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Research Article

Optimization of process parameters for metal removal rate in case of WEMM using Continuous DC supply by Taguchi methods and ANOVA Analysis

Mohd. Farhan Zafar[†*], **Taufeeque Hasan**[‡] **and Vipin Tyagi**[‡]

[†]Department of Mechanical Engineering, Aligarh Muslim University, Aligarh, India
[‡]MAE Deptt., Amity University Haryana, India

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Abstract

Wire Electrochemical Micromachining is a relatively new method of machining using electrochemical dissolution; it utilizes the principle of electrolysis and uses a micro-wire for metal removal to produce micro metal parts. Since there is no tool wear, a thinner wire can be used in this process. In the present study, Wire electrochemical machining input parameters are optimized using Taguchi approach for maximum metal removal rate. In this study continuous DC power supply is used for metal removal and the tool is made up of copper wire. After analysis, the optimum parameter range came out to be 200 g/l of electrolyte concentration and 24 V of machining voltage. The electrolyte used is aqueous Sodium Chloride solution.

Keywords: *Wire Electrochemical Micromachining, Taguchi Analysis, Continuous DC supply*

1. Introduction

The machining of materials in micrometer and sub-micrometer scales is considered to be a key future technology. Apart from the wide spread use of lithographic processes used in the fabrication of electronic devices, micromachining technologies play an increasing role in the miniaturization of complete machining setups (P. Rai Choudhury, 1997; Amato I, 1998) ranging from biological and medical applications (Amato I., M. A. J. T. Santini, 1999) to electrochemical sensors and actuators (H.Jerman *et al*) to chemical micro-reactors (M. U. Kopp *et al*, 2003). Various techniques have been developed to produce micro metal parts in different principles, including: i) material removal methods such as excimer laser machining, electric discharge machining, electrochemical machining. ii) material deposition techniques such as laser- assisted chemical vapor deposition and localized electrochemical deposition. ii) lithography based methods (Z.Y. Yu *et al*, 2003; T. Masuzawa *et al*. 1999; K.P. Rajurkar *et al*, 1999 J.A. McGeough, 2001) Electrochemical machining (ECM) process is based on the electrochemical dissolution, at a sufficiently high electrical current density, of an anodically polarized workpiece (J.A. McGeough, 1974-1998). ECM is an advantageous machining process when: (i) the absence of wear of the tool, (ii) the absence of a heat-affected zone and residual stresses in the workpiece, (iii) a good surface finish and (iv) a high machining rate, are important. D. Chakradhar and A. Venu Gopal have optimized the ECM parameters like electrolyte concentration, feed rate and voltage for EN-31 Steel by grey relational analysis using the target performance characteristics like MRR, overcut, cylindricity error and surface roughness. C. Senthilkumar *et. al.* have developed mathematical models for various predominant machining parameters on MRR and surface roughness using research surface methodology approach fir Al/SiCp composites. S. Rama Rao *et al.* has done modeling of the ECM parameters using fuzzy logics and evolutionary algorithms by taking different input parameters like current, voltage gap and feed rate and output parameters like MRR and surface roughness as output responses. P.Asokan *et al.* [18] have optimized cutting parameters like current, voltage, flow rate and machining gap for ECM based on multiple regression models and ANN model for MRR and surface roughness as responses. J. Munda and B. Bhattacharya have investigated the micro-electrochemical micromachining parameters like machining pulse on/off ratio, machining voltage, electrolyte concentration, voltage frequency and tool vibration frequency on the predominant micromachining parameters i.e. metal removal rate and the radial overcut through response surface methodology

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[*]Corresponding author: **Mohd. Farhan Zafar; Taufeeque Hasan** is working as Assistant Professor**; Vipin Tyagi** is a Scholar

approach, developed mathematical model and analyzed the validity of developed mathematical models. S.J. Ebeid *et al*. have developed the mathematical models for correlating the interrelationships of various machining parameters such as applied voltage, feed rate, back pressure, vibration amplitude on overcut and conicity. P. S. Kao and H. Hocheng has optimized the parameters for electro-polishing of stainless steel by grey relational analysis for target performance characteristics i.e. surface roughness and passivation strength, can be performed through this method.

