INVESTIGATION ON ELECTROCHEMICAL MACHINING(ECM) FOR OPTIMIZATION OF SURFACE ROUGHNESS USING RESPONSE SURFACE METHODOLOGY(RSM)

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY
IN
MECHANICAL ENGINEERING

By

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Department of Mechanical Engineering

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

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CERTIFICATE

This is to certify that work in this project report entitled,**"INVESTIGATION ON ELECTROCHEMICAL MACHINING(ECM) FOR OPTIMIZATION OF SURFACE ROUGHNESS USING RESPONSE SURFACE METHODOLGY(RSM)"** by **AJOY KUMAR CHOUDHURY** has been carried out under my supervision and guidance in partial fulfillment of the requirements for the award of **BACHELOR OF TECHNOLOGY** Degree in ***Mechanical Engineering*** specialization during session 2010-2011 in the Department of Mechanical Engineering, National Institute of Technology, Rourkela.

To the best of my knowledge, this work has not been submitted to any other university/ institute for award of any Degree or Diploma.

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ABSTRACT

Electrochemical Machining (ECM) has established itself as one of the major alternatives to conventional methods of machining difficult - to - cut materials of and generating complex contours, without inducing residual stress and tool wear. This thesis is devoted to the study of influences of variable ECM parameters like applied voltage and feed rate keeping other parameters constant on the surface roughness (Ra) using Response Surface Methodology (RSM).By using RSM method this thesis highlight features of the development of a comprehensive mathematical model for correlating the interactive and higher-order influences of various machining parameters on the dominant machining criteria, i.e. the surface roughness. Optimal combination of these two parameters is used in order to achieve minimisation of surface roughness for optimal accuracy of shape features. In the experiment, mild steel is used as specimen. Based on the Experimental result using RSM it is shown that minimum value of surface roughness can be obtained at the optimal combination of two parameters.

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Chapter 1

INTRODUCTION

Electrochemical machining (ECM) has seen a resurgence of industrial interest within the last couple of decades due to its many advantages such as no tool wear, stress free and smooth surfaces of machined product and ability to machine complex shape in electrically conductive materials, regardless of their hardness [1]. It has been applied in diverse industries such as aerospace, automotive and electronics, to manufacture airfoils and turbine blades, die and mold, artillery projectiles, surgical implants and prostheses, etc. Moreover with recent advances in machining accuracy and precision, based on the development of advanced electrochemical metal-removal processes, demonstrate that the ECM can be effectively used for micromachining components in the electronics and precision industries [2].

It is a non-traditional machining (NTM) process and is opposite of galvanic coating or deposition process .Thus ECM can be thought of a controlled anodic dissolution at atomic level of the work piece that is electrically conductive through an electrolyte which is quite often water based neutral salt solution[4].Because of various complex physico-chemical and hydrodynamic phenomena that occur in the machining gap during the course of machining, the machining rate at any instant depends not only on the end gap, but also on other process parameters[3]. The other parameters may include applied voltage, feed rate, electrolyte concentration, electrolyte flow rate etc. They directly influence the metal removal rate and surface quality of the work piece during machining. Optimal quality of the work piece in ECM can be generated through combinational control of various parameters [3].

Therefore the present thesis emphasises features of the development of comprehensive mathematical models for correlating the interactive and higher-order influences of the various machining parameters, such as the applied voltage and feed rate on the most dominant machining criteria, i.e. the surface roughness, for achieving good quality controlled ECM. The investigation into the surface roughness and controlled ECM has been carried out through response surface methodology (RSM) in the software MINITAB, utilising the relevant experimental data as obtained through experimentation[3].

