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Research Article

Effect Of Edm-Drilling Process Parameters Using Brass, Copper And Zinc Coated Tubular Electrodes On Drilling Of Ti-6al-4v

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Abstract

Electric Discharge machining drilling (EDMD) is a recognized machining process in the field of micro-manufacturing. The researcher is still concern about the surface of EDMD. The energy discharge transferred to the workpiece surface is not precise enough for high-quality machining due to the uneven spark. The spark energy is controlled by electrode material and Process variables. The selection of appropriate process variables and electrode material results in the quality of the surface and hole overcut. The present work is to investigate brass tubular electrode, copper tubular electrode and zinc electroplated brass electrode are compared at different process variables on drilling of worldwide adequate aerospace and automobile applicable titanium material (Ti-6Al-4V). The selection of experiments was carried out according to the Box-Behnken design in Respons surface methodology. Special attention was given to machining Parameters TON, TOFF, Current and electrode material on the machining characteristics. The optimal parameters obtained are ZEBE is the best suitable electrode for reducing EWR and HOC. The EDM-D parameters TON, TOFF and DA are 4 µsec, 7 µsec and 15 Amps.

Keywords: Electric Discharge Machining Drilling, zinc electroplated brass tubular electrode, Material removal rate, Electrode wear rate, Surface Roughness, Overcut and Response surface Methodology.

Abbreviations:

BTE:	Brass Tubular Electrode
CMM:	Coordinate Measuring Machine
CTE:	Copper Tubular Electrode
DA:	Discharge Current
EDMD:	Electric Discharge Machining Drilling
EWR:	Electrode Wear Rate
HOC:	Hole Over Cut
MRR:	Material Removal Rate
TOFF:	Pulse Off Time
TON:	Pulse On Time
ZEBE:	Zinc Electroplated Brass Electrode

1. Introduction

Present Day, there is an increasing demand for micro components in most of the advanced components in the application of Aerospace, Orthopedics, Marine etc due to reduction in the density and volume of the components in the devices. The production of micro components with micro features like drilling was critical to attaining high accurate and precise dimensions[1]. The intricate micro-level components made of hard materials like titanium using traditional machining techniques such as micro-milling, micro-drilling and micro turning. The removal of material from high hardness material is difficult and tolerance limits are high when comparing with unconventional processes[2]. The drilling operation in micro features are overcome by employ a novel method Electric discharge machining- Drilling (EDM-D) which has many advantages like reduction of tolerance limits, non-contact process and independent of material hardness[3]. The conductive materials are machined in this processes, high energy spark is triggered between the gap between the tool and workpiece. The schematic diagram Figure.1 showing EDM-D which has a rotatable tool electrode[4]. A high energy spark is generated due to the potential difference between the tool electrode and workpiece which breaks dielectric which causes a plasma channel to discharge material from the workpiece in form of evaporation and melting [5]–[7]. The frequent spark in between the tool electrode and workpiece remove material in the form of evaporation and melting. The energies evolved at the spark are less than W_e = 100mJ per single discharge. EDM-D generator of a machine tool can generate impulses with a discharge energy of W_e = 0.1mJ with spark duration of T_{ON} = 40ms at a discharge current of I_e = 1mA[8]. EDM-D electrodes readily available in Graphite, Copper and brass has high melting point and good thermal conductivity. The electrodes are hollow or single pass to flush the dielectric fluid made with a hot extrusion process[9], [10]

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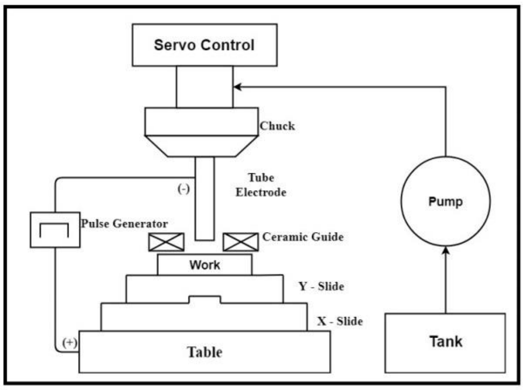