In this study, we have studied Wire Electrochemical micro- machining process (WEMM) is a process in which metal is removed by anodic dissolution process. In contrast to wire electric-discharge machining, the wire electrode in wire electrochemical micromachining is not worn out and so thinner wire can be used and narrower grooves can be fabricated. Therefore, wire electrochemical micromachining is a promising micromachining method. Therefore, the wire electrochemical machining is a promising micro machining method. However the micron scale wire electrode is breakable and difficult to be fixed onto the machining system.

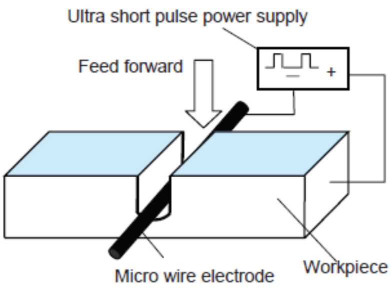

Fig. 1 Schematic Diagram of Wire Electrochemical machining process

In this study, different machining parameters like machining voltage, electrolytic concentration were optimized using Taguchi method to study the response like MRR and overcut. Also the results thus obtained are validated using analysis of variance.

2. Taguchi Experiments: Design and Analysis

Taguchi methods have been widely utilized in engineering analysis and consist of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behavior of a given process. One important factor in design of experiment is number of performing experiments and also cost of performing them. In some cases, the constraint of number of experiment is very important and performing all experiments may not be possible. The greatest advantage of this method is saving of effort in conducting experiments; saving experimental time, reducing the cost and discovering significant factors quickly. Taguchi's robust design method is a powerful tool for the design of a high quality system. In addition to the S/N ratio, a statistical analysis of variance (ANOVA) can be employed to indicate the impact of process parameters on metal removal rate values. The steps applied for Taguchi optimization in this study are as follows:

- Select noise and control factors
- Select Taguchi orthogonal array
- Conduct Experiments
- Metal Removal Rate measurement
- Analyze results; (Signal-to-noise ratio)
- Predict optimum performance
- Confirmation experiment

3. Experimental Procedure

Taguchi methods combines the experiment design theory and the quality loss function concept, has been used in developing robust design of products and processes in solving some taxing problems of manufacturing. The degree of freedom for two factors and four levels were calculated as follows:

DOF = 1 + (No. of factors * (No. of levels-1)) = 1 + (2 * (4 – 1)) = 7

In this study nine experiments were performed at different parameters. Figure below shows the setup used for performing experimentation. The experimental conditions discussed are tabulated as under:

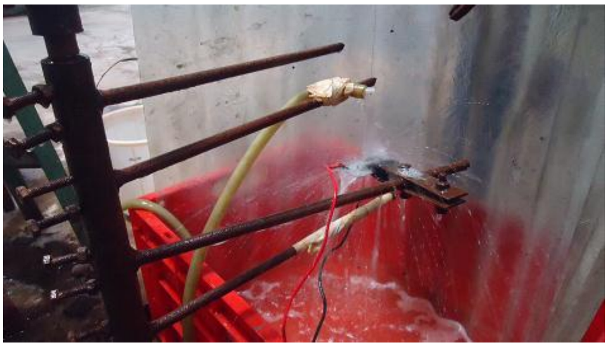

Fig. 2 Experimental Setup Used

In this study nine experiments were performed at different parameters. Figure below shows the setup used for performing experimentation. The experimental conditions discussed are tabulated as under:

Table 1 Experimental Conditions

Machining Current	1 A
Electrolyte	NaCl Solution (recycled)
Wire (tool) Diameter	260 microns
Job material	Galvanized iron Sheet
Job thickness	500 microns
Type of power supply	Continuous DC supply

3.1 Selection of machining parameters and their levels

The input parameters which are optimized in this study were electrolyte concentration and machining voltage. These parameters are selected in accordance with the researcher's infrastructural limitations. Table 2 enlists parameters and their levels to be used for Taguchi experiment. Our initial conditions are level 2 i.e. Electrolyte concentration of 100 g/l and machining voltage 12 V.

