International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-1, Issue-6, August 2013

Evaluation Of Material Removal Rate Using Circular-Shaped Tube Electrode In Electrochemical Machining

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Abstract— **The many new materials and alloys that have been developed for specific uses possess a very low mach inability producing complicated geometries in such materials becomes extremely difficult with the conventional methods. Hence, Non-traditional machining has grown out of the need to machine exotic engineering metallic materials, composite materials and high tech ceramics. Electrochemical Machining has been accepted worldwide as a standard process in manufacturing and is capable of machining geometrically complex or hard material components, that are precise and difficult-to-machine. The principle of anodic dissolution of metal theory is the most accepted mathematical model for evaluating material removal from electrodes during electrochemical process. If two suitable metal poles are placed in a conducting electrolyte and a direct current passed through them, the metal on the positive pole get depleted and its material is deposited on the negative pole. Keeping this in view, the present work has been undertaken to finding the material removal rate by electrochemical dissolution of an anodically polarized work piece with a circular-shaped copper electrode.**

Index Terms— **AISI Type 304L, Material removal rate (MRR), Taguchi, S/N ratio, ANOVA**

I. Introduction

Electrochemical Machining (ECM) is a non-traditional machining (NTM) process belonging to electrochemical category. ECM is opposite of electrochemical or galvanic coating or deposition process. With the industrial and technological growth, development of harder and difficult to machine materials, which find wide application in aerospace, nuclear engineering and other industries owing to their high strength to weight ratio, hardness and heat resistance qualities has been witnessed.

Non-traditional machining has grown out of the need to machine these exotic materials. The machining processes are non-traditional in the sense that they do not employ traditional tools for metal removal and instead they directly use other forms of energy.

Electrochemical Machining (ECM) is the controlled removal of metal by anodic dissolution in an electrolytic cell in which the work piece is the anode and the tool is cathode. The electrolyte is pumped through the gap between the tool and the work piece, while direct current is passed through the cell, to dissolve metal from the work piece. ECM is widely used in machining of jobs involving intricate shapes and to machine very hard or tough materials those are difficult or impossible to machine by conventional machining. It is now routinely used for the machining of aerospace components, critical deburring, fuel injection system components, ordnance components etc.

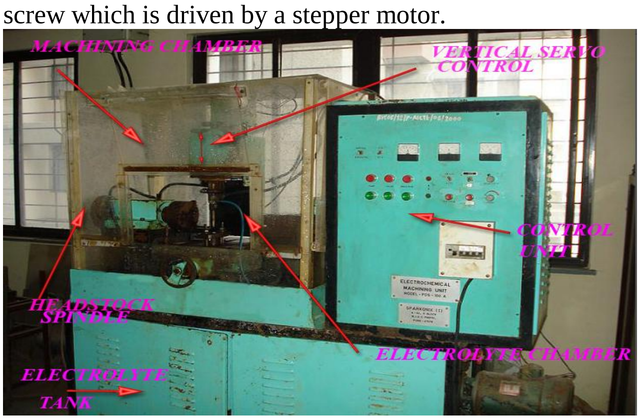
A. *SCOPE OF WORK:*

The scope of present work is an attempt to finding out the feasibility of making drilled hole using circular-shaped tube copper electrode in electrochemical machining .The work piece material is stainless steel and the machining parameters selected for study are diameter of electrode, electrolyte conductivity and applied voltage with Taguchi design approach.

II. EXPERIMENTAL PROCEDURE

A. *EXPERIMENTAL SET UP*

The ECM setup consists of control panel, machining chamber, electrolyte circulation system. The electrolyte is pneumatically pumped. An electrolyte flow rate of 8 liters per min., and an inter electrode gap of 0.3 mm was maintained constant for all the experiments. The machining has been carried out for fixed time interval and MRR was measured from weight loss. This electro-mechanical assembly is a sturdy structure, associated with precision machined components, servo motorized vertical up / down movement of tool, an electrolyte dispensing arrangement, illuminated machining chamber with see through window, job fixing vice, job table lifting mechanism and sturdy stand. All the exposed components, parts have undergone proper material selection and coating / plating for corrosion protection. The workpiece is fixed inside the chamber and tool is attached to the main screw which is driven by a stepper motor.



Manuscript received August 20, 2013.
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Fig 2 Experimental setup of Electrochemical machine

The process parameters like current, voltage and feed rate are varied by the control panel. The electrolyte $NaNO_3$ is pumped from a tank, lined by corrosion resistant coating with the help of corrosion resistant pump & is fed to the job. Spent electrolyte will return to the tank. Electrolyte solution is being measured by digital conductivity meter.

