International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 6, June - 2014

Multicriteria Optimization of Surface Roughness Produced in Electro Chemical Machining

1. Bishnu.M.Jha*#
2. A.Mandal*
* Deptt. of Manufacturing Engineering,NIFFT,Hatia,Ranchi, India.
#Corresponding author

***Abstract*— Surface roughness has strong influence on functional performance of engineering components in service. A single surface texture parameter is not sufficient to analyze the functional properties of the part surface such as friction & wear or lubrication. Hence, combination of parameters is necessary to characterize the functional property of a surface. The objective of this work is to locate optimal values of process parameters for ECM namely applied potential, inter-electrode gap and machining time for low coefficient of friction in this study two cases i.e. dry and lubricated conditions have been considered. In dry case, the constraints used are maximum Sq, S_{HTp} and minimum Ssk, S_{ku} . For lubricated case the constraints used are minimum Sq, S_{sk}, S_{HTp} and maximum S_{ku}. It is observed that Overall Desirability Function as implemented in Design- Expert ® software together with Box-Behnken design can be used effectively for simultaneous optimization four surface roughness parameters S_q, S_{sk}, S_{ku} and S_{HTp} based on constraints referred above. The effects of ranges, weights, importance of response variables on the results have been studied.**

***Keywords*— ECM, surface roughness, multicriteria optimization, desirability function.**

I. INTRODUCTION

Electrochemical machining (ECM), a nontraditional machining process offers a number of advantages. The advantages include ability to machine very complex features in hard and difficult to machine materials with negligible tool wear, reasonable accuracy and acceptable surface finish.

However, there are many parameters both controllable and uncontrollable that dictate the material removal rate, accuracy and surface texture. [1-12]. Functional performance of engineering components in service is strongly influenced by surface roughness [13-17] and hence, it is treated as an index of product quality. 2D parameters have been used extensively to characterize the surface roughness. However, 3D parameters or combination of different 3D/ areal parameters [14,18-22] are found to be more effective for surface characterization than a combination of 2D parameters. There are a large number of 3D surface texture parameters/ areal parameters. A single surface texture parameter is not sufficient to reflect true quality of the product [13-16, 18]. Combination of parameters is necessary to characterize the functional property of a surface. For example friction and wear has been reported to be influenced by surface roughness parameters such as (R_a, R_q), (R_t,R_z), R_{sk}, R_{ku}, R_{DelA},W_a [13]. Wear is reported [15] to be larger when the initial values of the amplitude parameters S_a, S_q and S_{Htp} as well as rms. slope S_{Dq} are high. It is reported [16] that 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. It is found [16] that increase in parameter R_{ku} led to increase in friction in lubricated case and decrease in friction in dry tests. Friction also is observed to be lower when the parameter R_{sk} tends to be more negative in lubricated tests.

Based on the above reports it is decided to locate optimal process parameters for ECM namely applied potential, inter-electrode gap and machining time for low coefficient of friction for the two cases i.e. dry and lubricated conditions. The constraints used are:

1. Dry case-maximize Sq, S_{HTp} and minimize S_{sk}, S_{ku}.
2. Lubricated case- minimize S_q, S_{sk}, S_{HTp} and maximize S_{ku}.

The first step is to develop mathematical models to predict the effect of process variables on surface roughness parameters- S_q, S_z, S_{sk}, S_{ku}, S_{Htp}. The models will be used to calculate the values of roughness parameters at any point in the allowable design space.

The second step is to use these models to generate optimum levels of process parameters for minimum coefficient of friction for dry and lubricated conditions.

II. MATHEMATICAL MODEL

The mathematical models used in this work are taken from reference [23]. The essential details and truncated results are presented here. The matrix is a fifteen point Box Behnken design [24]. The fifteen experiments allowed estimation of the linear, quadratic and two-way interaction effects of the variables on the surface parameters. The actual and coded values of the different variables are listed in Table-1. The design matrix is shown in Table-2.

