PERFORMANCE ANALYSIS OF EDM ON GREY CAST IRON USING RSM AND TOPSIS METHOD

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Abstract:
Electro discharge machining (EDM) process is applied to machine hard and difficult to cut materials. In this research hard material namely, grey cast iron is used as a workpiece and copper electrode 2 *mm* in diameter is used for making holes through EDM process. The effect of input parameters such as pulse-on time (T_{on}), pulse off time (T_{off}), gap voltage (V_g) and current (I) on material removal rate (MRR) and tool wear rate (TWR) were studied. Based on Response Surface Methodology (RSM) analysis the gap voltage and pulse on time has significant impact on MRR and TWR respectively. The mathematical model is developed for MRR and TWR using RSM. Analysis of variance (ANOVA) shows that voltage has notable impact on MRR. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used to estimate the best combination for higher MRR and lower TWR. Based on the analysis the estimated combination is pulse-on time of 45 μs, pulse-off time of 3 μs, gap voltage of 25 *V* and current of 10 *A*.

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1. INTRODUCTION

Electro discharge machining (EDM) is a non-traditional machining process which finds its application in aerospace, biomedical and tool manufacturing industry. Specifically, this process is most considered for machining super alloys such as inconel, stainless steel, metal matrix composites and titanium. Świercz et al. [1] have studied the influence of EDM process parameters on material removal rate (MRR) and surface integrity and applied Response Surface Methodology (RSM) and analysis of variance (ANOVA) for analysis. It is reported that the discharge current has 50% more influence on MRR and surface quality followed by the discharge time. Singaravel et al. [2] have used vegetable oil as a dielectric medium for machining titanium alloys. The use of vegetable oil shows same dielectric qualities, in the erosion mechanism over conventional dielectric oil. Singh and Singh [3] have used Teaching Learning Based Optimization (TLBO) algorithm and found the best parameter combination for copper tool electrode as 6 *A*, 50 *V*, t_{on} 200 μs, t_{off} 90 μs and a lift time of 2 *s* and for brass tool electrode as 12 *A*, 40 *V*, t_{on} 120 μs, t_{off} 15 μs and a lift time of 2 *s* are recommended according to TLBO algorithm.

Mausam et al. [4] have analyzed the EDM performance using grey relational analysis (GRA) for machining carbon fiber nano-composite. Estimated process parameters by GRA show notable improvement of 0.000003 in MRR and significant decrease of 0.001904 in TWR. Abidi et al. [5] have optimized the EDM process variables using multi-objective genetic algorithm for machining shape memory alloys. The results show that the brass electrode produces high MRR with high tool wear and good quality holes. Moderate capacitance value

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and low discharge voltage shows better MRR, surface quality and low tool wear. Thanigaivelan et al. [6] studied the effect of using a cryogenic treated tool on Tungsten Alloy- HDS-H21. The use of cryogenic treated tool enhances the electrode performance and generates fewer cracks. Raj and Kumar [7] studied the effect of EDM process parameters on EN45 steel and found that the peak current and peak off time are the most influential factor on MRR. Kumar et al. [8] studied the influence of cryogenic treated copper-tungsten electrode on a titanium alloy through EDM. The cryogenic treatment of the tool, pulses on time and flushing pressure are the important factor that affects the MRR. Phan et al. [9] optimized the EDM performance for SKD61 die steel using MCDM and improved the MRR and surface roughness significantly. Voltage of 90 *V*, current of 10 *A* and pulse on time of 100 *µs* is the optimal combination for higher MRR and lower surface roughness, according to them. Nguyen et al. [10] have used Taguchi-TOPSIS method to optimize the EDM process parameters for a titanium alloy. The best combination for depth of cut, lower TWR and overcut are 10 *nF*, 160 *V*, and 400 *rpm* electrode speed, according to their findings. Bharathi raja et al. [11] have used EDMed hardened die steel and studied the performance using firefly algorithm. They have obtained suitable mathematical model based on the conducted experiments. It is clear from the above literature that researchers have machined difficult to cut materials, however there is sparse data on EDM of grey cast iron and process optimization. Grey cast iron finds application in the production of manifolds, tool, die making, etc. To understand the performance characteristics of EDM on grey cast iron a detailed experiment was conducted using Response Surface Methodology (RSM) and an optimal combination of process parameters is obtained using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) Using the RSM mathematical model equation for MRR and TWR were determined.

