Statistical analysis and Optimisation of Process Parameters by Using Micro- EDM

[1] Priyanka Gangurde, [2] Megha Nagrale
[12] Department of Mechanical Engineering
[12] Sardar Patel College of Engineering, University of Mumbai, India.

Abstract: Micro parts and systems are playing crucial roles in the area of semiconductor, biomedical device, micro fluid devices, automotive, aerospace and so forth. Micro manufacturing is one of the most important technologies in realizing miniaturization. The lack of correlations between the cutting rate, the surface finish and the physical material parameters of this process made it difficult to use. This research work focusses on the development of a comprehensive mathematical model for correlating the interactive and higher order influences of various electrical discharge machining parameters through response surface methodology (RSM), utilizing relevant experimental data as obtained through experimentation. The adequacy of the above the proposed models have been tested through the analysis of variance (ANOVA). Optimal combination of these parameters was obtained for achieving controlled EDM of the work pieces.

***Keywords* - Electrical discharge machining; Response surface methodology; CCD; TWR; MRR.**

I. INTRODUCTION

Electrical Discharge Machining (EDM) is a non-traditional machining process, which removes electrical conductive material by a series electric sparks between two electrodes submerged in the dielectric fluid. The main material removal mechanism in EDM is melting and vaporization of work piece material caused by the electrical discharge sparks [1]. In non-traditional machining processing, electrical discharge machining (EDM) has tremendous potential on account of the versatility of its applications and it is expected that it will be successfully and commercially utilized in modern industries.

There has been continuing development of miniaturized, lighter and higher density products in a wide variety of fields because of the growing needs of micro devices for mechanical, electronics and medical applications. Therefore, various micro-machining methods have been introduced such as cutting, laser, ion, and electron beams, ultrasonic, electrochemical, and electrical discharge machining. Especially, electrical discharge machining (EDM) is non-contact thermal process, which has advantages such as high precision machining of conductive materials regardless of material hardness. Therefore, micro-EDM has been adopted as one of most valuable techniques for micro fabrication [2]. The basic difference between EDM and micro EDM (for both wire and die sinking EDM) is the dimension of the plasma channel radius that arises during the spark.

Although the EDM technology and its fundamental mechanism have been investigated by many researchers, some additional aspects of the process still need to be thoroughly investigated for enhancing its application potential and performance in future technologies. P. Kuppan, A. Rajadurai & S. Narayanan [3] investigated experimentally small deep hole drilling of Inconel 718 using the EDM process. Mathematical models were derived for the material removal rate (MRR) and depth averaged surface roughness (DASR) responses considering parameters such as peak current, pulse on-time, duty factor and electrode speed using response surface methodology (RSM). Sameh S. Habib [4] has proposed a comprehensive mathematical model for correlating the interactive and higher order influences of various electrical discharge machining parameters through response surface methodology (RSM), utilizing relevant experimental data as obtained through experimentation. S. Assarzadeh & M. Ghoreishi [5] has made an attempt model and optimize process parameters in EDM of tungsten carbide-cobalt composite using cylindrical copper tool electrodes in planing machining mode based on statistical techniques. G. Bissacco & J. Valentincic [6] has presented an investigation on wear and material removal in micro-EDM milling for selected process parameter combinations typical of rough and finish machining of micro-features in steel. Teepu Sultan, Anish Kumar and Rahul Dev Gupta [7] has proposed a model of material removal rate, electrode wear rate, and surface roughness through response surface methodology in a die sinking EDM process. I. Puertas, C.J. Luis & L. Álvarez [8] focused on the die-sinking EDM of a ceramic material and performed an analysis on the influence of intensity, pulse time and duty cycle over surface roughness, electrode wear (EW) and material removal rate. In the present work, central composite design and response surface methodology is used to develop mathematical models for output responses and to analyse the effects of process parameters on the responses. Finally, the process parameters are optimized to get the desired material removal rate with minimum tool wear rate.