ECM machine model ECMAC - II, manufactured by MetaTech Industries, Pune, is used along with flat hexagon shaped tool made of copper. Electrolyte used is KCl solution (250 grams of KCl / litre of tap water).

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

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

A. Work-piece material specification:

SG Iron: Chemical Composition:

%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

Hommel Tester T-8000 is used for measuring the surface texture parameters.

To correlate the effects of the variables and the response factor i.e. the surface roughness parameters Sq, S_{sk}, S_{ku}, and S_{Htp} the following second order polynomial is used.

$$Y = B_o + B_1T + B_2V + B_3G + B_{11}T^2 + B_{22}V^2 + B_{33}G^2 + B_{12}TV + B_{13}TG + B_{23}VG \;.\;.\;.\;.\;.\;.\; (1)$$

Where, B's are the regression coefficients. The controllable ECM parameters T, V, G and their combinations are in coded values. The coefficients of the models developed and model statistics are given in Table 3.

Table-3: The Coefficients of the Models Developed and the Statistical Model Parameters for KCl electrolyte.

		S_q	S_{sk}	S_{ku}	S_{Htp}
Coefficients Of The Models Developed	B_o	8.30667	-0.18087	2.84333	13.43334
	B_1	0.44000	0.06925	0.18750	2.14625
	B_2	1.12625	-0.22128	-0.2387	2.11500
	B_3	0.08125	-0.19798	0.22875	0.44375
	B_{11}	0.01666	-0.28504	0.19083	-0.30792
	B_{22}	2.06916	0.15891	0.31333	4.57458
	B_{33}	-3.08084	-0.00009	-0.3367	-4.83792
	B_{12}	-1.25750	0.36600	0.68250	-1.60000
	B_{13}	0.55250	-0.29150	0.12750	0.00250
	B_{23}	1.29000	0.09155	0.30000	2.03000
	F_{RATIO}	0.82413	0.05233	0.50843	0.35424
	σ^2	0.27373	0.08892	0.02243	2.94333
	R^2	98.5071	91.5377	98.2455	96.8652
	$R^2_{(adj)}$	95.8199	76.3056	95.0874	91.2227
	$R^2_{(pred)}$	85.2914	72.4920	85.6117	77.9881

The variance for the mean estimated values can be calculated using equation (2) [25].

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

To validate the models further three experiments were carried out at levels different than those of design matrix. The conditions and results are given in Table 4. The confidence interval is calculated based on the equation (3).

$$y_{io} = \hat{y}_{io} \pm \sqrt{S_{io}^2 \times F_{0.05,1,5}}$$

Where,

$$S_{io}^2 = S_t^2[1 + V(\hat{y})] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

The experimental values are within the confidence interval.

Design- Expert ®[26] is used For locating the optimum levels of ECM process parameters for minimum coefficient of friction for dry and lubricated conditions. Design- Expert uses an optimization method developed by Derringer and Swich [27], as described by Meyrs,Montgomery and Anderson-Cook[28].

Derringer and Swich [27] has developed an overall desirability function (D) by combining the quality attribute from multiple responses. For measuring single quality attribute three types of desirability functions (D) were defined. The individual desirability function $\mathbf{d_i}$ varies over the range [29].

Table 4: Model Validation.

	Sl.No	1		Confidnce interval (±)	2		Confidnce interval (±)	3		Confidnce interval (±)
ECM Parameters		coded	actual		coded	actual		coded	actual	
	T (min)	0.15	3.15		0.5	3.5		-1	3.5	
	V (volt)	-0.4	18		-0.2	19		0.5	19	
	G (mm)	-1	0.64		1	1.28		0.34375	19	
From Experiments Models	S_q	4.99			4.99			8.52		
	S_{sk}	0.262			-0.55			-0.259		
	S_{ku}	2.51			3.06			2.7		
	S_{Htp}	9.08			8.58			14.8		
From Model	S_q	5.6		1.515	5.533		1.5268	9.288		1.535
	S_{sk}	0.199		0.6	-0.5656		0.6043	-0.7412		0.6075
	S_{ku}	2.516		0.385	2.873		0.388	2.511		0.39
	S_{Htp}	9.26		4.11	9.55		4.14	13.909		4.165