2. MATERIALS AND METHODS

In this study, making holes in a grey cast iron plate of 3 *mm* thickness and copper electrode of 2 mm diameter was considered for the experiments. ZNC EDM machine is used for machining as shown in Fig.1. An EDM oil with specific gravity 0.763 and a freezing point of 94 ˚*C* was used as dielectric fluid. The dielectric is allowed to flow externally with a pressure of 0.2 kgf/cm^2. The EDM machine mainly comprises the dielectric reservoir, pump and circulation system, X-Y direction moving working table, tool holder and servo system for tool feed. The workpiece which is 75x50x3 *mm* in size is cut with the application of Wire cut EDM. Performance measurements such as MRR and TWR are analyzed with input variables such as, pulse-on time (T_{on}), pulse off time (T_{off}), gap voltage (V_g) and current (I) [12]. Factors and levels are shown in Table 1. The experiments are designed using central composite design with four input factors. Each factor has five levels and a total of thirty experiments were conducted. Each experiment was repeated twice. Fig.2 shows the workpiece with machined holes. Table 2 lists the process parameters, actual levels, and their coded levels.

Fig.1. EDM setup

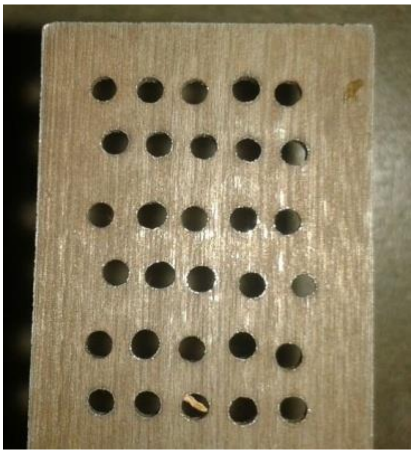

Fig.2 Workpiece with machined holes

MRR and TWR are calculated by weighing workpiece and tool before and after machining. RSM method establishes the relationship between different input parameters on output responses. Moreover, this is a statistical method for analyzing the problems [13,14].

Table 1. Factor's and Levels

Factors in SI units	**Levels**				
	-2	-1	0	1	2
Pulse-on time (T_{on}),in *μs*	40	45	50	55	60
Pulse-off time (T_{off}), *in μs*	1	3	5	7	9
Gap voltage (V_g) in *V*	20	25	30	35	40
Current (I) in *A*	5	10	15	20	25

Table 2. Experimental combinations and responses

T_{on}	T_{off}	V_g	I	MRR *g (min⁻¹)*	TWR *g (min⁻¹)*
45	3	25	10	0.0294	0.002
55	3	25	10	0.196	0.025
45	7	25	10	0.1715	0.018
55	7	25	10	0.147	0.015
45	3	35	10	0.196	0.018
55	3	35	10	0.1715	0.017
45	7	35	10	0.1715	0.015
55	7	35	10	0.196	0.023
45	3	25	20	0.1838	0.018
55	3	25	20	0.147	0.015
45	7	25	20	0.2083	0.019
55	7	25	20	0.1593	0.016
45	3	35	20	0.3186	0.029
55	3	35	20	0.1838	0.018
45	7	35	20	0.1715	0.017
55	7	35	20	0.1593	0.015
40	5	30	15	0.1838	0.018
60	5	30	15	0.196	0.02
50	7	30	15	0.1593	0.016
50	9	30	15	0.1715	0.017
50	5	20	15	0.1838	0.018
50	5	40	15	0.1715	0.016
50	5	30	5	0.1715	0.016
50	5	30	25	0.1838	0.019
50	5	30	15	0.1715	0.017
50	5	30	15	0.1715	0.016
50	5	30	15	0.196	0.02
50	5	30	15	0.1715	0.017
50	5	30	15	0.1715	0.018
50	5	30	15	0.196	0.017

T_{on} -Pulse-on time in *μs*, T_{off} - Pulse-off time in *μs*, V_g- Gap voltage in *V*, I- Current in *A*

2.1 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS method is used to find the optimal solution among the various combinations of experiments. The steps given below are adapted to find the optimal parameter combination [15-17].

Step 1: D is the decision matrix:

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & \cdots & \cdots & X_{1n} \\ X_{21} & X_{22} & X_{23} & \cdots & \cdots & X_{2n} \\ X_{31} & X_{32} & X_{33} & \cdots & \cdots & X_{3n} \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\ X_{\alpha 1} & X_{\alpha 2} & X_{\alpha 3} & \cdots & \cdots & X_{\alpha\beta} \end{bmatrix}, \quad (1)$$

where X_{ij} is the performance of i^{th} alternative with respect to j^{th} attribute.