1.1 EXPERIMENTAL SET-UP AND PRINCIPLE OF ECM :

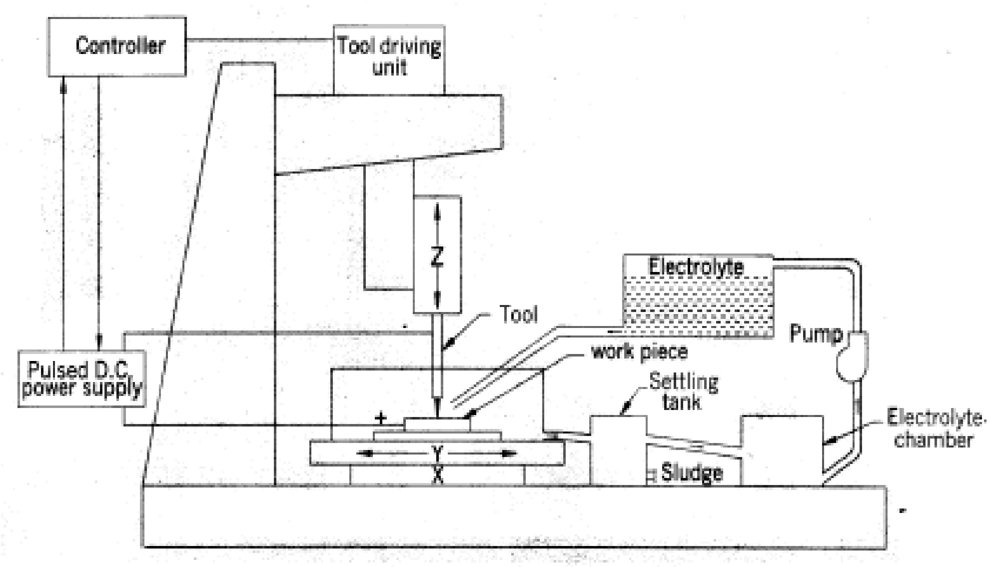

Fig 1 .Experimental set-up [1]

ECM works on the principle of Faradays law i.e. when two conductive electrodes are placed in an electrolyte maintained at low potential difference then there is discharge of electrons taking place. When the current is switched on, the electrolyte ($NaCl+H_2O$) gets ionised according to the following relationship,

$$NaCl \longrightarrow Na^+ + Cl^-$$

$$H_2O \longrightarrow H^+ + OH^-$$

As hydrogen ions reach the cathode (tool), they combine with free electrons resulting into evolution of H_2 gas.

$$2H^+ + 2e^- \longrightarrow H_2\uparrow$$

Assume that pure iron is being machined by this process, reactions that would occur are

$$2Na^+ + 2OH^- = 2NaOH \quad \&$$

$$Fe^{2+} + 2Cl^- = FeCl_2$$

$$2NaOH + FeCl_2 = 2NaCl + Fe(OH)_2$$

Thus in ECM of iron, using NaCl as the electrolyte, iron is removed as $Fe(OH)_2$ and sodium chloride is recovered back. The iron hydroxide produced during the process must be removed continuously from the electrolyte by filtration before it is recirculated.

Removal of material from the work piece during ECM can be calculated from Faraday's law of electrolysis as follows..

$$MRR = \frac{AIt}{\rho ZF}\eta$$

Where,

A = atomic weight of cation

Z= valency of cation

I = current

t = machining time

F = Faraday's constant =96,500

ρ= density

η = current efficiency < 50 %

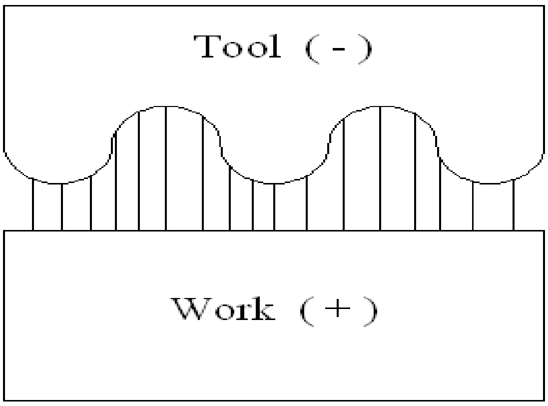

Fig 2: Before machining

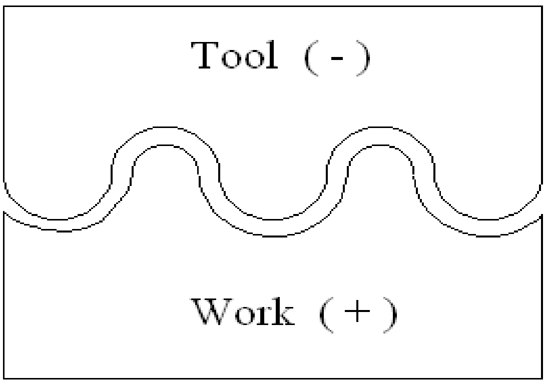

Fig 3: After machining

It is to be noted that in ECM process, the machining gap size increases as the metal is removed. The larger gap leads to a decrease in the metal removal rate. Therefore to maintain a constant gap between the tool and the work piece, the cathode (tool) should be advanced towards the anode (work) at the same rate at which the metal is removed.