Figure.1 Schematic Diagram of EDM-D with rotatble tubular electrode

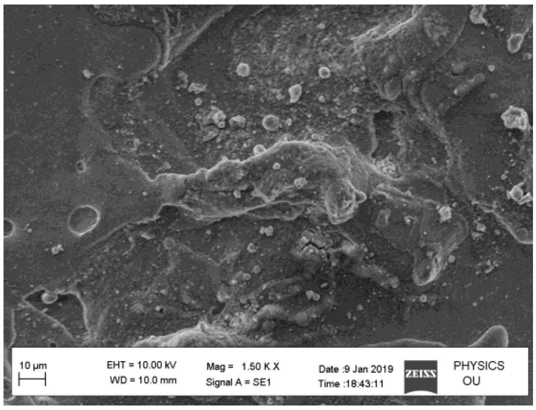

Figure.2 Microstrucuture of Ti-6Al-4V

In current years. Considerable study has been carried out and various issues are emphasized on EDM. Puranik & Joshi Studied the precision of drilled hole via micro EDM drilling. They attained a depth of 5 mm by using 200 micrometres diameter tool electrodes by monitoring the regular procedure constraints [11]. Kuppan et al investigated Surface integrity of the EDM drilling using 2 mm diameter tubular brass & copper electrodes on Inconel-718 tool seel under the parameters current, T_{ON} and T_{OFF} [12]. Meena et al studied the taperness in EDM drilling, the hole diameter at the top side of the workpiece are more than the lower side is due to the electrode wear [13]. Rai Tanabe et al studied Zinc coatings on tungsten electrode of EDM drilling improved the circularity of the hole and reduces tool wear rate. The presence of ultrasonic vibration in Zinc Electroplating results in a smooth surface and even cladding on the electrode [14]. Marcin klekotka et al investigated acidic bath of Zinc coating on the material is enough and no requirement of any additional processes and component. These coatings result in higher wear and erosion resistance. Hence it enhances the life of the components. This study also exposes the improvement of mechanical properties [15].

2. METHODOLOGY

The EDM-D have been performed using different variant electrodes like CTE, BTE and other composite tubular electrodes tungsten copper. In this, a novel method of zinc electroplating to base metal brass is performed and this electrode performance is compared with the market available BTE and CTEs. Titanium G-V material selected as the workpiece material due to a wide array of applications in the field of aerospace, marine and space systems. The Chemical analysis and material properties of the material are examined with the standard material of titanium G-V. Effect of T_{ON}, T_{OFF} and current on the MRR, EWR, SR and HOC are analysed using the Response Surface Method. The MRR and EWR are calculated as per the volume of the material erosion in the process.

3. EXPERIMENTAL DETAILS

3.1 WORK MATERIAL & ELECTRODE SELECTION

In the current work titanium (Ti-6Al-4V) is the selected workpiece material and its microstructure is shown in Figure.2. Preliminary studies are carried through literature and selected two commercially available EDMD electrodes of CTE and BTE. In addition to CTE & BTE, a new tubular electrode of zinc electroplated on brass was developed in this work. In this study diameter of the drill hole is considered as 1600μm based on the machine drilling range. Rum Sen et al investigated that zinc coating improves the surface quality of the workpiece and reduces electrode wear in Wire-Electric discharge machining [16]. The Zinc electroplating process is carried out for a thickness of 5μm at an electrolyte solution in which surface cleaned brass electrodes are dipped and an electrical DC is applied to the anode (zinc bath) for the time based on the surface area contact with the Zinc bath. During this time the zinc ions deionized from the zinc bath and deposited on the surface of the electrode. This process is carried out at Manideep Technocoats, Hyderabad.

3.2 MACHINING CONDITIONS

The day to day advancement in technology produced so many varieties of EDMD machines based on the different control units. In this work, Ratnarprakashi Electronics India Pvt makes EZEE Drill used at the Saraswathi Engineering Research Centre, Cherlapally, Secunderabad. This EDMD consists of a CNC operating table that moves in longitudinal and transverse directions. Dielectric fluid deionized water is flushed into the tubular electrode through the electrode holder which rotates at a speed of 150 rpm. Flush pressure is maintained at a constant pressure of 5mpa using an electric pump. In this T_{ON}, T_{OFF} and D_A varied based on the conduction of preliminary results.

3.3 EXPERIMENTAL DESIGN

The primary goal of experimental design is to investigate the relationships between the response as a dependent variable and the various parameter levels. It allows researchers to investigate not only the individual effects of each factor but also their interactions. The design of experiments is a technique for reducing the number of experiments required to achieve the best results[17]. The influence of various predominant EDM-D process parameters (e.g., pulse on time, discharge current, pulse off time and tubular electrode material) on machining characteristics (e.g.MRR, EWR, HOC, SR) are explored using experiment design. The studies in this paper were created using the response surface design approach, which is based on an experimental design approach. To obtain the equation of the response surface, an experimental design was created to approximate this equation with the fewest number of tests feasible. In this paper, the Boxbenkens design is adopted to enhance the dependability of outcomes and lower the size of experiments without sacrificing accuracy[18]. The levels coded for all process parameters are shown in Table.1.