II. EXPERIMENTAL DETAILS

2.1 Experimental Setup

For carrying out the experiments, a numerical control programming electrical discharge machine known as ‘‘NOVIFORM 250S” was used. The machine has the provisions of programming in the Z-vertical axis-control and manually operating X and Y axes that has a resolution 0.1μm and an accuracy of 1μm.The electrode-rotating device consists of a precision spindle, a timer belt drive mechanism, and a speed control unit. The spindle was designed with built-in seals to effect flushing through the electrode.

2.2 Materials Used

The present experiments have been performed using workpiece material as brass and electrode material as tungsten carbide. The electrode used is 5mm in diameter and 20 mm in height. Commercial kerosene was used as a dielectric fluid. The material properties of workpiece and electrode is depicted in Table 1 and Table 2 respectively.

2.3 Experimental Procedure

Before experimentation, the workpiece top and bottom faces were ground to a good surface finish using a surface grinding machine. The bottom of the electrode is polished using a very fine grade emery sheet before every experiment. The initial weight of the work piece was weighed using a 1 mg accuracy digital weighing machine. The workpiece and tool were connected to the negative and positive terminals of power supply, respectively. The dielectric fluid was flushed at a pressure of 2 kgf/cm2 through the electrode. Through holes of 25 mm depth were drilled in all the experiments. The time taken for machining a hole was recorded using an electronic timer. The completion of hole was signaled by the emergence of the dielectric jet through the bottom of work piece. The experiments were conducted in a random order so as to remove the effects of any unaccounted factors. End of each experiment, the work- piece was removed from the machine, washed, dried, and weighed on an electronic balance.

Material removal rate (MRR) in mm3/min and electrode wear ratio (EWR) can be calculated by the following formulae:

$$\mathrm{MRR} = \frac{1000 \times \mathrm{Ww}}{\rho\mathrm{w} \times \mathrm{T}}$$

$$\mathrm{VEW} = \frac{1000 \times \mathrm{We}}{\rho\mathrm{e} \times \mathrm{T}}$$

$$\mathrm{EWR} = 100 \times \frac{\mathrm{VEW}}{\mathrm{MRR}}$$

where VEW is the volumetric electrode wear in mm3/min, Ww is the workpiece weight loss in gms, We is the electrode weight loss in gms, ρw is the work piece material density in gm/cm3, ρe is the electrode material density in gm/cm3 and T is the machining time in min.

III. STATISTICAL ANALYSIS

3.1 Design of experiments

Design of experiments (DOE) is a structured, organized method for determining the relationship between factors, which affect the process and the output of that process. The main objective of experimental design is studying the relations between the response as a dependent variable and the various parameter levels. It provides an opportunity to study not only the individual effects of each factor but also their interactions. Design of experiments is a method used for minimizing the number of experiments to achieve the optimum conditions.

The design of experiments for exploring the influence of various predominant micro-EDM process parameters (i.e. capacitance (C), voltage (V), feed rate (f), and electrode speed (N))on the machining characteristics (e.g. the material removal rate, electrode wear ratio, gap size and the surface finish), were modelled. In the present work, experiments were designed on the basis of experimental design technique using response surface design method.

3.2 Response Surface Modelling

In statistics, response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. The main idea of RSM is to use a set of designed experiments to obtain an optimal response. Central composite design can be implemented to estimate a second-degree polynomial model, which is still only an approximation at best. In this work, response surface modelling (RSM) is utilized for determining the relations between the various EDM process parameters with the various machining criteria and exploring the effect of these process parameters on the responses, i.e. the material removal rate and electrode wear ratio. In order to study the effects of the EDM parameters on the above mentioned machining criteria, second order polynomial response surface mathematical models can be developed [9].

In the general case, the response surface is described by an equation of the form:

$$\mathrm{Y_u} = \beta\mathrm{o} + \sum_{\mathrm{i=1}}^{\mathrm{s}} \beta_{\mathrm{i}}\mathrm{x_i} + \sum_{\mathrm{i=1}}^{\mathrm{s}} \beta_{\mathrm{ii}}\mathrm{x}_{\mathrm{ii}}^2 + \sum_{\mathrm{i<j=2}}^{\mathrm{s}} \beta_{\mathrm{ij}}\mathrm{x_i}\mathrm{x_j}$$

where, Yu is the corresponding response, i.e. the MRR and TWR, produced by the various process variables of EDM and the xi (1,2, . . . , S) are coded levels of S quantitative process variables, the terms βo, β_i, $\beta_{ii}$and$\beta_{ij}$are the second order regression coefficients. 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.