1.2 ECM MACHINE PARAMETERS:

1.2.1 SERVO SYSTEM:

The servo system controls the tool motion relative to the work piece to follow the desired path. It also controls the gap width within such a range that the discharge process can continue. If tool electrode moves too fast and touches the work piece, short circuit occurs. Short circuit contributes little to material removal because the voltage drop between electrodes is small and the current is limited by the generator. If tool electrode moves too slowly, the gap becomes too wide and electrical discharge never occurs. Another function of servo system is to retract the tool electrode when deterioration of gap condition is detected. The width cannot be measured during machining; other measurable variables are required for servo control.

1.2.2 ELECTROLYTE:

The electrolyte is essential for the electrolytic process to work. The electrolyte has three main functions in ECM. These three functions are:

1. It carries the current between the tool and the workpiece.

2. It removes the products of machining from the cutting region.

3. It dissipates heat produced in the operation.

Electrolytes must have high electrical conductivity, low toxicity and low corrosiveness. The electrolyte is pumped at about $14 kg/cm^2$ and at speed of at least 30 m/s.

1.2.3 TOOL FEED RATE:

In ECM process a gap of about 0.01 to 0.07 mm is maintained between the tool and the work piece. For smaller gap, the electrical resistance between the tool and work is least and the current is maximum and accordingly maximum metal is removed. The movement of the tool slide is controlled by a hydraulic cylinder giving some range of feed rate.

1.2.4 TEMPERATURE CONTROL:

The temperature of the electrolyte must be constant so that variation in conductivity will not occur. If the temperature of the electrolyte is low it means lower rate of metal removal and if it is higher temperature may lead to the vaporization of the electrolyte. Therefore temperature of electrolyte must be maintained between 25° and 60°.

1.2.5 MATERIAL REMOVAL RATE:

It is a function of feed rate which indicates the current passed between the work and the tool. As the tool advances towards work, gap decreases and current increases which increases more metal at a rate corresponding to tool advance. A stable spacing between tool and work is thus established. It may be noted that high feed rate not only is industrious but also produces best quality of surface finish. However feed rate is restricted by removal of hydrogen gas and products of machining. Metal removal rate is lower with low voltage, low electrolyte concentration and low temperature.

1.2.6 TOOL DESIGN:

As no tool wear takes place, any good conductor is applicable as a tool material, but it must be designed strong enough to withstand the hydrostatic force, caused by electrolyte being forced at high speed through the gap between tool and work. The tool is made hollow for drilling holes so that electrolyte can pass along the bore in tool. Cavitations, stagnation and vortex formation in electrolyte flow must be avoided because these result a poor surface finish. It should be given such a shape that the desired shape of job is achieved for the given machining condition.

Both external and internal geometries can be machined with an electrochemical machine. Copper is often used as the electrode material. Brass, graphite, and copper-tungsten are also often used because of the ability to be easily machined, they are conductive materials, and they will not corrode.

- There are two major aspects of tool design. These are :-

    1. Determining the tool shape so that the desired shape of the job is achieved for the given machining conditions.

    2. Designing the tool for considerations other than e.g. electrolyte flow, insulation, strength and fixing arrangements.

1.2.7 SURFACE FINISH:

ECM can produce surface finish order of 0.4 µm by turning round of tool or work. Any defect on tool face produce replica on work piece. Tool surface should therefore be polished. The finish is better in harder material. For optimum surface finish, careful electrode design, maximum feed rate, and surface improving additives in electrolyte are selected. Low voltage decreases the equilibrium machining gap and result in better surface finish and tolerance control. Low electrolyte concentration decreases the machining gap and gives the better surface finish. Low electrolytic temperature also promotes better surface finish.

1.2.8 PUMPS:

Single or multi-stage centrifugal pumps are used on ECM equipment. A minimum flow rate 15 litres/ min per 1000 A electrolyzing current is generally required. A pressure of 5-30 kg/cm^2 meets most of the requirements of ECM application.