$0 \leq d_i \leq 1$ [29]

(i) For the response '**y**' is maximum:

$$d = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{T-L}\right)^{r} & L \leq y \leq T \\ 0 & y > L \end{cases}$$

(ii) For response '**y**' is minimum:

$$d = \begin{cases} 0 & y < T \\ \left(\dfrac{U-y}{U-T}\right)^{r} & T \leq y \leq U \\ 0 & y > U \end{cases}$$

(iii) The two sided desirability function:

$$d = \begin{cases} 0 & y < L \\ \left(\dfrac{y-L}{T-L}\right)^{r1} & L \leq y \leq T \\ \left(\dfrac{U-y}{U-T}\right)^{r2} & T \leq y \leq U \\ 0 & y > U \end{cases}$$

Where, L, U, T stand for lower limit, upper limit, target or objective of the response y. r, r1 & r2 are the weights.
The overall desirability function (D) is calculated as .
$D = (d_1 . d_2 . d_3 . . d_n)^{\frac{1}{n}}$
The design variables are then chosen to maximize the overall desirability.
The overall desirability function as implemented in Design – Expert depends on a number of factors: (i) Range of the individual parameters (ii) weights assigned to the parameters and (iii) relative importance of the parameters. Design – Expert, however calculates the desirability functions from -1 to 1 limits for all the parameters. The models developed can be used for estimating the roughness parameters reliably as long as the coded values of T,V and G satisfy the relation.

$$\sqrt{T^2 + V^2 + G^2} \leq \sqrt{2}.$$

For all experimental and desirability values presented here this constraint has been satisfied.

Case 1: Dry Case

Table 5. Constraints used in Dry Case

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:T	is in range	-1	1	1	1	3
B:V	is in range	-1	1	1	1	3
C:G	is in range	-1	1	1	1	3
Sq	maximize	3.21333	12.375	1	1	3
Ssk	minimize	-1.009	0.48876	1	1	3
Sku	minimize	1.7524	4.09373	1	1	3
Shtp	maximize	5.31714	20.6819	1	1	3

Table:6 Optimized Parameters for dry case.

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	**D**
--0.992	1	0.078	12.375	--0.922	2.272	19.441	**0.906**

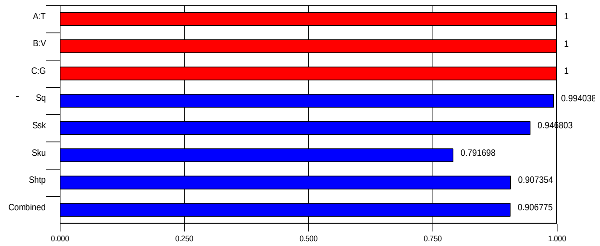

Fig.1.a

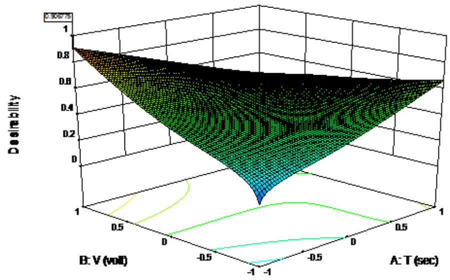

Fig.1.b

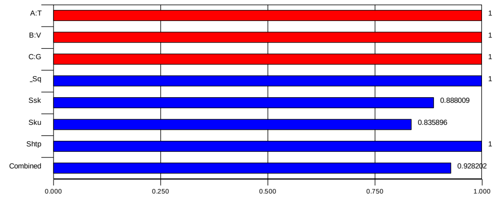

Fig.2.a.

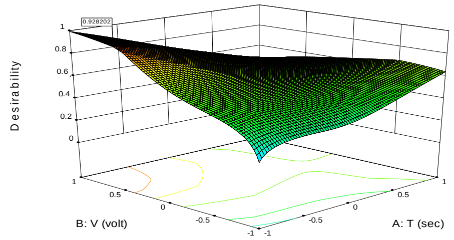

Fig.2.b.