Table 1: Electrode material properties (tungsten carbide)

Density (g/cm3)	Hardness	Melting point (°C)	Tensile strength (kg/mm2)	Compressive strength (kg/mm2)	Toughness (kg/mm2)
15.1	HRA 87.0	2597	179	410	50

Table 2: Work-piece material properties (Brass)

Melting point (°C)	Density (gm/mm3)	Electrical resistivity (Ωm)	Coefficient of Thermal Expansion (cm/cm°C)	Surface Roughness (μm)
930	0.007388	6.6 x 10-8	19 x 10-6	0.612

In the present experimental investigation, the controllable parameters chosen were capacitance (C), voltage (V), feed rate (f), and electrode speed (N). Other factors such as gap voltage (40 V), machine servo sensitivity, lift time, and mode of flushing were kept constant during the experimentation. In this study, a central composite design (CCD), fractional factorial DOE technique was selected. It contains an imbedded factorial or fractional factorial design with center points that is augmented with a group of `star points' that allow estimation of curvature. If the distance from the center of the design space to a factorial point is ±1 unit for each factor, the distance from the center of the design space to a star point is ±α with |α|>1. A central composite design always contains twice as many star points as there are factors in the design. The star points represent new extreme values (low and high) for each factor in the design.

Table 3 shows the controllable parameters and their levels in coded and actual values. The design consists of mixed factorial design 21 x 33 with 18 experiments. The design consists of 18 experiments factorial points, six star points to form a central composite design with α=±2, four center points for replication.

The design was generated and analyzed using Minitab® 17 statistical package. The significant terms in the model were found by analysis of variance at 5% level of significance.

Table 3: Process parameters and their levels

Levels	Capacitance(nF)	Voltage(V)	Electrode Speed(rpm)	Feed Rate (μm/s)
-1	3	125	500	5
0	-	150	1000	10
1	4	175	1500	15

The experiments were performed as per design matrix shown in Table 4 and output responses were recorded simultaneously.

Table 4: Plan of experiments and output responses

Parameters				Responses	
C	V	N	f	MRR(mm3/min)	TWR(mm3/min)
3	125	500	5	0.09008	0.10154
3	125	1000	10	0.08241	0.0875
3	125	1500	15	0.09604	0.08153
3	150	500	5	0.085842	0.10329
3	150	1000	10	0.07967	0.13061
3	150	1500	15	0.09892	0.04239
3	175	500	10	0.09658	0.07135
3	175	1000	15	0.09214	0.10018
3	175	1500	5	0.09786	0.10827
4	125	500	15	0.087476	0.07922
4	125	1000	5	0.08169	0.06461
4	125	1500	10	0.0754	0.06179
4	150	500	10	0.07675	0.08008
4	150	1000	15	0.06987	0.07365

4	150	1500	5	0.07976	0.1242
4	175	500	15	0.09654	0.17253
4	175	1000	5	0.09105	0.10564
4	175	1500	10	0.07963	0.09924

3.3 Mathematical modelling of MRR

The ANOVA table for the MRR response is shown in Table 5.

Table 5: Analysis of Variance for MRR model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	13	0.001232	0.000095	8.44	0.081
Linear	4	0.000501	0.000125	5.87	0.057
C	1	0.000250	0.000250	11.71	0.027*
V	1	0.000102	0.000102	4.76	0.094*
N	1	0.000031	0.000031	1.43	0.298
f	1	0.000002	0.000002	0.09	0.784
Square	3	0.000497	0.000166	7.76	0.038
V*V	1	0.000179	0.000179	8.39	0.044
N*N	1	0.000165	0.000165	7.73	0.050
f*f	1	0.000121	0.000121	5.69	0.076
2-Way Interaction	6	0.000171	0.000028	1.33	0.408
C*V	1	0.000003	0.000003	0.14	0.031*
C*N	1	0.000050	0.000050	2.32	0.202
C*f	1	0.000054	0.000054	2.52	0.188
V*N	1	0.000007	0.000007	0.34	0.592
V*f	1	0.000001	0.000001	0.04	0.858
N*f	1	0.000001	0.000001	0.06	0.813
Error	4	0.000085	0.000021		
Total	17	0.001317			