Table 2 Cutting parameters and their levels

Symbol	Machining parameter	Unit	Levels			
			1	2	3	4
A	Electrolyte Conc.	g/l	50	100	150	200
B	Machining Voltage	Volt	5	12	18	24

3.2 Cutting Performance Measure

The responses measured after machining is metal removal rate. MRR was measured as the difference in initial and final weight of workpiece before and after machining respectively. These weights were weighed using weighing scale having specifications as: Make: Denver Instruments, Gottingen, Series: TP Series, Range: 0- 200 gm, Sensitivity: 0.0001 gm

3.4 Orthogonal Array Experiment

To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between design parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level design parameter counts for two degrees of freedom. The degrees of freedom associated with the interaction between two design parameters are given by the product of the degrees of freedom for the two design parameters. In the present study, the interaction between the machining parameters is neglected. Therefore, there are seven degrees of freedom owing to there being two cutting parameters. Once the required degrees of freedom are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the design parameters. In this study, an L16 orthogonal array with four columns and sixteen rows was used. This array has fifteen degrees of freedom and it can handle four-level design parameters. Each machining parameter is assigned to a column, sixteen cutting-parameter combinations being available. Therefore, only sixteen experiments are required to study the entire parameter space using the L16 orthogonal array. The experimental layout for the two machining parameters using the L16 orthogonal array is shown in Table 3. Since the L16 orthogonal array has four columns, two column of the array is left empty for the error of experiments: orthogonality is not lost by letting one column of the array remain empty.

Table 3 Experimental Condition using L16 Orthogonal Array

Exp. No.	A	B	Electrolyte Conc.(g/l)	Voltage (V)
1	1	1	50	5
2	1	2	50	12
3	1	3	50	18
4	1	4	50	24
5	2	1	100	5
6	2	2	100	12
7	2	3	100	18
8	2	4	100	24
9	3	1	150	5
10	3	2	150	12
11	3	3	150	18
12	3	4	150	24
13	4	1	200	5
14	4	2	200	12
15	4	3	200	18
16	4	4	200	24

3.5 Experimental Observations

Experiments were performed using the parameters and conditions that are enlisted as above and the responses thus tabulated as mentioned below

Table 4 Experimental Observations

Exp. No.	Electrolyte Conc.(g/l)	Voltage (V)	MRR (g/min)	Overcut (mm)
1	50	5	0.00011	0.092
2	50	12	0.00344	2.33
3	50	18	0.00571	3.675
4	50	24	0.00898	5.746
5	100	5	0.0008	2.038
6	100	12	0.00104	2.392
7	100	18	0.01031	5.459
8	100	24	0.00766	5.13
9	150	5	0.00107	2.684
10	150	12	0.00367	3.162
11	150	18	0.01102	7.162
12	150	24	0.01135	7.377
13	200	5	0.00564	4.387
14	200	12	0.00835	8.975
15	200	18	0.00957	12.86
16	200	24	0.01151	7.743

4. Results and Discussion

4.1 Taguchi Analysis

Taguchi method uses Signal to Noise(S/N) ratio to measure the quality characteristic deviating from the desired value. The S/N rate is defined as

$$S/N = 10 \log \mu^2 / \sigma^2 \qquad (1)$$

Where
μ = mean or average
σ = Standard deviation or natural variation.