1.2.9 FILTRATION AND STORAGE TANKS:

The filtration of electrolyte is essential to prevent small particles of sand, metal, plastics and products of machining from entering the machining gap and causing interference in the process. These filters get blocked and need cleaning once in 30 hrs.

1.6.10 VALVES AND PIPING:

The piping and control valves which supply electrolyte to the ECM tooling, must not commence foreign matter into the electrolyte. Stainless steel is the most suitable material for valves and piping. Materials such as fibre glass and reinforced plastics are used with some degree of success.

1.3 ECM PROCESS PARAMETERS :

Tool	Copper, brass or steel
Power supply	2-35 DC volt
Current	50-40,000 amp

Material removal rate	1600 mm3/min
Specific power consumption	7w/mm3/min
Electrolytic solution	NaCl and $NaNO_3$ solution
Accuracy and surface finish	0.02 mm, 0.4µm
Feed Rate	0.5 mm/min to 15 mm/min
Overcut	0.2 mm to 3 mm
Surface roughness, Ra	0.2 to 1.5 µm

Chapter 2

LITERATURE SURVEY

In this chapter, few selected research papers related to ECM and RSM is reported on surface roughness (Ra), metal removal rate (MRR), overcut and other responses.

B. Bhattacharyya*, S. Mitra, A.K. Boro [5] : This journal provides us the better understanding of high rate anodic dissolution processes like electrochemical machining (ECM) and electrochemical micromachining (EMM) as these processes are become a widely employed manufacturing process in the electronic and precision manufacturing industries particularly in the micromanufacturing domain. A successful attempt has been made to develop an EMM setup for carrying out in depth independent research for achieving satisfactory control of electrochemical machining process parameters to meet the micromachining requirements. The developed EMM setup mainly consists of various sub-components and systems, e.g., mechanical machining unit, microtooling system, electrical power and controlling system and controlled electrolyte flow system, etc. In addition to need for electrochemical micromachining and EMM setup ,the other topics like fundamentals of ECM related to EMM, material removal method in EMM ,influence of various process parameters etc. are also studied.In the development of experimental setup for EMM consists of tool feeding arrangement ,work mounting device ,electrical power and drive system ,monitoring and controlling of the inter-electrode gap ,stepper motor drive system ,electrolyte flow system and detailed specification of the EMM setup.

Jo˜ao Cirilo et al. [6] : This journal shows a study of the intervening variables in electrochemical machining (ECM) of SAE-XEV-F Valve-Steel. A prototype developed at the laboratory was used. The material removal rate (MRR), roughness and over-cut were studied. Four parameters were changed during the experiments: feed rate, electrolyte, flow rate of the electrolyte and voltage. Forty-eight experiments were carried out in the equipment developed. The electrolytic solutions, sodium chloride (NaCl) and sodium nitrate (NaNO3), were used. The results show that feed rate was the main parameter affecting the material removal rate. The suface roughness decreases with feed rate. Irregular removal of material is more likely to occur at low feed rates. The electrochemical machining with the electrolytic solution sodium nitrate presented the best results concerning surface roughness and over-cut.

Jagannath Munda & Bijoy Bhattacharyya [7] : They reported that when ECM is used in the micron range, it is called electrochemical micromachining (EMM) and it is used as one of the best micromachining technique for machining electrically conductive ,tough and difficult to machine material with appropriate machining parameters combination. This paper attempts to establish a comprehensive mathematical model for correlating the interactive and higher-order influences of various machining parameters, i.e. machining voltage pulse on/off ratio, machining voltage, electrolyte concentration, voltage frequency and tool vibration frequency on the predominant micromachining criteria, i.e. the material removal rate and the radial overcut through response surface methodology (RSM), utilizing relevant experimental data as obtained through experimentation. Optimization of this parameters using mathematical model of RSM gives higher accuracy of the response parameter during machining.

The optimum value of different parameters are obtained as : pulse on/off time -1.0,machining voltage -3V ,electrolyte concentration- 15g/l, voltage frequency – 42.118 Hz and tool vibration as 300 Hz. The nature of machined micro-hole is depicted through the different SEM micrographs. The results and discussions are analyzed from the different graphs like machining voltage v/s electrolyte concentration on ROC; machining voltage v/s tool vibration frequency on MRR and pulse on/off ratio v/s voltage frequency on MRR. All the graphs and planning of the experimental design are obtained using the software called MINITAB.