Table 7: Modified Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:T	is in range	-1	1	1	1	3
B:V	is in range	-1	1	1	1	3
C:G	is in range	-1	1	1	1	3
Sq	maximize	3.21333	8	1	1	3
Ssk	minimize	-1.009	0.48876	1	1	3
Sku	minimize	1.7524	4.09373	1	1	3
Shtp	maximize	5.31714	10	1	1	3

Table_8: Optimized Parameters for dry case with modified constraints.

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	D
-1	0.595	-0.766	8.0	-0.887	1.997	10.71	0.952

In the above case all the factors have been given equal weight. Next the effects of weights on the overall desirability function (D) and it's position in the design space have been studied.

Table-9: Effect of weights on the overall desirability function (D) and the optimized parameters.

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	D	Weight
-0.997	1	0.006	12.34	-0.93	2.24	19.29	0.827	All :2
-0.999	1	-0.033	12.31	-0.94	2.23	19.19	0.753	All : 3
-0.992	1	-0.039	12.29	-0.93	2.23	19.18	0.681	All : 4
-1	0.999	-0.031	12.30	-0.94	2.23	19.18	0.625	All : 5
-0.997	1	0.003	12.34	-0.94	2.24	19.28	0.387	All : 10
-0.999	0.993	-0.071	12.22	-0.94	2.21	18.99	0.797	$S_{sk=5}$, all others 2
-0.991	1	-0.062	12.26	-0.94	2.22	19.11	0.731	$S_{sk=5}$, all others 3

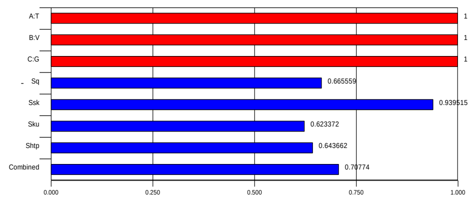

Fig.3.a

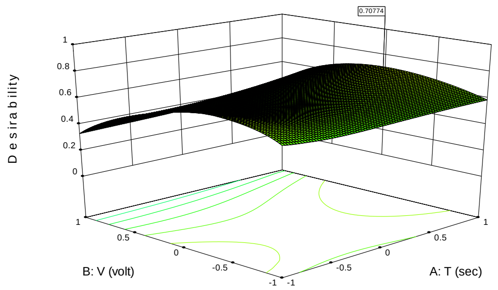

Fig.3.b.

Table 10. Effect of changing the importance of the parameters.

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	D	Condition
-1	-0.36	0.884	4.061	-0.267	2.949	6.2	0.614	S_{sk} at ****, All others at **
-1	1	-0.036	12.29	-0.939	2.226	19.18	0.799	S_{sk} at *****, All others at **
-1	1	-0.062	12.27	-0.936	2.217	19.11	0.731	S_{sk} at *****, All others at ***

Case 2:Lubricated Case

Table 11. Constraints used in Lubricated Case.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:T	is in range	-1	1	1	1	3
B:V	is in range	-1	1	1	1	3
C:G	is in range	-1	1	1	1	3
Sq	minimize	3.21333	12.375	1	1	3
Ssk	minimize	-1.009	0.48876	1	1	3
Sku	maximize	1.7524	4.09373	1	1	3
Shtp	minimize	5.31714	20.6819	1	1	3

Table:12 Optimized Parameters for lubricated case.

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	D
1	-0.040	0.999	6.277	-0.92	3.212	10.8	0.708

Table-13: of weights on the overall desirability function (D)

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	D
-0.60	-0.379	1	3.811	-0.188	2.793	6.357	0.608

Table-14: Effect of weights on the overall desirability function (D) and it's position in the design space.