Table.1 EDM-D Coded Process parameters

Parameter	+1	0	-1
T_{ON} (μsec)	4	7	10
T_{OFF} (μsec)	4	7	10
D_A (Amp)	5	15	25
Electrode	BTE	CTE	ZEBE

3.4 PERFORMANCE CHARACTERISTICS

The EDM is performed on Ti-6Al-4V as per the sequence of the Boxbenken design. The MRR is calculated in terms of volume removed per secon. Sample after drilling on EDM-D are shown in Figure.3 and these images are developed using a macroscope. HOC is the gap between the electrode diameter and hole diameter and it is measured by using CMM at CIPET- Vijayawada and the depth of the hole (Thickness of material) is taken as 10 mm for all the experiments. The electrode wear rate is measured in the volume eroded for one sec.

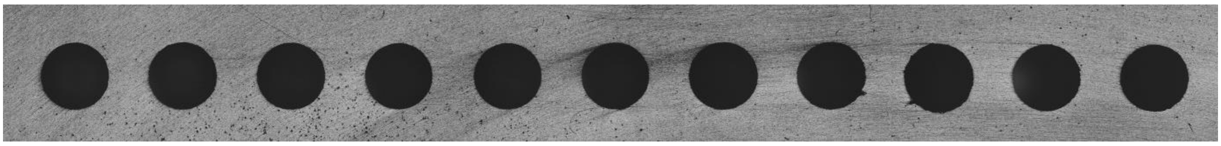

Figure.3 EDM- D holes on Ti-6Al-4V

4. RESPONSE SURFACE MODELLING

Response surface methodology (RSM) is a statistical technique that investigates the relationships between many explanatory factors and one or more response variables. The basic principle of RSM is to employ a series of well-prepared tests to find the best possible answer. Boxbenken design is used to estimate a second-degree polynomial model, but this is still merely an approximation at best. Response surface modelling (RSM) is used in this study to determine the relationships between various EDM-D process parameters and various machining criteria, as well as to investigate the influence of these process parameters on the responses ie. MRR, EWR, HOC and SR. Second-order polynomial response surface mathematical models may be created to investigate the impact of EDM-D variables on the aforementioned machining requirements. In general, equation.2 shown describes the response surface.

$$Y_m = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i=1}^{n} \beta_{ij} X_i X_j \ldots\ldots \qquad \textbf{Equation. 1}$$

where, Y_m is the corresponding response, e.g. the MRR, EWR, HOC and RS produced by the various process variables of EDM-D and the x_i (1,2,. . .,n) are coded levels of n quantitative process variables, the terms β_0,β_i, β_{ii}, and β_{ij} are the second-order regression coefficients. The second term under the summation sign of this polynomial equation is traceable to linear effects, while the third term is attributed to higher-order effects; the fourth term of the equation incorporates the interacting effects of the process parameters. In this work, Equation.2 can be rewritten according to the four variables used:

$$Y_m = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{44} X_4^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{342)\ e.g.the\ MRR,EWR,OC\ and\ Rstab} X_3 X_4 \ \ldots\ldots\ldots\ldots \qquad \textbf{Equation. 2}$$

Where X_1, X_2, X_3 and X_4 are T_{ON}, T_{OFF}, D_A and electrode material respectively.

4.1 Mathematical Modelling for MRR

The influence of the above-mentioned process factors on the magnitude of the MRR has been investigated using Equation.3 by obtaining the values of the various constants of Equation. 2 using a curve fitting software Minitab and employing the relevant data from Table 2. The following mathematical relationship was found for correlating the MRR with the examined process variables.

$$MRR : -7.5 + 0.70T_{ON} - 0.11T_{OFF} + 0.357D_A + 4.15\ Electrode - 0.0009\ T_{ON}*T_{ON} + 0.0310\ T_{OFF} * T_{OFF} + 0.00959\ D_A * D_A - 0.825\ Electrode*Electrode + 0.0045T_{ON}*T_{OFF} - 0.0365\ T_{ON}* D_A + 0.035\ T_{ON}*Electrode - 0.0243T_{OFF} * D_A - 0.119T_{OFF}*Electrode - 0.0086\ D_A *Electrode$$

Equation.3

4.2 Mathematical Modelling for EWR

A thorough model based on Equation.2 has been constructed to correlate the impacts of the previously specified process factors on the EWR criterion, employing pertinent experimental data as seen throughout the course of machining for such purposes as altering parametric combinations. The mathematical relationships so developed for assessing the effects of the numerous major machining parameters on the EWR criterion are as follows:

$$EWR\ 121 - 27.9T_{ON} - 14.8T_{OFF} - 13.50\ D_A + 90\ Electrode + 1.60T_{ON}*T_{ON} + 0.92\ T_{OFF}*T_{OFF} + 0.450\ D_A * D_A - 22.5\ Electrode*Electrode – 0.02\ T_{ON} *T_{OFF} + 0.478T_{ON}* D_A + 0.01T_{ON}*Electrode+ 0.168\ T_{OFF}*D_A + 0.01\ T_{OFF} *Electrode + 0.01\ D_A *Electrode$$