Taha Ali El-Taweel & S. A. Gouda [8] : Wire electrochemical machining (WECM) is a cutting process in which the workpiece acts as anode and the wire is the cathode (tool).In this paper Taha and Gouda discusses the feasibility of using a wire as a tool in electrochemical turning process (WECT). They measured the performance criteria of the WECT process through investigating the effect of working parameter namely voltage, wire feed rate, wire diameter, workpiece rotational speed,and overlap distance on the response parameter which is metal removal rate,surface roughness and roundness error. Using the Response Surface Methodology (RSM) the regression model and analysis of variance were studied based on the experimental result. From the results and discussion the conclusions were obtained :

1. More effective micro-size turned parts can be produced using wire as an electrode in electrochemical turning instead of using a profiled tool .

2. The increase of the wire feed rate increases the surface roughness while improving the roundness error.

3. The increase of rotational speed of the work piece improves both the productivity of the process and geometrical error of the produced parts.

4. The optimum combination of parameters value was obtained as :

applied voltage of 32.5 V, wire feed rate of 0.4 mm/min, wire diameter of 1.3 mm, overlap distance of 0.03 mm, and rotational speed of 750 rpm for maximizing metal removal rate and minimizing both surface roughness and roundness error.

S.C. TAM, N.H. LOH [9] : Reported the study of ECM-Abrasive polishing of mild steel (resinoid-bonded silicon carbide) using Response Surface Methodology(RSM). ECM Abrasive polishing is a mechanical process where the material of surface layer is influenced by the rubbing, ploughing and cutting actions of abrasive grains and exploits the advantages of the micro-milling effect of ECM to generate the highly polished surfaces. Here three process parameters were taken as variables which are voltage, electrolyte concentration and tool holding pressure while the surface roughness was the response variable that had to be minimized. A second-order central composite design was used to locate the optimum conditions for achieving the best surface finish. The optimum value of surface roughness using RSM method was found to be 0.67µm while it was predicted as 0.64µm at an ECM voltage of 5.64V, electrolyte concentration of 7% and a tool-holding pressure of 0.61 bar.

S.K. Sorkhel and B. Bhattacharyya [10] : They designed and developed an Electrochemical Machining set-up with a microprocessor-controlled stepper motor drive control unit for providing variable and automatic tool feed rates. They also used an electronic circuit for auto-sensing of inter electrode gap during the course of machining so that automatically feed-rate can be controlled and thus secure constant current electrochemical machining. Here they took electrolyte flow rate, electrolyte concentration, current density and applied voltage as process parameters for obtaining minimum surface roughness and bearing properties of the machined surface using the help of a computerised Talysurf unit. The results showed that depending upon the objective of achieving a desired surface roughness, suitable combinations of the process variables considered can be explored and surface topography and surface - profile characteristics of the workpiece was analysed.

B. Bhattacharyya *, S.K. Sorkhel [11] : In this journal, researchers performed a experiment in a microprocessor-based ECM system having DC power supply with controlled electrolyte flow and automatic tool feeding. They developed a comprehensive mathematical model for correlating the interactive and higher-order influences of various machining parameters on the dominant machining criteria, i.e. the metal removal rate and the overcut phenomena, through response surface methodology (RSM), utilising relevant experimental data as obtained through the experimentation. The analysis of the experimental observations highlight that the MRR in ECM increases non-linearly with increase in the electrolyte flow rate and concentration and with the applied voltage. The observations and analysis carried out for over cut (OC) confirmed that an optimal control of the OC effect could be found for various process parameters to secure effective dimensional control of electrochemically-machined work piece.