Step 2: The normalize decision matrix values were calculated using the below equation:

$$\sigma_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i-1}^{m} X_{ij}^2}} \quad (2)$$

$$i = 1,2, \ldots ,.\alpha \ and \ j = 1,2 \ldots .\beta$$

Step 3: The weighted normalized decision matrix is obtained as:

$$n_{ij} = w_i \times \sigma_{ij} \quad (3)$$

w_i represents the weight of the i^{th} attribute or criteria.

Step 4: Positive ideal solution (PIS) and negative ideal solution (NIS) are determined as follows:

$P^+ = (P_1^+, P_2^+, \ldots . P_\beta^+)$ maximum values (4)

$P^- = (P_1^-, P_2^-, \ldots . P_\beta^-)$ minimum values (5)

Step 5. The separation of each alternative from positive ideal solution (PIS) is determined as:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (N_{ij} - N_j^+)^2} \quad (6)$$

i=1,2….α

The separation of alternatives form the negative-ideal solution can be obtained from equation 7.

$$S_i^- = \sqrt{\sum_{j=1}^{n} (N_{ij} - N_j^-)^2} \quad (7)$$

Step 6: Equation 8 used to find the relative proximity of the different alternative to the ideal solution.

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \pi r^2 \quad (8)$$

i= 1,2….α; 0≤ P_i ≤1

Step 7: the P_i values are placed in descending order to determine the optimal combination of parameters.

3. RESULTS AND DISCUSSION

3.1 Effect of Voltage, Current on MRR and TWR

The effcet of voltage and current on MRR were presented in Fig.3 and 4. Based on Fig.3 and Table 3 it is apparent that voltage has a significant effect on MRR. The increase in gap voltage increases the temperature between the tool and the workpiece. This increase in temperature melts and evaporates the workpiece material. The material removal is found to be higher for higher voltage levels. The trend of the graph increases with the increase in current value. More current contributes to more MRR. Similarly, TWR has been found to increase with the increase in voltage upto 30 V and then gradually decreases. The increase in voltage increases the ionization effect between the tool and workpiece. More ionization leads to a larger amount of material removal both in the tool electrode and workpiece. The removal of a larger amount of material obstructs the ionization process between the tool electrode and workpiece. This leads to a decrease in TWR when voltage is increased to a higher level.

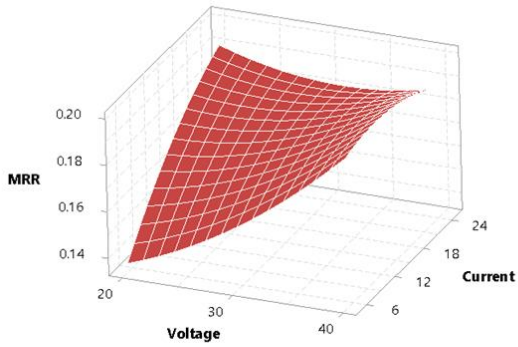

Fig.3. Surface plot of MRR ($gmin^{-1}$) Vs current (I) and voltage (V)

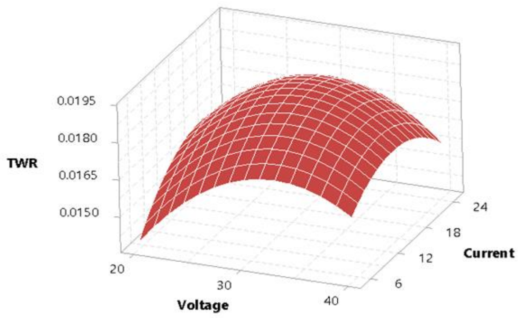

Fig.4. Surface plot of TWR ($gmin^{-1}$) vs current (I) and voltage (V)

Table 3. ANOVA for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.00980	0.00245	1.59	0.208
Pulse on time	1	0.00026	0.00026	0.17	0.681
Pulse off time	1	0.00005	0.00005	0.04	0.852
Voltage	1	0.00598	0.00598	3.88	0.060
Current	1	0.00350	0.00350	2.27	0.144
Error	25	0.03854	0.00154		
Lack-of-Fit	20	0.03773	0.00188	11.62	0.006
Pure Error	5	0.00081	0.00016		
Total	29	0.04835			

3.2 Effect of Pulse on time and off time on MRR and TWR

The trend seen in Fig.5 show that the MRR increases with pulse on time. During pulse on time more current is available for machining, hence higher MRR is achieved. At lower pulse on time the possibility for flushing of debris is higher due to a shorter pulse on time. It is for this reason that the MRR is higher at lower pulse on time. Moreover, at pulse off time the current available for ionization is grater, therefore MRR is found to be higher and it decreases with the increase in pulse off time.