B. DESIGN OF ELECTRODE

In this experiment we have taken copper as electrode material at cathode. It is designed in circular shaped so as to cut the cavity in stainless steel in the similar profile. A long hollow cupper pipe was taken having length of 70mm. The ECM tooling is approximately the mirror image of the machined area of the completed part. The tool dimensions are slightly different to allow for overcut (side and front machining gaps) which can range from 0.025 to 0.5 mm depending upon the feed rate, electrolyte flow etc. The side overcut is about 1.5 times the front gap.

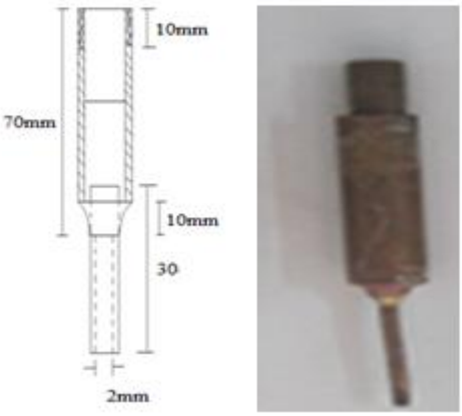

Fig. 3.7 Design of electrode

C. SPECIFICATION OF WORKPIECE MATERIAL

Work piece material: Stainless steel (AISI Type 304L)

Material Composition

Elements	Weight %
C	0.03
Mn	2.00
Si	1.00
Cr	18.0 – 20.0
Ni	8.0 – 12.0
P	0.045
S	0.03

Mechanical Properties

Density (×1000 kg/m3)	8
Poisson's Ratio	0.27 – 0.30
Elastic Modulus (GPa)	190 – 210
Tensile Strength (Mpa)	480
Yield Strength (Mpa)	170
Elongation (%)	40

III. GETTING INTO TAGUCHI

The Taguchi method is based on statistical design of experiments and is applied at the parameter design stage to establish optimum process settings or design parameters. The participation and commitment of top management are also vital for the successful implementations.

CONTROL FACTORS AND LEVELS

1. Voltage (A) volts
2. Feed rate (B) mm/min
3. Electrode diameter (C) mm.
4. Electrolyte concentration (D) mMhos/cm .

Factors / Levels	Voltage A	Feed Rate B	Electrode daimeter C	Electrolyte D
1	10	0.8	2	84
2	14	0.9	3	94
3	18	1.0	4	104

Table 3.4 Factors and level combination

SELECTION OF AN ORTHOGONAL ARRAY

The objective of this work is to obtain optimal values of ECM parameters- voltage; tool feed rate, electrode diameter and concentration of electrolyte. In the said analysis 04 (four) factors at 03 (three) levels (i.e. 3^4 experiments), were taken i.e. 3^4 experiments it is found that the L9 orthogonal array is the best suitable option.

Table 3 Taguchi L9 Orthogonal Array Design Matrix:

Test No.	A	B	C	D
E1	1	1	1	1
E2	1	2	2	2
E3	1	3	3	3
E4	2	1	2	3
E5	2	2	3	1
E6	2	3	1	2
E7	3	1	3	2
E8	3	2	1	3
E9	3	3	2	1

EXPERIMENTAL OBSERVATION :

Experiments were conducted according to Taguchi method. The control parameters like applied voltage, feed rate , diameter of electrode, and conductivity were varied to conduct nine different experiments and the weights of the work piece were taken for calculation of MRR.

MRR = (initial weight-final weight) / Time

Based on Taguchi L9 orthogonal array the values of input factors are placed in design matrix and each experiment was conducted twice to get the response more correctly.