Equation.4

4.3 Mathematical Modelling for HOC

As stated in Equation.2, a constructed model was examined to associate HOC with the EDM-D settings used in this work. The following is an empirical mathematical relationship

$$HOC\ 0.14 + 0.009\ T_{ON} + 0.120\ T_{OFF} + 0.0276\ D_A+ 0.436\ Electrode - 0.0149\ T_{ON}*T_{on} - 0.0217\ T_{OFF}*T_{OFF} - 0.00169\ D_A*D_A - 0.120\ Electrode*Electrode + 0.0228\ T_{ON}*T_{OFF}+ 0.00267\ T_{ON}*D_A- 0.0125\ T_{ON}*Electrode - 0.00058\ T_{OFF}* D_A + 0.0075\ T_{OFF}*Electrode + 0.0045\ D_A*Electrode$$

Equation.5

Table.2 Box-Behnken Design for controllable EDM-D Process paramters & Results

S.No	T_{ON} µsec	T_{OFF} µsec	D_A Amp	Electrode	MRR mm^3/sec	EWR mm/sec	HOC mm
1	4	4	15	2	1.7644	1.135	0.372
2	4	7	25	2	9.0000	1.204	0.639
3	4	10	15	2	0.7799	1.825	0.497

4	4	7	5	2	0.7542	1.060	0.39
5	7	7	5	1	1.6971	0.820	0.654
6	4	7	15	3	1.0523	1.732	0.583
7	7	4	25	2	9.0000	1.155	0.546
8	7	10	25	2	5.0000	1.350	0.276
9	7	10	5	2	1.3600	0.655	0.482
10	7	4	5	2	2.4392	0.760	0.486
11	7	4	15	3	4.0337	1.119	0.463
12	7	7	15	2	2.9991	1.165	0.394
13	7	7	25	1	2.8285	1.160	0.654
14	7	10	15	1	2.6271	1.090	0.402
15	7	4	15	1	2.9554	1.480	0.397
16	7	7	15	2	3.0121	1.161	0.471
17	7	7	15	2	2.9989	1.159	0.582
18	10	4	15	2	4.2362	1.095	0.478
19	7	10	15	3	2.2790	0.860	0.379
20	4	7	15	1	1.1032	1.550	0.296
21	7	7	5	3	2.1668	0.955	0.593
22	10	7	25	2	6.0000	1.770	0.387
23	10	7	5	2	2.1316	0.740	0.395
24	7	7	25	3	2.9541	1.655	0.605
25	10	7	15	1	3.4938	1.030	0.503
26	10	7	15	3	3.8664	1.320	0.289
27	10	10	15	2	3.4145	1.190	0.257

5. RESULTS & DISCUSSION

5.1 The effect of the EDM-D parameters on the MRR

In EDM-D, the MRR is an essential component in estimating the time required to complete the drilling in Ti-6Al-4V material of depth 10 mm. These values are relatively lesser in this work. Equation.3 Studies were conducted to analyse the effects of the various process variables on the MRR, as developed through experimental observations and RSM. Figure 5 depicts the effect of T_{ON}, Current and electrode material variation on EDM-D MRR. It can be seen that increase in T_{ON} generates a little rise in the MRR until it reaches to 10µsec. When the T_{ON} is increased, the heat flux is applied for a period. As the plasma channel grows, the amount of heat transmitted into the workpiece increases, resulting in a rise in the MRR[19]. The pressure inside the plasma channel decreases as the discharge duration rises[20]. An increase in MRR since the molten metal volume does not change and further increase may be a cause to decrease MRR slightly. The fluctuation of MRR values is increased in the CTE and ZEBE. The rise in MRR at CTE is higher than the other two electrodes and ZEBE is also slightly better than BTE. The figure shows that the metal removal rate rises with increasing D_A for all T_{ON}, D_A increases the pulse discharge energy channel diameter, resulting in an increase in crater diameter and depth, which can enhance metal removal rate. The picture also shows that the MRR rises non-linearly as the D_A increases[21].