There are three categories of quality characteristics, i.e. the lower-the-better, the higher- the-better, and the nominal-the-better. We have used the larger the better characteristic. The S/N ratio for larger the better quality characteristic is given as under:

$$\frac{S}{N} = -10\log_{10}\left\{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i^{2}}\right)\right\} \tag{2}$$

Where n is the number of measurements in a trial/row, in this case n=1 and y is the measured value in a run/row. Table 4 shows the values of Metal removal rate and the corresponding S/N ratios. Regardless of the quality characteristic, the greater S/N ratio corresponds to the smaller variance of the output characteristic around the desired value (Eqn. 2). Figure 3 shows the S/N response graph for metal removal rate.

Table 5 S/N ratios for Metal removal rate

Exp. No.	Electrolyte Conc.(g/l)	Volt.(V)	MRR (g/min)	S/N Ratios (dB)
1	50	5	0.00011	-79.1721
2	50	12	0.00344	-49.2688
3	50	18	0.00571	-44.8673
4	50	24	0.00898	-40.9345
5	100	5	0.0008	-61.9382
6	100	12	0.00104	-59.6593
7	100	18	0.01031	-39.7348
8	100	24	0.00766	-42.3154
9	150	5	0.00107	-59.4123
10	150	12	0.00367	-48.7067
11	150	18	0.01102	-39.1564
12	150	24	0.01135	-38.9001
13	200	5	0.00564	-44.9744
14	200	12	0.00835	-41.5663
15	200	18	0.00957	-40.3818
16	200	24	0.01151	-38.7785

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8	100	24	0.00766	-42.3154
9	150	5	0.00107	-59.4123
10	150	12	0.00367	-48.7067
11	150	18	0.01102	-39.1564
12	150	24	0.01135	-38.9001
13	200	5	0.00564	-44.9744
14	200	12	0.00835	-41.5663
15	200	18	0.00957	-40.3818
16	200	24	0.01151	-38.7785

Table 6 S/N response table for Metal removal rate

	1	2	3	4	Range
A	-53.5607	-50.9119	-46.5438	-41.4252	12.1355
B	-61.3743	-49.8003	-41.0351	-40.2321	21.1422

Based on the analysis of the S/N ratio, the optimum machining performance for metal removal rate is obtained at level 4 each of parameters A and B i.e. 200 g/l of electrolyte concentration and 24 V of machining voltage. Figure below shows the effect of electrolyte concentration and machining voltage on metal removal rate. As it is evident from the graph a linear relationship exists between the metal removal rate and electrolyte concentration. This is due to the fact that as the electrolyte concentration increases, the resistivity of the electrolyte changes which ultimately results in increase in metal removal rate. As far as machining voltage is concerned metal removal rate varies according to Faraday's law which states that the amount of metal dissolved or deposited is proportional to the quantity of the electricity passed. i.e. m ∝ I.

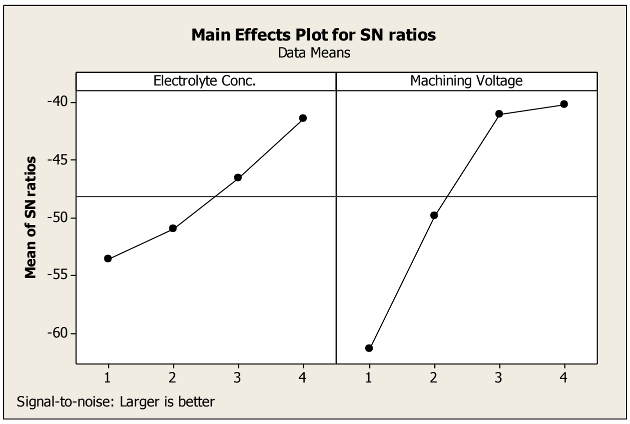

Fig. 3 Response graphs for Metal removal rate

4.2 ANOVA Analysis

The purpose of the analysis of variance (ANOVA) is to investigate which design parameters significantly affect the output characteristic. This is to be accomplished by separating the total variability of the S/N ratios, which is measured by the sum of the squared deviations from the total mean S/N ratio, into contributions by each of the design parameters and the error. First, the total sum of squared deviations SST from the total mean S/N ratio ηm can be calculated as:

$$SS_T = \sum_{i=1}^{n}(\eta_i - \eta_m)^2 \tag{3}$$

Where ηi is the mean S/N ratio for the ith experiment ηm is the total mean S/N ratio and n is the number of experiments in the orthogonal array. The total sum of spared deviations SST is decomposed into two sources: the sum of squared deviations SSd due to each design parameter and the sum of squared error SSe. The percentage contribution by each of the design parameters in the total sum of squared deviations SST is a ratio of the sum of squared deviations SSd due to each design parameter to the total sum of squared deviations SST.

Table 7 ANOVA table for Metal Removal Rate

Source	D.F	S.S	M.S	F value	P value	% Cont.
Electrolyte Concentration (g/l)	3	0.0000446	0.0000149	4.47	0.035	17.531
Machining Voltage	3	0.0001798	0.0000599	18.03	0.000	70.676
Error	9	0.0000299	0.0000033			11.753
Total	15	0.0002544				100

In the analysis, the F-ratio is a ratio of the mean square error to the residual error, and is traditionally used to determine the significance of a factor. The P-value reports the significance level in Table 6. Percent (%) is defined as the significance rate of the process parameters on the metal removal rate. The percent numbers depict that the applied voltage and electrolyte concentration have significant effects on the metal removal rate. It can be observed from Table 6 that the machining voltage and electrolyte concentration affect the metal removal rate by 17.531% and 70.676% in case of electrochemical machining respectively. A confirmation of the experimental design was necessary in order to verify the optimum cutting conditions. Also it can be seen from the table that the effect of machining voltage and electrolyte concentration is significant (since P-value < 0.05).

4.3 Confirmatory 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 experiment, the experimental and predicted values are tabulated as under. The corresponding value of metal removal rate is obtained from the eqn. 1.

Table 8 Results of the confirmation experiment for maximum metal removal rate at optimum conditions

	Optimal Machining Parameters	
	Prediction	Experiment
Level	A4B4	A4B4
Metal removal rate (g/min)	0.02102	0.01151
S/N ratio (dB)	-33.5469	-38.7785

The above table depicts that there is quite good conformance of experimental and predicted value at the optimal machining conditions depicted by Taguchi design.

Conclusions

- This study has presented the Wire Electrochemical Micromachining in a new light that it is possible to machine electrochemically using continuous DC supply and also following conclusions can be drawn:
- Taguchi's robust orthogonal array design method is suitable to analyze the metal removal rate as described in this study.
- It can also be concluded that the parameter design of the Taguchi method provides systematic and efficient methodology for the optimization of the machining parameters. (Electrolyte Concentration and machining voltage).
- The experimental results show that machining voltage and electrolytic concentration are the important parameters that can be controlled to influence the metal removal rate.
- In case of metal removal rate, the significant parameters are both machining voltage followed by electrolyte concentration, the role of electrolyte concentration and machining voltage on metal removal rate being 17.53% and 70.68% respectively as analyzed using ANOVA.
- For maximum metal removal rate, use of maximum electrolyte concentration and machining voltage (A4B4) is recommended to obtain a higher amount of metal removal. This level of electrolyte concentration and machining voltage corresponds to 200 g/l and 24 V respectively.
- Deviations between actual and predicted S/N ratio of metal removal rate and overcut are small and within the experimental errors of the setup.

References

P. Rai-Choudhury (1997), Ed., Handbook of Microlithography, Micromachining and Microfabrication, SPIE Optical Engineering Press, Bellingham, WA.

Amato I. (1998), Science 282, 402.

M. A. Burns *et al.* (1998), Science 282, 484.

J. T. Santini, M. J. Cima, R. Langer(1999), Nature 397, 335.

H.Jerman and S. Terry, Handbook of Microlithography, Micromachining, & Microfabrication, SPIE Optical Engineering Press, Bellingham, WA , vol. 2, pp. 379-434.