	A	B	C	D	Initial wt.	Final wt.	Time	MRR
1	10	0.8	2	84	109	108.664	24	0.014
	10	0.8	2	84	108.664	108.208	24	0.019
2	10	0.9	3	94	108.208	107.208	25	0.040
	10	0.9	3	94	107.208	105.908	25	0.052
3	10	1.0	4	104	105.908	105.446	22	0.021
	10	1.0	4	104	105.446	105.028	22	0.019
4	14	0.8	2	104	105.028	104.118	26	0.032
	14	0.8	2	104	104.118	103.130	26	0.038
5	14	0.9	3	84	103.130	101.605	25	0.061
	14	0.9	3	84	101.605	99.98	25	0.065
6	14	1.0	4	94	99.98	99.112	28	0.031
	14	1.0	4	94	99.112	98.104	28	0.036
7	18	0.8	2	94	98.104	97.378	22	0.033
	18	0.8	2	94	97.378	96.696	22	0.031
8	18	0.9	3	104	96.696	95.842	24	0.036
	18	0.9	3	104	95.842	94.842	24	0.042
9	18	1.0	4	84	94.842	93.499	25	0.053
	18	1.0	4	84	93.499	92.249	25	0.050

Table. L_9 Design Matrix With Input Factor Values and MRR calculations

Fig. Drilled Workpiece Photograph

IV. RESULT ANALYSIS

The two responses are taken for further analysis to find out the optimum combination, which can yield into higher MRR. Statistical analysis was performed on the calculated values and the mean change in strength and signal to noise ratio values were calculated for the 9 experiments conducted.

Mean change in strength:

$\Sigma A_1=0.033+0.092+0.04 = 0.165$

$\Sigma A_2=0.073+0.125+0.067 = 0.265$

$\Sigma A_3=0.064+0.078+0.103 = 0.245$

Dividing ΣA_1, ΣA_2 and ΣA_3 by 3×2 (i.e. three factor combinations and two repetitions), the mean change in strengths under the conditions A_1, A_2 and A_3 was obtained. Thus;

$A_1= 0.165/6 = 0.0275$

$A_2= 0.265/6 = 0.04416$

$A_3= 0.245/6 = 0.04083$

Similarly calculating the mean change in length under the conditions B_1, B_2, B_3, C_1, C_2, C_3, D_1, D_2, D_3

Signal to Noise (S/N) Ratio

Larger is Better (S/N) Ratio is used when there is no predetermined value for the target (T=∞), and larger the value of the characteristic, the better the strength of the joint.

$$\text{S/N Ratio} = -10\log_{10}\left(\frac{1}{n}\Sigma\frac{1}{y_i^2}\right)$$

$$\therefore \text{S/N Ratio for } E_1 = -10\log_{10}\left(\frac{1}{2}\Sigma\frac{1}{0.014^2}+\frac{1}{0.019^2}\right) = -35.651$$

Similarly S/N Ratio for T_2 to T_9 was calculated.

Table Calculation of Signal to Noise ratio for various Response Factors

Test	MRR RESPONSE (Repetition) 1st	2nd	Test Response Total	Mean Response (MRR)	S/N Ratio
E1	0.014	0.019	0.033	0.0165	-35.6503
E2	0.040	0.052	0.092	0.0460	-26.7448
E3	0.021	0.019	0.04	0.020	-33.9794
E4	0.035	0.038	0.073	0.0365	-28.7541
E5	0.061	0.065	0.125	0.0630	-24.0132
E6	0.031	0.036	0.067	0.0335	-29.4991
E7	0.033	0.031	0.064	0.0320	-29.8970
E8	0.036	0.042	0.078	0.0390	-28.1787
E9	0.053	0.050	0.103	0.0515	-25.7639

Also mean change and S/N Ratio for Individual Factors were calculated;

S/N Ratio under the condition A_1 is,

$$\text{S/N Ratio for } A_1 = \left(\frac{35.6503+26.7448+33.9794}{3}\right) = 32.31$$

Similarly S/N Ratio under the conditions, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3, D_1, D_2 and D_3 was calculated.

Table 3.10 Mean Change and S/N Ratio for Individual Factors

Factor	Total Result	Mean Change	S/N Ratio
A_1	0.165	0.0275	32.31
A_2	0.265	0.04416	27.458
A_3	0.245	0.04083	27.98
B_1	0.17	0.0284	31.546
B_2	0.295	0.0492	26.416
B_3	0.21	0.035	29.786
C_1	0.178	0.0297	31.260
C_2	0.268	0.0447	27.172
C_3	0.229	0.0382	29.316
D_1	0.261	0.0435	28.83
D_2	0.223	0.0372	28.816
D_3	0.191	0.0318	30.348

The response table for signal to noise ratio for material removal rate (MRR) is shown in table ….

Table 3.12 Taguchi analysis response table for signal to noise ratios :

Level	Voltage	Feed rate	Electrode diameter	Electrolyte concentration
1	-32.12	-31.43	-31.11	-28.48
2	-27.42	-26.31	-27.09	-28.71
3	-27.95	-29.75	-29.30	-30.30
Delta	4.70	5.12	4.02	1.83
Rank	2	1	3	4

Rank is ordered on the basis of delta, higher the delta, greater is the influence of that parameter on material removal rate. Thus the material removal rate is highly influenced by feed rate then voltage, electrode diameter and electrolyte conductivity.