Chapter 3

RESPONSE SURFACE METHODOLOGY

3.1 Response Surface Modelling :

In statistics, response surface methodology (RSM) explores the relationships between several descriptive variables and one or more response variables. The main objective of RSM is to optimise that response variable which is influenced by other variable using a developed model of designed experiments. Central composite design (CCD) can be implemented to estimate a second-degree polynomial model [12]. In this thesis, response surface modelling (RSM) method is used for determining the relations between the various ECM process parameters like voltage and tool feed rate with the various machining criteria and developing the effect of these process parameters on the response, i.e. the surface finish. In order to study the effects of the ECM parameters on the above mentioned machining criteria, second order polynomial response surface mathematical models is developed [12]. In the general case, the response surface is described by an equation of the form :

$$\mathrm{Y_u} = \beta_o + \sum_{i=1}^{S} \beta_i x_i + \sum_{i=1}^{S} \beta_{ii} x^2{}_{ii} + \sum_{i,j=1}^{S} \beta_{ij} x_i x_j + €,$$

where, Y_u is the corresponding response, e.g. the Ra produced by the various process variables of ECM and the x_i (1,2, . . . , S) are coded levels of S quantitative process variables, the terms β_o , β_i, β_{ii} and β_{ij} are the second order regression coefficients and € is the experimental error. The second term under the summation sign of this polynomial equation is attributable to linear effect, whereas the third term corresponds to the higher-order effects; the fourth term of the equation includes the interactive effects of the process parameters.

3.2 DESIGN OF EXPERIMENTS:

In the design of experiment, 13 experiments are conducted in duplicate and average values of surface roughness with design matrix were tabulated in table 2 which was developed in MINITAB software using RSM method. RSM uses 13 experimental trials with 6 cube points, 4 central points, 2 axial points and 1 centre point in axial direction.

Fig 4 ECM setup

Fig 5 Work piece and tool

TABLE I

DIFFERENT VARIABLES USED IN THE EXPERIMENT AND THEIR LEVELS

Variables	Code	Levels		
		1	2	3
Voltage (v) in volt	A	5	7.5	10
Feed (f) in mm/min	B	0.1	0.2	0.3

TABLE 2 (Fixed quantity)

Fixed quantity	value	unit
Flow rate	10	l/m
Electrolyte conc.	30	%

TABLE 3

RESPONSE TABLE BASED ON EXPERIMENTATION

Run	Voltage (v)	Feed (f)	Surface roughness Ra (µm)
1	1	1	1.666
2	3	1	2.014
3	1	3	1.969
4	3	3	2.697
5	1	2	1.759
6	3	2	2.149
7	2	1	1.668
8	2	3	1.957
9	2	2	1.506
10	2	2	1.568
11	2	2	1.765
12	2	2	1.420
13	2	2	1.687

Models for surface roughness (Ra) as determined by the preceding analysis as

$$Ra = 4.6203 - 0.7486\,v - 7.9036\,f + 0.0514\,v^2 + 17.9466\,f^2 + 0.3800\,vf \quad .... \qquad (1)$$

The interaction term (vf) here is not significant as we can see from the regression table that the its value is greater than .05 i,e, not satisfies the confidence level. Minitab software is used for analyze the experimental data of the response parameter surface roughness (Ra).

TABLE 4

REGRESSION TABLE FOR SR

Term	Coef	SE Coef	T	P	Remark
Constant	4.6203	0.70676	6.537	0.000	(most significant)
v	-0.7486	0.18314	-4.087	0.005	significant
f	-7.9036	3.48121	-2.270	0.057	Non significant
v*v	0.0514	0.01170	4.390	0.003	significant
f*f	17.9466	7.31072	2.455	0.044	significant
v*f	0.3800	0.24299	1.564	0.162	Non significant
S = 0.1215 R-Sq = 92.3% R-Sq(adj) = 86.9%					

From this regression table it can be seen that the interaction term has P value much greater than 0.05 and hence it is not significant in the process. The standard deviation of the process is 0.1215 and adjusted square value of surface roughness is 86.9%.

TABLE 5

ANOVA TABLE FOR SR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	1.24391	1.24391	0.248781	16.85	0.001
Linear	2	0.62913	0.37931	0.189656	12.85	0.005
Square	2	0.57868	0.57868	0.289338	19.60	0.001
Interaction	1	0.03610	0.03610	0.036100	2.45	0.162
Residual Error	7	0.10333	0.10333	0.014761		
Lack-of-Fit	3	0.02686	0.02686	0.008953	0.47	0.720
Pure Error	4	0.07647	0.07647	0.019118		
Total	12	1.34724				

The value of coefficient of determination for R^2 of the shortened quadratic model is depicted as 92.3% from the ANOVA table. This indicates the amount of variation in the response according to the model. The higher value of R^2 gives the idea of better fitting of the model with the data. To avoid an incorrect or misleading conclusion it is necessary to check the adequacy of the fitted model. The checking for adequacy includes the test for significance of the regression model, model coefficients, and lack of fit, which is shown in ANOVA table using MINITAB software. The residual error is the sum of lack-of-fit and pure error and the total error for regression is the sum of linear, square and interaction terms. The column of fit summary recommended that the quadratic model is statistically significant for analysis of SR [13].