Time*	Voltage*	Gap*	Sq	S_{sk}	S_{ku}	S_{HTp}	D	Weight
0.969	-0.046	1	6.23	-0.893	3.187	10.72	0.5	ALL :2
0.998	-0.03	1	6.28	-0.915	3.218	10.80	0.4	ALL :3
0.99	-0.07	1	6.23	-0.916	3.182	10.70	0.3	ALL :4
0.998	-0.03	1	6.28	-0.915	3.218	10.80	0.2	ALL :5
1	-0.16	0.98	6.29	-0.931	3.137	10.76	0.5	S_{sk}=5, all others 2
0.988	-0.07	1	6.23	-0.913	3.185	10.71	0.3	S_{sk}=5, all others 3

For dry case the highest value of D calculated is 0.906 when all factors have equal weight of 1 and have same importance value of three. Under the same conditions highest value of D calculated is 0.708 in lubricated case (Table 6 & 12). The ideal value of D is 1.00. In the experimental space under the constraints considered, dry case is closer to ideal condition than lubricated one. With changing limits, value of D changed appreciably (Table 7 & 13). For dry case it has improved from 0.906 to 0.952; where as in lubricated case it has decreased from 0.708 to 0.608. In case of dry, S_{sk} and S_{ku} values have changed in opposite direction (Table 6 & 8). Though D value is greater in case of modified constraint but relative importance of the two parameters will decide which condition will be the best. In case of lubricated case, value of D has decreased from 0.708 to 6.08 when the constraints have been modified. Though D has decreased but, there is substantial reduction in S_q , S_{HTp} values and a very large increase in S_{sk} value (Table 12 & 13). Again the relative importance of S_q, S_{HTP} in one hand and S_{sk} on the other hand will decide the selection of optimum conditions.

The other interesting result is that' as weights of all the parameters are increased equally (Table 9 & 14) value of D has decreased continuously. But, there is little change in values of, S_q, S_{sk}, S_{ku} and S_{HTp}. Giving more weight to S_{sk} than other parameters has pulled the value of S_{sk} towards the absolute minimum. Under same weight of S_{sk} when the weights of all other parameters are increased from 2 to 3 , value of S_{sk} has increased slightly from -0.9446 to -0.9362 i.e. moved in reverse direction.

Changing the importance of parameter (Table 10) shows that when S_{sk} status is changed from (****) to (*****) keeping all other parameters at status of (**) S_{sk} value has changed from -0.267 to -0.93874. A very large change. However, when status of all other parameters except S_{sk} are changed to (***) a negligible change occurred in the value of S_{sk}. Between importance and weight, it is found that weight is slightly more effective in satisfying the constants than importance of parameters.

CONCLUSION

1. Overall desirability function together with Box-Behnken design can be used effectively for simultaneous optimization of several response parameters. In this study four surface roughness parameters S_q, S_{sk}, S_{ku} and S_{HTp} have been optimized based on constraints selected to minimize the coefficient of friction. The model verification results confirmed that the predictions of Box-Behnken models are reliable and hence can be used for optimization.

2. Design-Expert is used to locate the values of ECM process variables - applied potential, inter-electrode gap and machining time which will give lowest value of the functional characteristic i.e. coefficient of friction based on constraint applied to four surface roughness parameters S_q,S_{sk},S_{ku} and S_{HTp}.

3. Highest value of D calculated for dry case is 0.9523 for the ECM process variables: time at -1 level, potential at 0.59538 level and gap at -0.76617 level.

4. For lubricated case the highest value of D calculated is 0.708 for the ECM process variables time at 1 level, potential at -0.04 level and gap at 0.999 level.