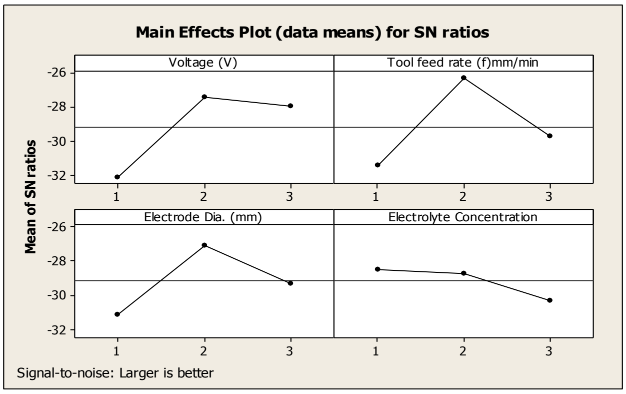

Fig. Graph of main effects plot for SN ratios

The machinability of ECM depends on the voltage, electrical conductivity of the electrolyte, feed rate of electrode, diameter of electrode. The MRR increases as the voltage increases from first to second level (ie. From 10 to 14 volts) but it decreases as it further increases to third level (18 volts). The electrode feed rate has enormous effect on MRR and it increases with increase in feed rate upto second level (0.9 mm/sec) and then decreases as the feed rate increases to the third level . MRR also increases from first level to second level (ie. From 2 mm to 3 mm) diameter of electrode; however, it decreases from second to third level (ie. From 3mm to 4mm). Material removal rate is thus small for 2 mm and 4 mm diameter of electrode and higher at 3mm diameter. The electrolyte concentration has very little effect on MRR and doesn't give any conclusive evidence of any impact on MRR. However MRR decreases slightly as concentration increases.

The optimum parameter setting for MRR is –

	Voltage	Feed rate	Electrode diameter	Electrolyte conductivity
Max. MRR	14	0.9	3	84

Table 3.13 Optimal combination for MRR

ANALYSIS OF VARIANCE (ANOVA)

The relative magnitude of the effect of different factors can be obtained by the decomposition of variance, called analysis of variance (ANOVA). The basic idea of analysis of variance is to partition (i.e. divide up) the variability observed in the data into two parts: variability that can be accounted for by group membership, and variability that cannot.

$$\text{Overall Mean} = \bar{\bar{y}} = \frac{\sum\sum y_{ij}}{n_T}$$

$$\therefore \bar{\bar{y}} = \frac{(0.033 + \ldots.. + 103)}{18} = \frac{0.675}{18} = 0.0375$$

$$\text{Total Sum of Squares} = \text{SSTO} = \sum\sum\left(y_{ij} - \bar{\bar{y}}\right)^2$$

$$\therefore \text{SSTO} = \left[\begin{array}{l}(0.014 - 0.0375)^2 + (0.019 - 0.0375)^2 + \ldots\ldots \\ \ldots\ldots\ldots + (0.050 - 0.0375)^2\end{array}\right]$$

$$\therefore \text{SSTO} = 0.0035665$$

$$\text{Treatment Sum of Squares} = \text{SSTR} = \sum n_j\left(\bar{y}_j - \bar{\bar{y}}\right)^2$$

$$\therefore \text{SSTR}_A = \left(\begin{array}{l}\left(6\times(0.0275 - 0.0375)^2\right) \\ +\left(6\times(0.04416 - 0.0375)^2\right) \\ +(6\times(0.04083 - 0.0375))^2\end{array}\right) = 0.00093266$$