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Chapter 4

RESULTS AND DISCUSSIONS

The effect of machining parameters on SR can be evaluated by performing the different experiments as shown in earlier table 2 and analyzed using the software “MINITAB 14” [2]. It is practically impossible to produce the geometry of engineering products perfectly, in agreement with ideal dimensions of the component. Surface roughness is a measure of the texture of a machined surface quality [1]. The regression model of the surface roughness (Ra) is shown in the eqn. (1). Based on this equation, the effect of the input process parameters on the surface roughness have been plotted in Figs. 6, 7, and 8.

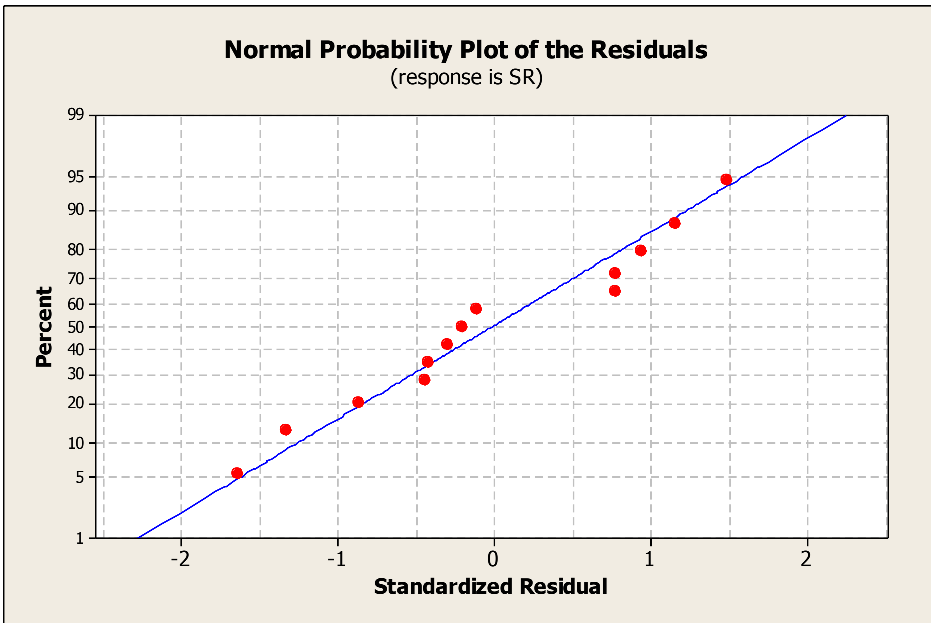

Fig 6.Normal probability plot for SR

It can be seen in Figure 6 that all the points on the normal plot lie close to the straight line (mean line). This implies that the data are fairly normal and a little deviation from the normality is observed. This shows the effectiveness of the developed model. It is noticed that the residuals fall on a straight line, which implies that errors are normally distributed .