It is apparent from Fig.6 that TWR is found to be lower at lower pulse on time and tends to increase with increase of pulse on time. At higher pulse on time the current available for machining exists in the tool for a longer period leading to more TWR. Similarly, during lower pulse off time the current from the tool electrode is carried away at higher frequency leading to more TWR. Fig.7 shows the SEM micrograph of a machined hole in grey cast iron. Based on SEM micrographs the circular hole is obtained during the EDM process and few circumference sections of the hole show the presence of a recast layer.

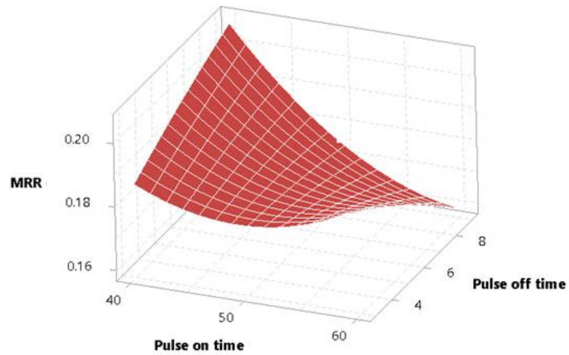

Fig.5. Surface plot of MRR ($gmin^{-1}$) vs pulse on time (μs) and pulse off time (μs)

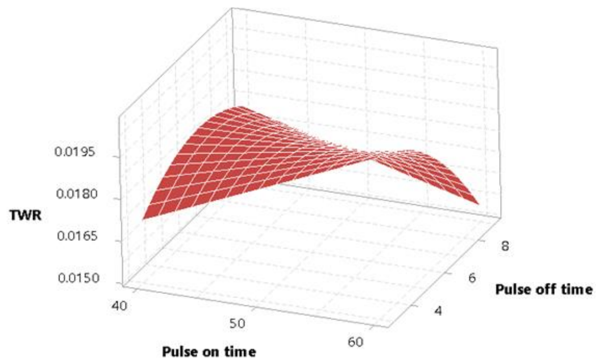

Fig.6. Surface plot of TWR ($gmin^{-1}$) vs pulse on time (μs) and pulse off time (μs)

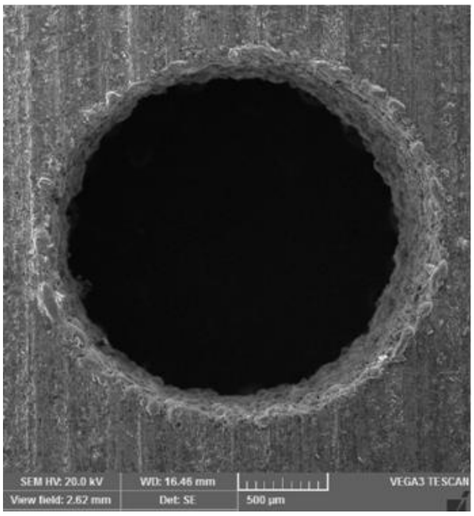

Fig.7 SEM micrograph of machine hole

3.3 Mathematical Model MRR and TWR

A simple regression analysis was carried out to show the fitness of the experimental values. MINITAB statistical software is utilized to develop First-order nonlinear polynomial model [18,19]. Normally, the fitness characteristic is depicted by the following equation:

$$Y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \epsilon, \quad (9)$$

where: $\beta_0, \beta_1, \beta_2, \beta_{3...}$ are the estimates of process varaiables, and ε is the error.

An empirical equation is obtained to express the functional relationship between the response to the process variables.

The influence of all input process parameters on MRR and TWR were calculated from the mathematical equations. The fit summary recommended that the quadratic model is statistically significant for analysis of MRR and DF and linear model for EWR. Equations (10) and (11) below are the final response equations for MRR and TWR.

MRR = 0.0858 - 0.00067 Pulse on time
- 0.00081 Pulse off time + 0.00316 Voltage
+ 0.00242 Current (10)

TWR = 0.0071 + 0.000079 Pulse on time
- 0.000185 Pulse off time + 0.000181 Voltage
+ 0.000166 Current (11)

4. TOPSIS Analysis

Based on the Eq.1 to 8 the values are estimated and presented in the Table 4 and 5. The significant combination for higher MRR and lower TWR is pulse-on time of 45 µs, pulse-off time of 3 µs, gap voltage of 25 V and current of 10 A.