*Highly significant

Model Summary

S	R-sq	R-sq(adj)
0.0046212	93.52%	72.44%

It can be concluded from Table that the main effect of parameter C (Capacitance) and V(Voltage) along with their dual interaction (C×V) are the only significant terms while the other factors are said to be insignificant from statistical point of view, their effects on the respective response are not as sensible as those belonging to significant group. The values of R2 and R2-(adj) for the MRR model are 0.935 and 0.924, respectively (Table 5). This indicates that the predictors excellently explain the amount of variation in the observed response values. The calculated F-value for the MRR model is 8.44. Further, the computed F-value is greater than the F-critical (tabulated value F0.05, 13, 4=2.35) for a significance level of α=0.05. It indicates that the model is adequate for 90% confidence level.

Hence, the equation for calculating the approximate MRR is,

$$\text{MRR} = 0.314 + 0.0077\,C - 0.00324\,V - 0.000004\,f + 0.00002\,N + 0.000011\,V{*}V + 0.000000\,f{*}f + 0.000241\,N{*}N + 0.000044\,C{*}V - 0.000012\,C{*}f - 0.001213\,C{*}N - 0.000000\,V{*}f - 0.000003\,V{*}N - 0.000000\,f{*}N$$

3.4 Mathematical modelling of TWR

The ANOVA table for the TWR response is shown in Table 6. It can be concluded from Table that the main effect of parameter C (Capacitance) and V(Voltage) along with their dual interaction (C×V) are the only significant terms while the other factors are said to be insignificant from statistical point of view, their effects on the respective response are not as sensible as those belonging to significant group. The values of R2 and R2-(adj) for the TWR model are 0.80 and 0.7326, respectively (Table 6). This indicates that the predictors excellently explain the amount of variation in the observed response values. The calculated F-value for the TWR model is 3.26. Further, the computed F-value is greater than the F-critical (tabulated value F0.05, 13, 4=2.35) for a significance level of α=0.05. It indicates that the model is adequate for 90% confidence level.

Hence, the equation for calculating the approximate TWR is,

$$\text{TWR} = 0.852 - 0.317\,C - 0.00285\,V + 0.000206\,N - 0.0142\,f - 0.000011\,V{*}V + 0.000000\,N{*}N + 0.000450\,f{*}f + 0.001790\,C{*}V + 0.000009\,C{*}N + 0.00194\,C{*}f - 0.000001\,V{*}N + 0.000076\,V{*}f - 0.000014\,N{*}f$$

IV. RESULTS AND DISCUSSIONS

4.1EDM parametric influence on the MRR

Metal removal rate in EDM is an important factor to estimate the time of finishing the machined part. The MRR is a function of the discharge pulse energy. The pulse energy varies with either the voltage or capacitance. Increased pulse energy results in the increase of MRR. It can be noticed that a decrease of voltage causes a decrease in the metal removal rate slightly until it reaches a point of 140V and then the material removal rate begins to increase rapidly as shown in Fig. 1. It demonstrates that the MRR decreases non-linearly with the increase of voltage, but after reaching a minimum value, it has a tendency to increase rapidly. This happens because at starting point there is ignition phase and formation of plasma channel where minimum spark energy is produced, which leads to decrease in the material removal rate However, in micro EDM, the MRR increases with the increase in capacitance at lower voltage but decreases at higher voltage since the applied feed rate to the tool electrode are so small that more energy is consumed in electrode movement.