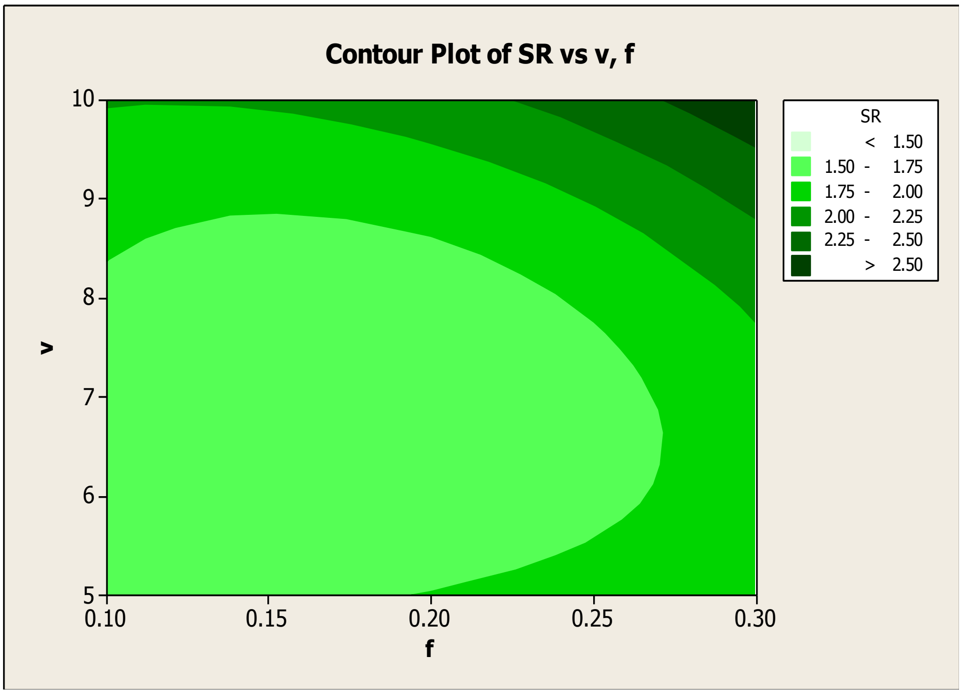

Fig 7.Contour plot of SR vs v,f

A contour plot graph is plotted taking the variables as feed rate, voltage and surface roughness. The various regions in the contour plot is represented by different coloured shades. The darker shade represents the maximum values of surface roughness and the texture is very rough. The lighter shades indicate the minimum values of surface roughness which implies that the surface is smooth. With the increase in the applied voltage and feed rate it can also be seen that the surface roughness increases.

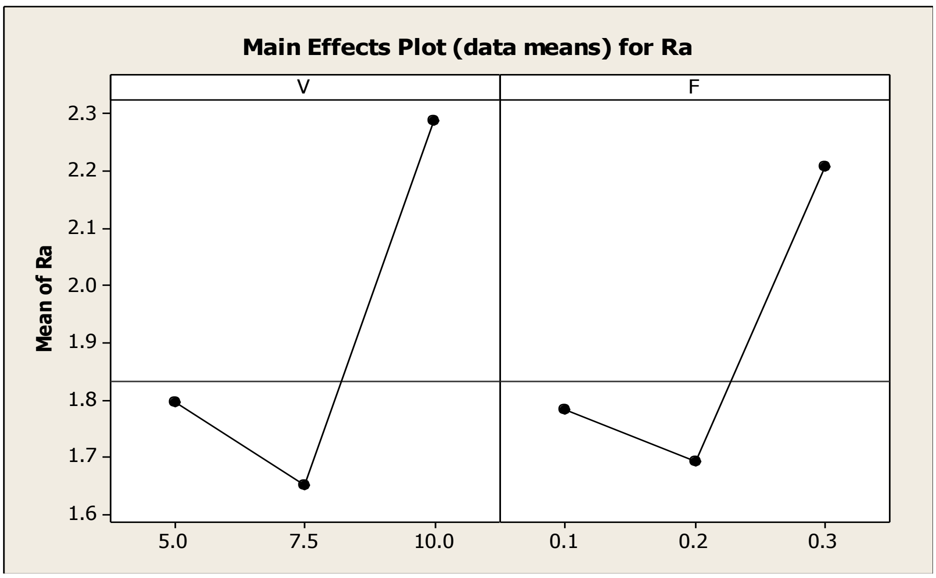

Fig 8.Main effect plot for SR

From the above main plot graph it is observed that the optimum value of surface roughness is obtained at voltage of 7.5V and feed rate of 0.2 mm/min which is most significant and applicable value amongst all other experimental values.

Chapter 5

CONCLUSION

The present study develops surface roughness (Ra) models for two different parameters namely voltage and feed rate for ECM process of mild steel as work piece and copper as tool material using response surface method . The second-order response models have been developed with analysis of variance [13]. From the above experiment and graph it is seen that surface roughness is minimum at the optimal value of voltage and feed. As we increase the voltage and feed rate surface roughness also increases .Hence an optimum value of voltage i.e. 7.5v and feed rate of 0.2 mm/min is most suitable and significant for the minimum value of surface roughness and good quality of the work piece.

Chapter 6

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Chapter 7

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