Table 4. The normalized values using TOPSIS method

Exp. No.	Experimental results		Normalization	
	MRR	TWR	MRR	TWR
1	0.0294	0.002	0.0296	0.4089
2	0.196	0.025	0.1972	0.0644
3	0.1715	0.018	0.1725	0.1692
4	0.147	0.015	0.1479	0.2142
5	0.1962	0.019	0.1972	0.1543
6	0.1812	0.017	0.1725	0.1842
7	0.1843	0.015	0.1725	0.2142
8	0.1963	0.023	0.1972	0.0944
9	0.1838	0.018	0.1849	0.1692
10	0.149	0.0152	0.1479	0.2112
11	0.2083	0.0192	0.2096	0.1513
12	0.1593	0.016	0.1603	0.1992
13	0.3186	0.0293	0.3205	0.0000
14	0.1834	0.018	0.1849	0.1692
15	0.1864	0.0176	0.1725	0.1752
16	0.162	0.015	0.1603	0.2142
17	0.1838	0.0183	0.1849	0.1647
18	0.196	0.02	0.1972	0.1393
19	0.1598	0.0162	0.1603	0.1962
20	0.1834	0.0174	0.1725	0.1782
21	0.1839	0.0181	0.1849	0.1677
22	0.1913	0.0162	0.1725	0.1962
23	0.1635	0.0164	0.1725	0.1932
24	0.184	0.0192	0.1849	0.1513
25	0.1717	0.0179	0.1725	0.1707
26	0.1715	0.0165	0.1725	0.1917
27	0.196	0.028	0.1972	0.0195
28	0.1713	0.0173	0.1725	0.1797
29	0.1716	0.0186	0.1725	0.1602
30	0.1964	0.0172	0.1972	0.1812

Table 5. Ranking based in TOPSIS analysis

Weighted Normalization		S_i^+	S_i^-	P_i	Rank
MRR	TWR				
0.0148	0.2044	0.1455	0.2044	0.5842	1
0.0986	0.0322	0.1829	0.0898	0.3292	29
0.0863	0.0846	0.1408	0.1108	0.4403	23
0.0739	0.1071	0.1301	0.1223	0.4846	5
0.0986	0.0771	0.1414	0.1139	0.4460	21
0.0863	0.0921	0.1345	0.1166	0.4643	12
0.0863	0.1071	0.1223	0.1287	0.5129	2
0.0986	0.0472	0.1689	0.0962	0.3628	28
0.0925	0.0846	0.1377	0.1149	0.4548	15
0.0739	0.1056	0.1312	0.1210	0.4798	7
0.1048	0.0756	0.1402	0.1175	0.4560	14
0.0801	0.0996	0.1320	0.1191	0.4744	10
0.1603	0.0000	0.2044	0.1455	0.4158	27
0.0925	0.0846	0.1377	0.1149	0.4548	15
0.0863	0.0876	0.1383	0.1131	0.4499	19
0.0801	0.1071	0.1261	0.1254	0.4987	3
0.0925	0.0824	0.1396	0.1132	0.4478	20
0.0986	0.0696	0.1482	0.1090	0.4237	26

Table 5. Ranking based in TOPSIS analysis - continued from the previous page

Weighted Normalization		S_i^+	S_i^-	P_i	Rank
MRR	TWR				
0.0801	0.0981	0.1331	0.1179	0.4696	11
0.0863	0.0891	0.1370	0.1142	0.4547	17
0.0925	0.0839	0.1383	0.1143	0.4525	18
0.0863	0.0981	0.1295	0.1214	0.4837	6
0.0863	0.0966	0.1308	0.1202	0.4789	8
0.0925	0.0756	0.1456	0.1084	0.4269	24
0.0863	0.0854	0.1402	0.1113	0.4427	22
0.0863	0.0958	0.1314	0.1196	0.4764	9
0.0986	0.0097	0.2042	0.0844	0.2923	30
0.0863	0.0899	0.1364	0.1148	0.4571	13
0.0863	0.0801	0.1447	0.1074	0.4260	25
0.0986	0.0906	0.1295	0.1234	0.4881	4

5. CONCLUSION

The results of the research showed the following:

1. The experiments were conducted with input parameters such as pulse-on time (T_{on}), pulse off time (T_{off}), gap voltage (V_g) and current (I) on material removal rate (MRR) and tool wear rate (TWR) using RSM design of experiments;
2. RSM experiments shows that the voltage and pulse on time has significant effect on MRR and pulse on/off time has a notable effect on TWR;
3. Regression models for MRR and TWR were developed for machining of grey cast iron using RSM. The ANOVA result predicts that the voltage is the most significant factor that affects the MRR;
4. The significant combination for higher MRR and lower TWR is pulse-on time of 45 µs, pulse-off time of 3 µs, gap voltage of 25 V and current of 10 A were estimated using TOPSIS;
5. Further high aspect holes and intricate shape can be studied using EDM on grey cast iron.

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