8	95.8	95.2	76.3	95.0	94.9	81.8	91.2
	$R^2_{(pred)}$	90.2	85.2	92.4	72.4	85.61	75.6054	84.95	77.98

$$V(\widehat{y}) = \frac{\sigma^2}{3} - \frac{5}{24}\sigma^2\left(\sum x_{io}^2\right) + \frac{13}{48}\sigma^2\left(\sum x_{io}^4\right) + \frac{7}{24}\sigma^2\left(\sum x_{io}^2 x_{jo}^2\right) \quad (3)$$

For the ease of discussion applied potential, inter-electrode gap, machining time, KCl and $NaNO_3$ based electrolytes will be referred to as potential, gap, time, KCl and $NaNO_3$ respectively.

The trends shown in figs.1-3 for KCl are quite similar for the two electrolytes. It is in conformity with the results reported by Nowicki [18] that strong correlations exist between Sa, Sq, Sz. Though ridges are observed in the figs.2 and 4 but the trends observed are quite different. The directions of the arrows show the directions of decreasing Sq. It clearly shows that the directions of decreasing Sq are in opposite directions in KCl and $NaNO_3$. Box-Behnken design is a spherical design. The Box Behnken design does not contain any points at the vertices of the cubic region created by the upper and limits of the variables [25]. The predictions based on fitted equations are adequate only in the immediate neighbourhood of the design [26]. It is observed that, in general, for the parameters Sa,Sq ,Sz,SHtp at any machining time level, the range of variation of a roughness parameter is wider and lower bound of the range of predicted value is smaller in case of $NaNO_3$ compared to that in KCl (Table 6).

Sku is the mean for 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. [27] The range of variation of Sku in case of KCl is from 1.966 to 4.08 whereas in case of $NaNO_3$ the range is from 1.45 to 7.825. In case of $NaNO_3$ the peaks are sharp and valleys are narrow relative to that in KCl. Ssk values changed from negative to positive in both the cases, $NaNO_3$ and KCl.

The range of variation is wider for $NaNO_3$ electrolyte. The range of variation of Ssk in case of KCl is from -1.005 to +0.488. In case of $NaNO_3$ the range is from -1.871 to 0.983. 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 this case, the surface is characterized by predominantly more pits and valleys than peaks [28].

The parameters Smmr in case of KCl has varied between 0.01 and 0.0348. Whereas, in case of $NaNO_3$, Smmr has varied between 0.0037 and 0.0335. 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[29]. Smvr values are quite high and will affect the functional properties of the surfaces significantly.

Roughness Parameter	Machining Time (coded)	$NaNO_3$ solution (Electrolyte)		KCl solution (Electrolyte)	
		Minimum value	Maximum value	Minimum value	Maximum value
Sa	-1	0.779	9.994	3.077	9.81
Sa	0	0.562	8.398	3.738	9.514
Sa	+1	2.299	7.919	4.632	8.935
Sq	-1	1.235	11.772	4.086	12.336
Sq	0	0.646	9.814	4.616	11.653
Sq	+1	2.424	9.448	5.048	10.963
Sz	-1	3.539	46.09	18.268	46.65
Sz	0	5.31	37.27	24.342	50.040
Sz	+1	12.285	39.27	22.075	48.05
Sku	-1	1.45	7.825	1.966	4.08
Sku	0	2.23	7.55	1.981	3.39
Sku	+1	2.056	5.056	3.091	4.07
Ssk	-1	0.088	0.983	-1.005	+0.211
Ssk	0	-0.219	-1.871	-0.405	+0.488
Ssk	+1	-1.48	0.552	-0.886	+0.094
Smmr	-1	$4.942*10^{-3}$	$3.359*10^{-2}$	$1.181*10^{-2}$	$2.701*10^{-2}$
Smmr	0	$3.723*10^{-3}$	$1.589*10^{-2}$		
Smmr	+1	$1.176*10^{-2}$	$2.479*10^{2}$		
Smvr	-1	$3.917*10^{-3}$	$3.005*10^{-2}$	$9.906*10^{-3}$	$2.947*10^{-2}$
Smvr	0	$3.454*10^{-3}$	$3.744*10^{-2}$	$1.429*10^{-2}$	$2.471*10^{-2}$
Smvr	+1	$5.493*10^{-3}$	$2.049*10^{-2}$	$1.434*10^{-2}$	$3.418*10^{-2}$
SHtp	-1	1.932	24.517	5.7	19.268
SHtp	0	1.262	19.229	8.15	20.429
SHtp	+1	3.89	18.382	9.987	20.36