5. As weights of all the parameters are increased equally value of D has decreased continuously. However, there is little change in values of S_q, S_{sk}, S_{ku} and S_{HTp}.
6. Giving more weight to S_{sk} than others parameters has pulled the value of S_{sk} to towards the absolute minimum. Under same weight of S_{sk} when the weights of all other parameters are increased from 2 to 3 , value of S_{sk} has increased slightly from -0.9446 to -0.9362 i.e. moved in reverse direction. This shows the sensitivity of the optimization method.
7. Weight has slightly more effect than importance (for setting up of effective constraints :ranges, weights, importance of response variables) knowledge of relative effects of the four roughness parameters on the coefficient of friction in dry and lubricated cases are important.
8. Design – Expert searches the design space of -1 to +1 for all the ECM process variables for optimization. In case of Box-Behnken design it should be limited to spherical radius of $\sqrt{2}$. Outside this range the prediction from Box-Behnken design is not reliable.
9. The software by default selects the maximum and minimum value from the given design points. However, those values may not be the global maximum and minimum. For each response, maximum and minimum may be calculated and the constraints may be formulated suitably.

<u>Roughness Parameters:</u>

All parameters starting with S is 3D 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_{sk}: Skewness of the Topography Height Distribution.

W_a : Mean Value of the Waviness of the Unfiltered Profile.

<u>Experimental Variables</u>

T : Time of machining (minutes)

V : Applied potential(volts)

G : Inter electrode gap(mm)

X : Variable (T,V,G)

<u>Statistical Analysis Parameters</u>

$V(\hat{y})$ = variance of estimated response at a point given by (x_{10}, x_{20})

S_t^2 = Mean Square of Residual

$\hat{y}_{io}$ = Mean estimated response at a point given by (x_{10}, x_{20}, x_{30})

y_{io} = Confidence interval for single estimated response at a point given by (x_{10}, x_{20}, x_{30})

$F_{0.05,1,5}$ = F ratio

σ^2 = Mean Square of Experimental Error

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. El-Hofy H, Advanced Machining Processes, McGraw-Hill, Mechanical Engineering Series, 2005, p. 89-95.
4. Konig W and Lindelauf P, Surface Generation in Electrochemical Machining, Annals of the CIRP, 1973, Vol.29, no.1, 97-100.
5. 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.
6. 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.
7. 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.
8. 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.
9. 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
10. 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.
11. 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
12. 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.
13. 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.
14. 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.
15. Grabon W, Pawlus P, Sep J, Tribological Characteristics of One-Process and Two-ProcessCylinder Liner Honed Surfaces Under Reciprocating Sliding Conditions, Tribology International ,2010, vol.43,1882–1892.
16. Sedlaček M, Podgornik B,Vižintin, Influence of Surface Preparation on Roughness Parameters, Friction and Wear, Wear, 2009, vol.266, 482-487.
17. Wang Wen-zhong, Chen Hui, Yuan-zhong Hu,Wang Hui, Effect of Surface Roughness Parameters on Mixed Lubrication Characteristics, Tribology International, 2006, vol.39,522-527.
18. Nowicki B, Multiparameter Representation of Surface Roughness, Wear,1985,Vol.102,pp. 161 – 176.
19. 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.
20. 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.
21. 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
22. G.P.Petropoulos, Multi-Parameter Analysis And Modelling Of Engineering Surface Texture, JAAMME, 2007, vol.24, no.1, p.91-100.
23. Jha B.M., Mandal A., Electrochemical Machining of SG Iron: Effect of Process Variables on Surface Roughness Parameters, Int. J. Engg. Research & Tech. (IJERT), 2013, vol.2 ,issue 7,
24. D.C.Montgomery, Design and Analysis of Experiments, 2007,5th Edition, Wiley Student Edition, 457-459.
25. Das M.N & Giri N.C, Design And Analysis of Experiments,2nd ed., Wiley Eastern Ltd., 1991 ,306-312.
26. Design-Expert V9®-product of M/s Stat – Ease Inc.
27. Derringer G, Suich R., Simultaneous Optimization of Several Response Variables, J. Quality Technology, 1980, vol,12, no.4 (October), 214-219.
28. Myers R.H., Montgomery D.C., Anderson-Cook Christine M, Response Surface Methodology, 3rd Edition, John Wiley and Sons, New York,2009.
29. D.C.Montgomery, Design and Analysis of Experiments, 2007,5th Edition, Wiley Student Edition, 451-454.