Table 6: Analysis of Variance for TWR model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	13	0.011993	0.000923	3.26	0.472
Linear	4	0.002335	0.000584	0.76	0.602
C	1	0.001085	0.001085	1.41	0.300*
V	1	0.000381	0.000381	0.50	0.520*
N	1	0.000053	0.000053	0.07	0.806
f	1	0.000241	0.000241	0.31	0.605*
Square	3	0.000575	0.000192	0.25	0.859
V*V	1	0.000169	0.000169	0.22	0.663
N*N	1	0.000000	0.000000	0.00	0.998
f*f	1	0.000423	0.000423	0.55	0.499
2-Way Interaction	6	0.007959	0.001327	1.73	0.311
C*V	1	0.004883	0.004883	6.35	0.065*
C*N	1	0.000030	0.000030	0.04	0.854
C*f	1	0.000138	0.000138	0.18	0.693
V*N	1	0.000416	0.000416	0.54	0.503
V*f	1	0.000519	0.000519	0.68	0.457
N*f	1	0.004056	0.004056	5.28	0.083
Error	4	0.003075	0.000769		
Total	17	0.015068			

*Highly significant

Model Summary:

S	R-sq	R-sq(adj)
0.0277279	80.01%	73.26%

Fig. 2 shows variation of the MRR with respect to the electrode rotation and feed rate. It can be shown that as the rotational speed of electrode and feed rate increases the MRR decreases to a certain minimum value and then decreases. This shows that the electrode speed and feed rate is not very significant on average MRR.

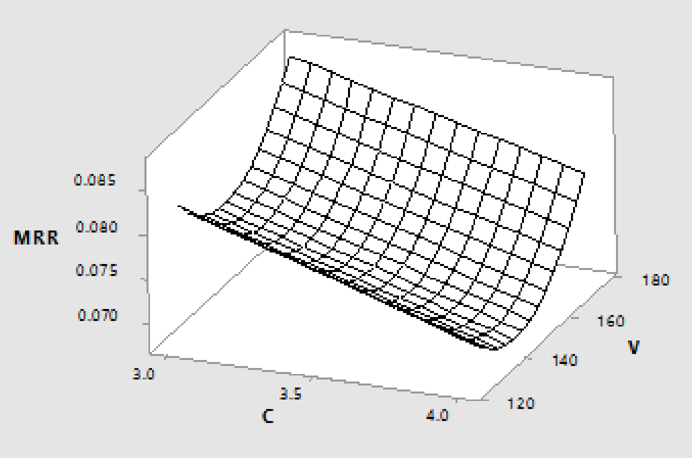

Fig.1 Estimated response surface of MRR vs. C and V

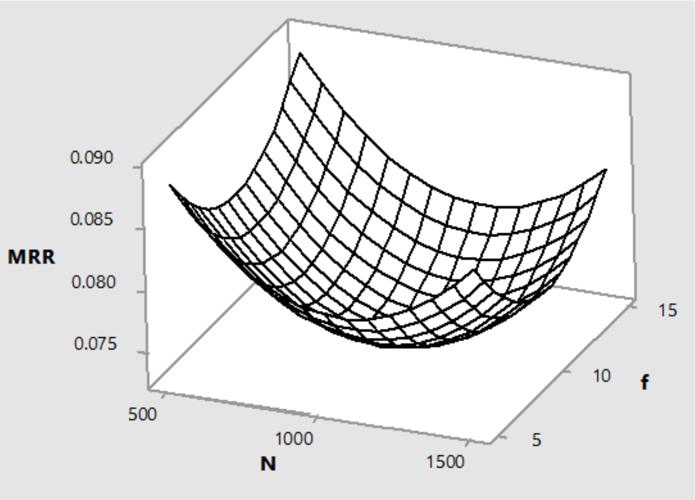

Fig. 2 Estimated response surface of MRR vs. N and f

4.2 EDM parametric influence on the TWR

The variation of TWR with voltage and capacitance are shown in Fig. 3. It can be seen that the TWR increases with the increase in either voltage or capacitance. This variation in TWR is proportional to the discharge energy.