Table 6. The maximum and minimum values of the roughness parameters

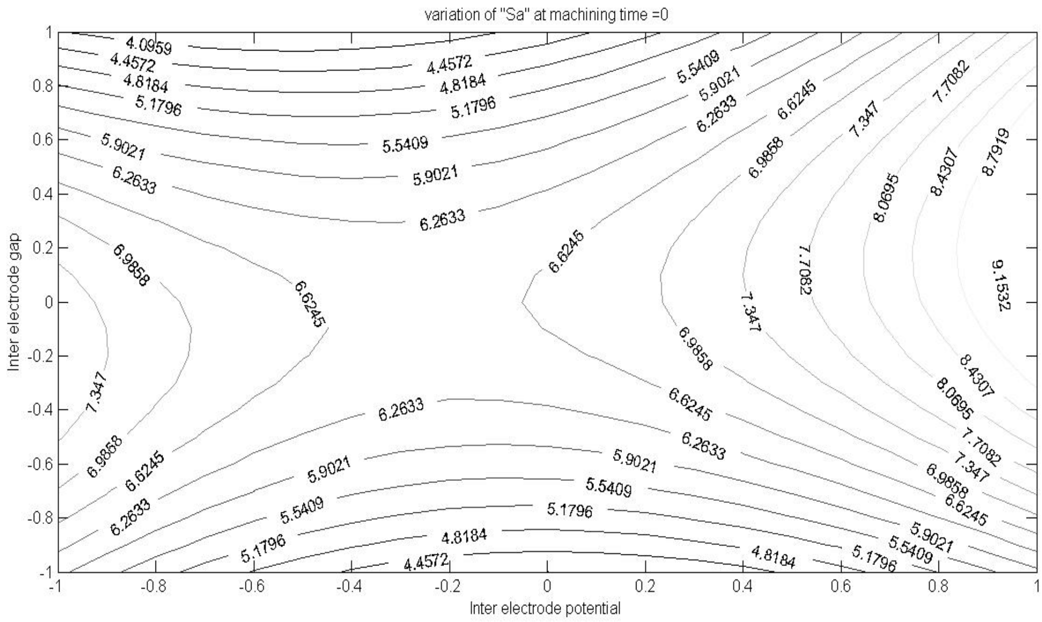

fig 1. Variation of Sa at t = 0 for KCl

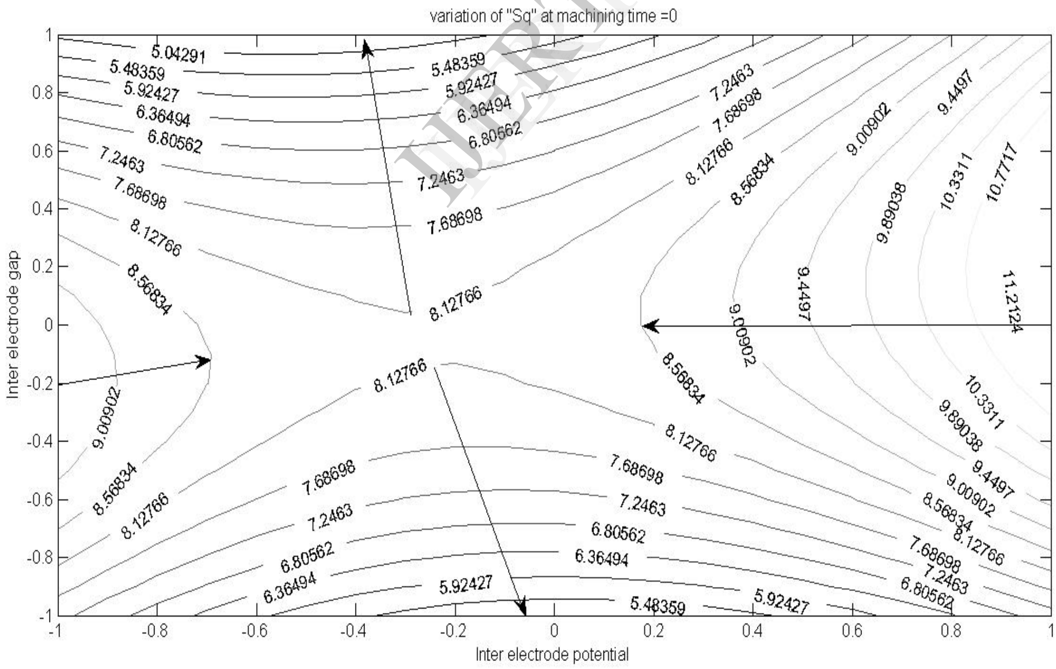

fig 2. Variation of Sq at t = 0 for KCl

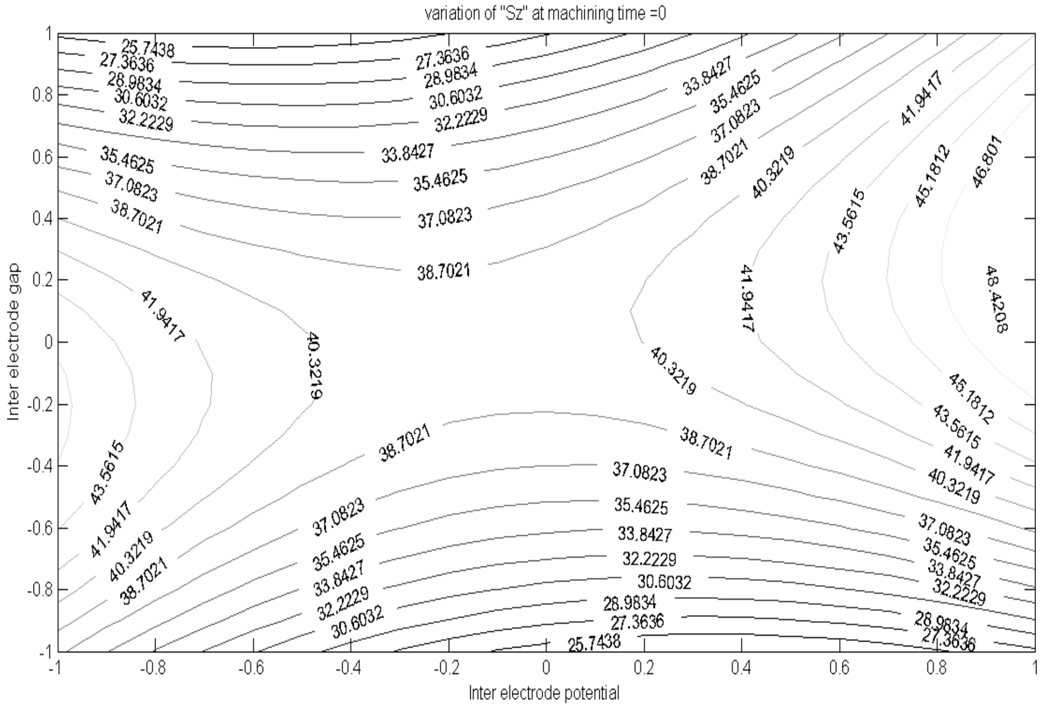

fig 3. Variation of Sz at t = 0 for KCl

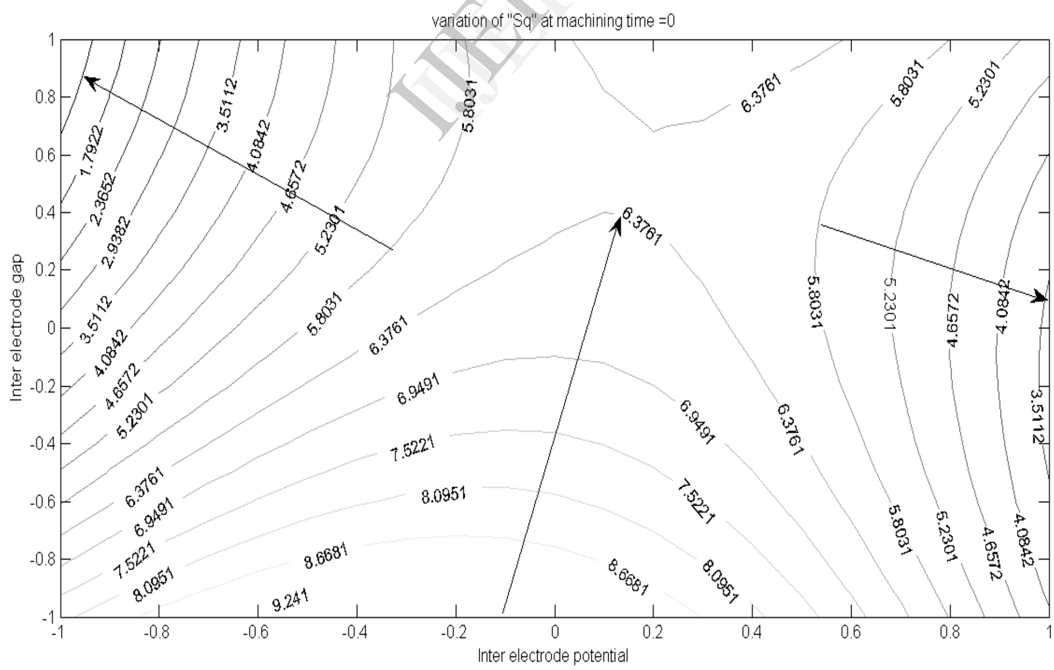

fig 4. . Variation of Sq at t = 0 for $NaNO_3$

The parameter SHtp in case of KCl has varied between 5.7 and 19.268 at time -1, 9.987 and 20.36 at time -1. Whereas, in case of $NaNO_3$, SHtp has varied between 1.932 and 24.517 at time -1 , 3.89 and 18.382 at time +1. 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 [30]. Depending on the functional requirement it is possible to select the process variables to maintain SHtp in a specified range.

In general, all the roughness amplitude parameters are in high range. A possible reason is the microstructure of SG Iron used in this study. The matrix is ferritic. Most of the electrolytes preferentially