M. U. Kopp, A. J. d. Mello, A. Manz (1998), Science 280, 1046.

Z.Y. Yu, J. Kozak, and K.P. Rajurkar (2003), Modelling and simulation of micro EDM process, CIRP Annals, vol. 52, pp.143-146.

T. Masuzawa, K. Okajima, T. Taguchi (2002), EDM-lathe for micromachining, CIRP Annals, vol. 51, , pp.355-358.

K.P. Rajurkar, D. Zhu, J.A. McGeough, and J. Kozak (1999), New developments of electrochemical machining, CIRP Annals, vol. 48, pp.567-570.

J.A. McGeough, M. Leu, K.P. Rajurkar, De Silva AKM, and Q. Liu (2001), Electroforming process and application to micro/macro manufacturing, CIRP Annals, vol. 50, pp.499-514.

J.A. McGeough (1974), Principles of Electrochemical Machining, Chapman and Hall, London.

J.A. McGeough, Advanced Methods of Machining, Chapman and Hall, London, 1988.

M.A. Bejar, F. Eterovich (1995), Wire-electrochemical cutting with a NaNO3 electrolyte, International Journal of Materials Processing Technology 55 417–420.

Chakradhar D, Venu Gopal (2011) A Multi-objective optimization of electrochemical machining of EN31 steels by grey relational analysis. International Journal of Modeling and Optimization, 1(2), 113-117.

Senthilkumar C, Ganesan G, Karthikeyan R (2009), Study of electrochemical machining characteristics of Al / SiCp composites, International Journal of Advanced Manufacturing Technology, 43, 256-263.

Rama Rao S, Padmanabhan G, Sureka B, Pandu R. V (2009), Optimization of electrochemical machining process using evolutionary algorithms,(Journal of machining and forming technology, 1, 265-278.)

Rama Rao S, Sravan C.R.M Padmanabhan G, Pandu R. V (2009) Fuzzy logic based forward modeling of electrochemical machining process. Proc. 2009 World Congress on Nature & Biologically Inspired Computing (NaBIC 2009, Coimbatore, Indi , 1431-1435)

Asoken P, Ravi Kumar R, Jeypaul R, Santhi M (2008), Development of multi-objective optimization models for electrochemical machining process, International Journal of Advanced Manufacturing Technology 39, 55-63.

Munda J., Bhattacharya B. (2008), Investigation into electrochemical micromachining (EMM) through response surface methodology based approach, International Journal of Advance Manufacturing Technology 35 821-832.

Ebeid S.J, Hewidy M.S, EI-Taweel T.A, Youssef H (2004), Towards higher accuracy for ECM hybridized with low-frequency vibrations with response surface methodology, Journal of Material Processing Technology 149, 432-438.

Kao P.S, Hocheng H (2003) Optimization of electrochemical polishing of stainless steel by grey relational analysis, Journal of Material Processing Technology 140, 255-259.

Zhu D., Wang K., Qu N.S., Micro Wire Electrochemical Cutting by Using In Situ Fabricated Wire Electrode., Annals of the CIRP Vol. 5, 1/200, 241-244

Taguchi G (1990), Introduction to quality engineering, Asian Productivity Organization, Tokyo

Tsao CC, Hocheng H (2004), Taguchi analysis of delamination associated with various drill bits in drilling of composite material, International Journal of Machine Tools Manufacturing 44, 1085–1090.

Taguchi G, Hocheng (1987), Taguchi methods orthogonal arrays and linear graphs, tools for quality engineering, Dearborn, MI: American Supplier Institute, 35 – 38.

Yang W. H., Tang Y.S. (1998), Design optimization of cutting parameters for turning operations based on the Taguchi method, Journal of Material Processing Technology, (84;122-129)

Ghosh A., Mallik A. K.; Manufacturing Sciences; EWP Pvt Ltd.