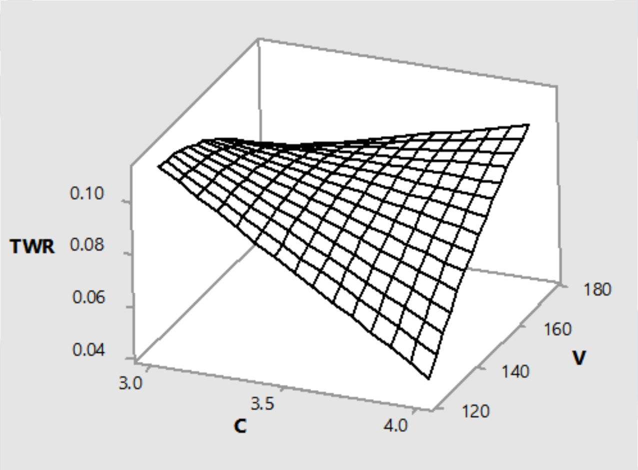

Fig. 3 Estimated response surface of TWR vs. C and V

There is a steep rise in the TWR with the increase in capacitance, with respect to voltage. With the increase in the capacitance, the discharge energy increases. As a result of this, more heat is generated and the electrode consumption increases. The TWR is also related to the discharge status. When the layer depth increases, the amount of workpiece material removed increases. When the layer depth increases for a particular feed, the time required for material removal may be short and hence results in abnormal discharges leading to higher wear. The increase in EWR for higher layer depths is shown in Fig. 4. When the electrode moving speed (feed) increases, the time available for machining the material is less and thereby results in abnormal sparking. Therefore feed is also significant parameter to be considered for TWR.

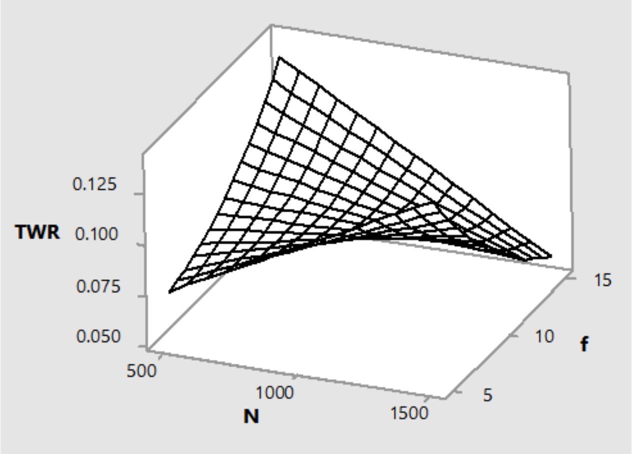

Fig. 4 Estimated response surface of TWR vs. N and f

V. CONCLUSION

1. The µEDM is an adequate process to machine brass using tungsten carbide with good MRR and TWR.
2. The MRR obtained is ranged between 0.069870 mm3/min and 0.098920 mm3/min. The maximum MRR was obtained when the parameters were set at capacitance = 3nF, voltage = 150V, speed= 1500rpm, feed rate = 15 (µm/s).
3. The minimum EWR 0.04239mm3/min was obtained when the parameters were set at capacitance = 3nF, voltage = 150V, speed= 1500rpm, feed rate = 15 (µm/s). The interaction effect of capacitance and voltage influences the most.
4. The optimized values of MRR, and TWR are 0.10839mm3/min and 0.038995mm3/min respectively, obtained at the optimum setting of parameters capacitance = 3nF , voltage = 175V , speed= 1500rpm , feed rate = 15 (µm/s).
5. The confirmation tests showed that the error between experimental and predicted values of MRR and TWR, are 6.98% and 5.90%, 7.48% and 5.66%, respectively.

VI. REMARKS AND FUTURE TRENDS

After an elaborate scrutiny of the published work, the following remarks emerge from the existing published work.

1. Hollow tube and eccentric drilled holes type electrodes are reported to have a positive impact on MRR due to improved flushing conditions. Such designs need investigations for more work materials to evaluate their case to case effects.
2. Some non-electrical parameters like electrode rotation and workpiece rotation while machining improve the flushing conditions and thus may improve MRR. Case to case impact of these parameters while machining may be evaluated for more work materials.
3. Very less work has been reported on MRR improvement using powders of important alloying elements like chromium and vanadium. Also, many materials like water hardened die steel, molybdenum high speed tool steel have not been tried as work material in powder mixed electric discharge machining. The same may be tried in future works.
4. The dry EDM technique in combination with sinking EDM, wire EDM, ultrasonic assisted EDM and EDM milling may be tried for optimization of MRR, EWR, surface roughness etc.in future works.
5. Not so much published work is reported on composites and harder materials like alumina and ceramics. The hybrid techniques can be tried for new material combinations.

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