attack ferrite-graphite interface. It is reported [24] that the difference in electrical conductivity between iron and graphite increases the intensity of local electricity field. This in turn leads to inhomogeneous oxidation of microstructure leading to a rough surface finish.

3. Conclusion

1. Mathematical models based on Box Behnken design have been developed to predict the effect of process variables on surface texture parameters- Sa, Sq, Sz, Ssk, Sku, Smmr, Smvr, SHtp.

2. The range of variation in the parameters Sa,Sq,Sz,SHtp at any machining time level, is wider and the lower bound of the range predicted is smaller in case of $NaNO_3$ compared to that of in KCl.

3. The observed trend in Ssk values is predominantly negative for both the cases ,$NaNO_3$ and KCl. The range of variation is wider for $NaNO_3$. The range of variation of Ssk in case of KCl is from -1 to +0.3 whereas in case of $NaNO_3$ the range is from -1.6 to +0.88.

4. With $NaNo_3$ the peakedness or sharpness of the surface height distribution is more compared to that of KCl.

5. Depending on the functional requirement it is possible to select the process variables to maintain a surface roughness parameter within a specified range.

4. Abbreviations Used

Sa: Arithmetic Mean Deviation of the Surface ,µm

Sq: Root-Mean-Square (RMS) Deviation of the Surface,µm

Ssk: Skewness of the Topography Height Distribution.

Sku: Kurtosis of the Topography Height Distribution.

Sz: Ten Point Height of the Surface,µm.

Smmr: Mean Material Volume Ratio, $\frac{mm^3}{mm^2}$

Smvr: Mean Void Volume Ratio, $\frac{mm^3}{mm^2}$

SHTp: Surface section height difference (20% - 80%)

T : Time of machining (minutes)

V : Applied potential(volts)

G : Inter electrode gap(mm)

A : measured values of response.

$V(\bar{y})$: variance of estimated response at a point given by (x_{1o}, x_{20}, x_{30})

X_c : Coded value of a variables at any value c.

X_{max} : Maximum value of a variable

X_{min} : Minimum value of a variable

X : Variable (T,V,G)