Similarly, $SSTR_B$ =0.001355, $SSTR_C$ =0.000909 , $SSTR_D$ = 0.0004114

Total Sum of Squares = $SSTR_{All}$ = (0.00093266 +……+ 0.0004114) = 0.00360806

$$\text{Error Sum of Squares} = \text{SSE} = \sum_j\left[\sum_i\left(y_{ij} - \bar{y}_j\right)^2\right]$$

$$\therefore \text{SSE} = 0.000136$$

As we know, SSTO = SSTR + SSE

SSTO = 0.00360806 + 0.000136 = 0.00374406

$$\text{Mean Square} = \text{MS} = \frac{\text{SS}}{\text{DOF}}$$

$$\text{Treatment Mean Square} = \text{MSTR} = \frac{\text{SSTR}}{8}$$

$$= \frac{0.00360806}{8} = 0.000451$$

$$\text{Error Mean Square} = \text{MSE} = \frac{\text{SSE}}{9} = \frac{0.000136}{9} = 0.0000151$$

$$\text{Variance} = \text{V} = \frac{\text{Sum of Squares}}{\text{Degrees of Freedom}}$$

$$\therefore \text{V}_\text{A} = \frac{\text{SS}_\text{A}}{\text{DOF}} = \frac{0.00093266}{2} = 0.00046633$$

F-test is used to determine which process parameters have a significant effect on the quality characteristic. The variance ratio denoted by F is given by;

$$\text{F} = \frac{\text{Mean Square of Factor( )}}{\text{Error Mean Square}}$$

$$\therefore \text{F}_\text{A} = \frac{\text{MS}_\text{A}}{\text{MSE}} = \frac{\left(\frac{\text{SS}_\text{A}}{\text{DOF}}\right)}{\text{MSE}} = \frac{\left(\frac{0.00093266}{2}\right)}{0.0000151} = 30.88278$$

Percentage Pooled Error (%p)

$$\%\,\text{p} = \frac{\text{Sum of Squares}}{\text{Total Sum of Square}}$$

$$\therefore \%\,\text{p}_\text{A} = \frac{\text{SS}_\text{A}}{\text{SSTO}} \times 100 = \frac{0.00093266}{0.00360806} \times 100 = 25.84$$

Table Analysis Of Variance (ANOVA) for MRR

	DOF	SS	V	F	P (%)
A	2	0.00093266	0.00046633	30.88278	25.84
B	2	0.001355	0.0006775	44.8675	37.55
C	2	0.000909	0.0004545	30.09933	25.19
D	2	0.0004114	0.0002057	13.62251	11.40
Total	8	0.00360806	0.001804	119.472	100

The P-value reports the significance level (suitable and unsuitable) in Table 6.4 Percent (%) is defined as the significance rate of the process parameters on the metal removal rate. The percent numbers depict that the applied voltage, feed rate, electrode diameter and electrolyte concentration have significant effects on the metal removal rate. It can observed from Table 6.4 that the applied voltage (A), feed rate (B) electrode diameter (C) and electrolyte concentration (D) affect the metal removal rate by 25.84%, 37.55% , 25.19 % and 11.40 % in the electrochemical machining of AISI Type 304L.

CONFIRMATION TEST

The experimental confirmation test is the final step in verifying the results drawn based on Taguchi's design approach. The optimal conditions are set for the significant factors (the insignificant factors are set at economic levels) and a selected number of experiments are run under specified cutting conditions. The average of the results from the confirmation experiment is compared with the predicted average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended by Taguchi to verify the experimental results . In this study, a confirmation experiment was conducted by utilizing the levels of the optimal process parameters as voltage = 14 volts , feed rate = 0.9 , electrode diameter = 3mm , Conductivity = 84 mMhos/cm for which metal removal rate value in the electrochemical machining of SS – 304L is obtained as 0.0732 g/min.

V. CONCLUSION

This study has discussed an application of the Taguchi method for investigating the effects of process parameters on the material removal rate (gm /min) in electrochemical machining of SS - 304L. In ECM, the process parameters were selected taking into consideration of manufacturer and industrial requirements. From the analysis of experimental results in ECM process using conceptual signal-to-noise (S/N) ratio approach, analysis of variance (ANOVA), and Taguchi's optimization method, the following can be concluded from the present study:

- Statistically designed experiments based on Taguchi methods were performed using L_9 orthogonal arrays to analyze the material removal rate as response variable, conceptual S/N ratio and ANOVA approaches for data analysis drew similar conclusions.
- Statistical results show that the voltage (A), feed rate (B),electrode diameter (C) and electrolyte conductivity (D) affects the material removal rate by 25.84%, 37.55% , 25.19 % and 11.40 % in the electrochemical machining of SS- 304L, respectively.
- In this study, the analysis of the confirmation experiment for metal removal rate has shown that Taguchi parameter design can successfully verify the optimum machining parameters (A2B2C2D1), which are voltage=14 V (A2) feed rate= 0.9 mm/sec (B2) , electrode diameter =3 mm (C2) and electrolyte conductivity = 84 mMhos/cm (C1).

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