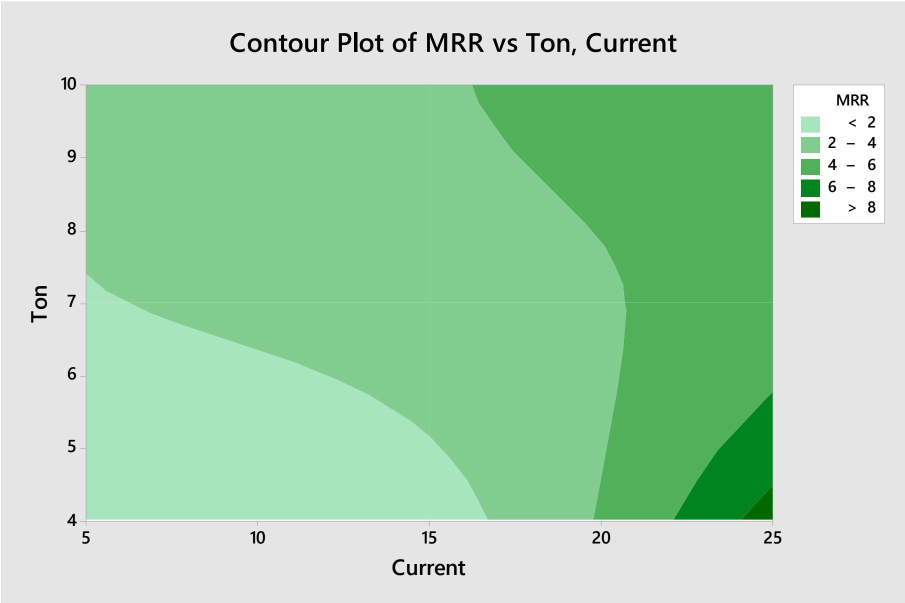

Figure.5A Contour plot of MRR with T_{ON} & D_A

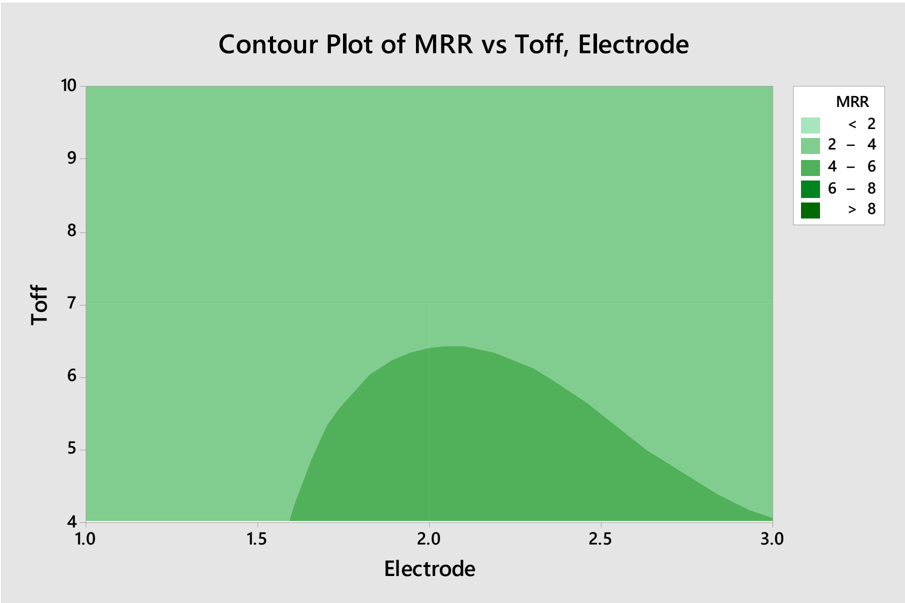

Figure.5B Contour plot of MRR with Electrode and T_{OFF}

5.2 The effect of the EDM-D parameters on the EWR

In this EDM-D, electrode material plays a prominent role. In this consumable electrodes of tubular form are used for drilling operation. These electrodes are made of conductive materials like Copper, Brass, tungsten copper etc., In this paper, one of the main objectives is to reduce electrode wear. Based on the mathematical model developed in RSM and experimental observations, Equation.4 investigates the effect of EDM-D parameters on EWR. Here EWR is calculated in terms of the change in length of electrode for each drilling operation. Figure.5 Shows an increase in D_A of more than 15 Amps increases the EWR and the effect of T_{ON} and T_{OFF} on EWR are an inconsiderable range. The CTE is more in EWR when compare other two. The newly developed ZEBE causes a significant change in EWR and it is lower than the BTE which is shown in Figure.6.Contour plots of EWR with T_{ON}, T_{OFF}, D_A and electrodes.