σ^2 : sum of square of experimental error

5. References

[1].McGeough J.A, Principles of Electrochemical Machining, Chapman and Hall, 1974
[2].Rumyantsev E, and Davydov A, Electrochemical Machining of Metals, Mir Publishers Moscow,1989, 13- -36.
[3].Ramasawmy H and Blunt L, 3D Surface Topology Assessment of the Effect of Different Electrolytes During Electrochemical Polishing of EDM Surfaces, Int. J. Machine Tools &Manufacture, 2002,vol.42, 567-574.
[4].Weller,E.J, and Haavisto, M., Nontraditional Machining Processes, 2nd Ed., SME, Dearborn, Michigan,1984, 75-93.
[5].El-Hofy H, Advanced Machining Processes, McGraw-Hill, Mechanical Engineering Series, 2005, p. 89-95.
[6].Konig W and Lindelauf P, Surface Generation in Electrochemical Machining, Annals of the CIRP, 1973, Vol.29, no.1, 97-100.
[7].Kops L and Quack V.B., Investigation of the Role of Workpiece Grain Size in Electrochemical Machining Process, Trans. ASME, J. Engg. Ind., 1976,Vol. 98, 360-368.
[8]. Kops,L, Effect of Pattern of Grain Boundary Network on Metal Removal Rate in Electrochemical Machining, Ann. CIRP, 1976, vol. 25, no.1, 125-131.
[9].Krishnaiah Chetty O.V, Murthy, R.V.G.K and Radhakrishnan V, On Some Aspects of Surface Formation in ECM, Trans. ASME, J. Engg. Ind., 1981,Vol. 103, 341-348.
[10].Rajurkar K.P, Schnacker C.L, Lindsay R.P, Some Aspects of ECM Performance and Control, Annals of the CIRP, 1988, vol. 31, no.1, 183-186.
[11]. J. F. Cooper, M. C. Evans., Electrochemical Machining of Metal Plates. Lawrence Livermore National laboratory. UCRL-TR-210474,March,14,2005. http://www.energystorm.us/ Electrochemical_Machining_Of_Metal_Plates-r318925.html
[12].João Cirilo da Silva Neto , Evaldo Malaquias da Silva , Marcio Bacci da Silva. Intervening Variables in Electrochemical Machining. Journal of Materials Processing Technology,2006,Vol.179,pp. 92–96.
[13].Wagner,T., High Rate Electrochemical Dissolution of Iron Based Alloys in NaCl and $NaNO_3$ Electrolytes. http://elib.uni-stuttgart.de/opus/volltexte/2003/1293/pdf/TWagDiss.pdf
[14].Jeng Ming-Chang, Doong Ji-Liang and Yang Chih-Wen, The Effects of Carbon Content and Microstructure on the Metal Removal Rate in Electrochemical Machining, J. Mater. Process. Technol., 1993, Vol.38,527-538.
[15].Petropoulus G.P, Pandazaras C.N, Paulo Davim J, Surface TextureCcharacterization and Evaluation Related to Machining, in Surface Integrity in Machining, Ed. Paulo Davim J, Springer,2010,37-66.
[16].Chiffre L.De, Lonardo P, Trumpold H, Lucca D.A, Gosh G, Brown C.A, Raja J, Hansen H.N, Quantitative Characterization of Surface Texture, Ann.CIRP, ,2000,vol.49,635-652.
[17].Benardos P.G., Vosniakas G.C, Predicting Surface Roughness in Machining : A Review, Int. J. Machine Tools & Manufacture, 2003, Vol. 43, 833-844.
[18].Nowicki B, Multiparameter Representation of Surface Roughness, Wear,1985,Vol.102, 161 – 176.
[19].G.P.Petropoulos, Multi-parameter analysis and modelling of engineering surface texture, JAAMME, 2007, vol.24, no.1, 91-100.
[20].Stout K.J, Sullivan P.J, Dong W.P,Mainsah E, Luo N,Mathia T, Zahouani H, The Development of Methods for the Characterisation of Roughness in Three Dimensions, EUR 15178 EN, 1993, 11-12.
[21].Aris N.F.M, Cheng K, Characterization of the surface functionality on precision machined engineering surfaces, Int. J. Adv. Manuf. Technol., 2008, Vol.38, 402-409.
[22].Deleanu L ,Georgescu C and Suciu C, A comparison between 2D and 3D surface parameters for evaluating the quality of surfaces, The Annals of "Dunarea De Jos" University of Galati", ISSN 1221-4566 ,2012,pp.5-12
[23]. Pihura D, Oruc M, Applications of Spheroidal Graphite Cast Iron in Bosnia and Herzegovina, Materials and Technology , 2007, Vol.41, no.4, 193–195.
[24]. Bahre D, Weber O& Rebschlagerb A, Investigation on pulse electrochemical machining characteristics of lamellar cast iron using a response surface methodology-based approach, The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM), Procedia CIRP 6 (2013), 363 – 368.
[25]. D.C.Montgomery, Design and Analysis of Experiments, 2007,5th Edition, Wiley Student Edition, 457-459.
[26].Davies O.L, Ed., The Design and Analysis of industrial Experiments, 2nd Ed., Longman Group Ltd., 1978, 526.
[27].Das M.N & Giri N.C, Design and analysis of experiments,2nd ed., Wiley Eastern Ltd., 1991 ,306-312.
[28].Cohen D.K, Michigan Metrology. Glossary of Surface Texture Parameters. http://www.lamdapacific.com/mlx_manage/upload/200611211405734.pdf
[29]. Zawada-Tomkiewicz A, Surface roughness produced by hard turning with PCBN tools, 7th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING" 22-24 April 2010, Tallinn, Estonia,
[30].http://www.impco.com/pickapara.htm