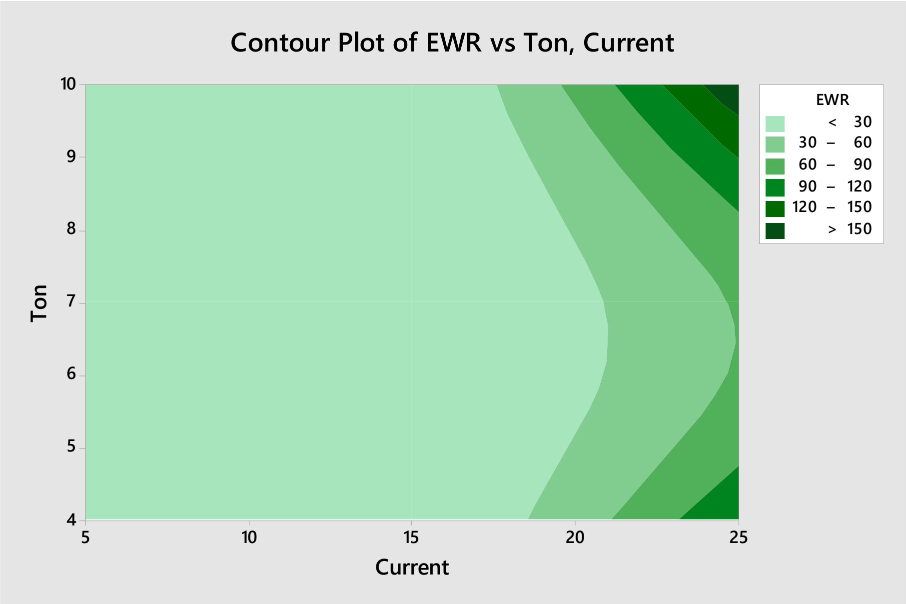

Figure.6A Contour plot of EWR with T_{ON} & D_A

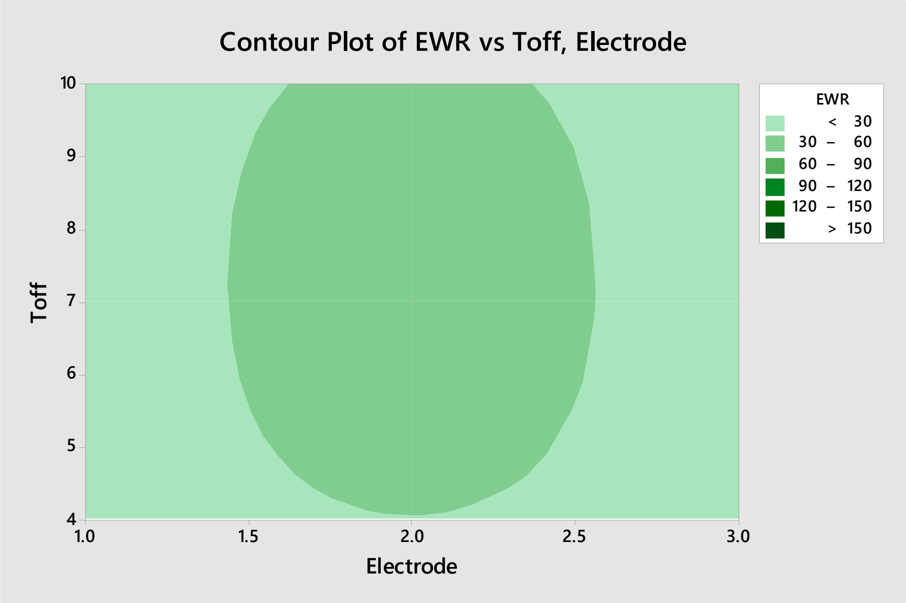

Figure.6B Contour plot of EWR with Electrode and T_{OFF}

5.3 The effect of the EDM-D parameters on the HOC

In EDM-D, one of the important machining performance characteristics is HOC. It is the difference between the electrode diameter and hole diameter. The mathematical equation developed base on RSM & experimental results shown in Equation.5. Effect of Electrode and D_A of process parameters on HOC shown in Figure.7A & 7B

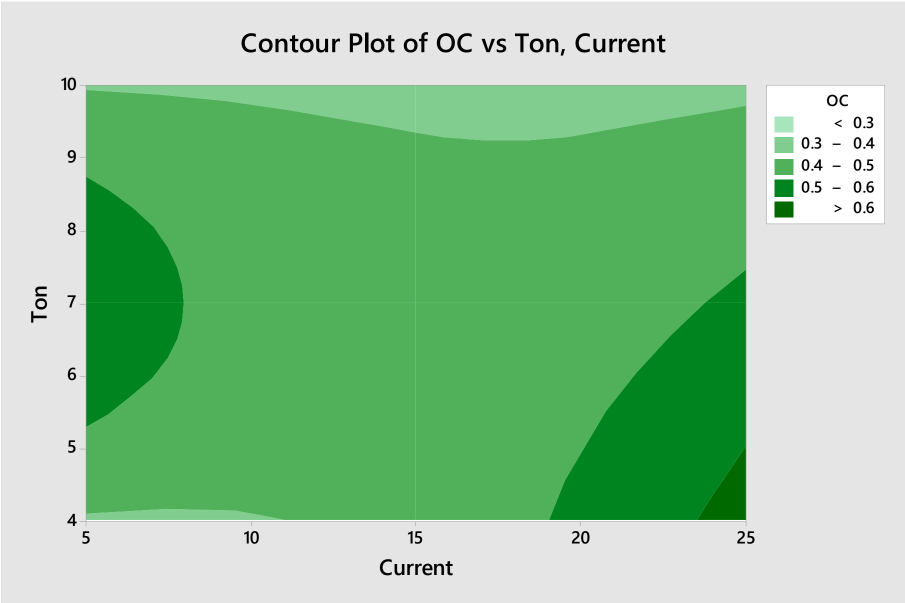

Figure.7A Contour plot of HOC with T_{ON} & D_A

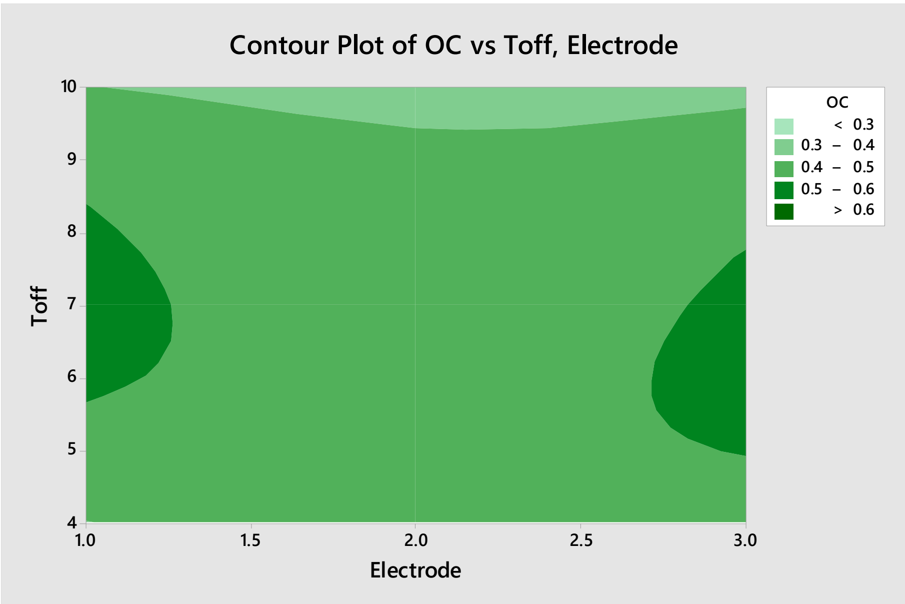

Figure. 7B Contour plot of HOC with Electrode and T_{OFF}

6. OPTIMALITY SEARCH

RSM mathematical model describes the best combination of the different process variables to enhance EDM-D performance charecteristics such as the MRR, EWR and HOC values may be evaluated for the goal of attaining controlled EDM-D The optimum search was developed for maximising the MRR and reducing the EWR and HOC values. Within the constraints of the created mathematical models, the best combination of numerous process variables is thus produced. **Table.3** displays the optimum values that were obtained.

Table.3 Optimal Values for the EDM-D variable parameters

Parameter	MRR	EWR	HOC
T_{ON} (μsec)	10	4	04
T_{OFF} (μsec)	4	7	10
D_A (Amp)	25	5	15
Electrode	CTE	ZETE	ZEBE

7. CONCLUSIONS

EDM-D techniques allow us to increase process capabilities such as MRR, EWR and geometrical precision. This method may be highly useful in achieving greater machining efficiency when fabricating complicated micro-parts on difficult-to-machine and multi-materials. It has been discovered that a little Zinc coating over plain brass greatly enhances EWR & HOC. It was also identified that, for improved machining quality, discharge energy should be maintained to a minimum. High machining rates are achieved by the CTE due to high thermal conductivity. The greater amount of zinc particles are flush out from the electrode and adhere to the hole surface.

References

[1] T. Masuzawa, “State of the art of micromachining,” CIRP Ann. - Manuf. Technol., vol. 49, no. 2, pp. 473–488, Jan. 2000, doi: 10.1016/S0007-8506(07)63451-9.

[2] D. Kumar, N. K. Singh, and V. Bajpai, “Recent trends, opportunities and other aspects of micro-EDM for advanced manufacturing: a comprehensive review,” Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 42, no. 5. Springer, May 01, 2020, doi: 10.1007/s40430-020-02296-4.

[3] W. Ming et al., “A comprehensive review of electric discharge machining of advanced ceramics,” Ceramics International, vol. 46, no. 14. pp. 21813–21838, 2020, doi: 10.1016/j.ceramint.2020.05.207.

[4] J. K. Siddani, C. Srinivas, and N. N. Ramesh, “Parametric Optimize and Surface Characterisation of Micro Electrical Discharge Machining Drilling Process,” 2019, pp. 361–369.

[5] A. B. M. A. Asad, M. T. Islam, T. Masaki, M. Rahman, and Y. S. Wong, “Analysis of micro-EDM electric characteristics employing plasma property,” CIRP J. Manuf. Sci. Technol., vol. 20, pp. 36–50, 2018, doi: 10.1016/j.cirpj.2017.09.005.

[6] S. N. B. Oliaei, M. P. Jahan, and A. Perveen, Micro-EDM Drilling. Springer Singapore, 2019.

[7] S. Mahanta, M. Chandrasekaran, S. Samanta, and R. M. Arunachalam, “EDM investigation of Al 7075 alloy reinforced with B4C and fly ash nanoparticles and parametric optimization for sustainable production,” J. Brazilian Soc. Mech. Sci. Eng., vol. 40, no. 5, p. 263, May 2018, doi: 10.1007/s40430-018-1191-8.

[8] E. Uhlmann, S. Piltz, and U. Doll, “Machining of micro/miniature dies and moulds by electrical discharge machining - Recent development,” J. Mater. Process. Technol., vol. 167, no. 2–3, pp. 488–493, 2005, doi: 10.1016/j.jmatprotec.2005.06.013.

[9] K. Kumar, V. Singh, P. Katyal, and N. Sharma, “EDM μ-drilling in Ti-6Al-7Nb: experimental investigation and optimization using NSGA-II,” Int. J. Adv. Manuf. Technol., vol. 104, no. 5–8, 2019, doi: 10.1007/s00170-019-04012-6.

[10] H. C. Tsai, B. H. Yan, and F. Y. Huang, “EDM performance of Cr/Cu-based composite electrodes,” Int. J. Mach. Tools Manuf., vol. 43, no. 3, pp. 245–252, 2003, doi: 10.1016/S0890-6955(02)00238-9.

[11] M. S. Puranik and S. S. Joshi, “Analysis of accuracy of high-aspect-ratio holes generated using micro-electric discharge machining drilling,” Proc. Inst. Mech. Eng. Part B J. Eng. Manuf., vol. 222, no. 11, pp. 1453–1464, 2008, doi: 10.1243/09544054JEM1186.

[12] P. Kuppan, A. Rajadurai, and S. Narayanan, “Influence of EDM process parameters in deep hole drilling of Inconel 718,” Int. J. Adv. Manuf. Technol. 2007 381, vol. 38, no. 1, pp. 74–84, May 2007, doi: 10.1007/S00170-007-1084-Y.

[13] V. K. Meena and M. S. Azad, “Grey relational analysis of micro-EDM machining of Ti-6Al-4V alloy,” Mater. Manuf. Process., vol. 27, no. 9, pp. 973–977, 2012, doi: 10.1080/10426914.2011.610080.

[14] R. Tanabe, Y. Ito, N. Mohri, and T. Masuzawa, “Development of peeling tool for micro-EDM,” CIRP Ann. - Manuf. Technol., vol. 60, no. 1, pp. 227–230, 2011, doi: 10.1016/j.cirp.2011.03.108.

[15] M. Klekotka, K. Zielińska, A. Stankiewicz, and M. Kuciej, “Tribological and anticorrosion performance of electroplated zinc based nanocomposite coatings,” Coatings, vol. 10, no. 6, 2020, doi: 10.3390/COATINGS10060594.

[16] R. Sen, B. Choudhuri, J. D. Barma, and P. Chakraborti, “An investigation on the effect of different coated electrodes on the surface quality of WEDM by varying discharge energy level,” Int. J. Adv. Manuf. Technol., vol. 106, no. 7–8, pp. 3285–3299, 2020, doi: 10.1007/s00170-019-04813-9.

[17] N. A. Armstrong, Pharmaceutical Experimental Design and Interpretation. CRC Press, 2006.

[18] K. Hinkelmann and O. Kempthorne, Design and Analysis of Experiments: Second Edition, vol. 1. 2007.

[19] S. Kumar, R. Singh, T. P. Singh, and B. L. Sethi, “Surface modification by electrical discharge machining: A review,” J. Mater. Process. Technol., vol. 209, no. 8, pp. 3675–3687, 2009, doi: 10.1016/j.jmatprotec.2008.09.032.

[20] S. Singh, S. Maheshwari, and P. C. Pandey, “Some investigations into the electric discharge machining of hardened tool steel using different electrode materials,” J. Mater. Process. Technol., vol. 149, no. 1–3, pp. 272–277, 2004, doi: 10.1016/j.jmatprotec.2003.11.046.

[21] S. S. Habib, “Study of the parameters in electrical discharge machining through response surface methodology approach,” Appl. Math. Model., vol. 33, no. 12, pp. 4397–4407, 2009, doi: 10.1016/j.apm.2009.03.021.