An Experimental Investigation of Material Removal Rate in Electric Discharge Machining of Heat Treated Carbon Tool Steel (SK2MCr4)

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Abstract - *Manufacturing with machining contributes to a large extent in most of the industry as even the formed parts needs finishing by removal of material. This study investigates the influence of EDM parameters on MRR while machining of SK2MCr4 as a workpiece material. The parameters considered are current (I), pulse on time (T_{on}), and servo voltage (V) whereas pulse off time is taken as a constant. The experiments were performed on the die-sinking EDM machine using copper electrode. The analysis and optimization of MRR was done using Taguchi method to find the contribution of different process parameters on MRR. It is found that the MRR is mainly influenced by current (64.29 percent contribution), whereas the other two parameters T_{on} and servo voltage have very less effect on material removal rate. The optimum combination of current, pulse on time and servo voltage for maximizing MRR is found as 12 A, 60 μs and 3 V respectively.*

Key Words: EDM, MRR, DOE, ANOVA

1. INTRODUCTION

In manufacturing industry, the electric discharge machine plays a significant role. Electrical Discharge Machining (EDM) is a machining method primarily used for hard metals or those that would be impossible to machine with traditional techniques. EDM is an electrically thermal non-conventional machining process, where electrical energy is used to generate an electrical spark and removal of material is mainly due to the thermal energy of the spark. EDM is a modern machine which can do drilling, milling, grinding and other conventional machining operations. In the manufacturing industry, EDM is commonly used for the production of mold and die components. This machine is used because of the ability of the machining process is very accurate in creating complex or simple shapes within parts and assemblies. Since EDM was developed, so much theoretical and experimental work has been done to find the elemental processes involved. Now it is one of the main methods used in die production as there is no direct physical contact between the electrodes and hence no mechanical stresses are developed in the work-piece. The precise production parameters of the process are the material removal rate (MRR) and electrode wear rate (EWR) [1, 2].

2. LITERATURE REVIEW

The material removal mechanism of the EDM process is not regulated by mechanical force, so the machining characteristics of the EDM process are not governed by the mechanical properties of the workpiece material. The material is removed by a high localized temperature associated with a very high energy density caused by ionization within the discharge between the work piece and electrode. Hence, the material removal mechanisms of the EDM process are thermal erosion due to melting and vaporization. The feasibility of applying the EDM process on difficult-to-machine materials has been studied by many researchers [3-5]. A number of studies are found with work piece materials like tool steels, die steel, composites and alloys, but limited work on machining parameters optimization for heat treated carbon tool steel is available in existing literature. The technique of design of experiment based on the Taguchi method has been used to find the parameter setting for optimum machining performance in turning operation, die-sink EDM and wire electrical discharge machining (WEDM) for maximum MRR and minimize the tool wear rate (TWR) and surface roughness (SR) [6-9]. EDM is a feasible method for machining difficult-to-machine materials, such as tungsten carbide, conductive ceramics, composite materials and carbon tool steels. In relation to carbon tool steels, the relationships between EDM machining parameters and the output parameters such as material removal rate (MRR) require further investigation. Carefully selecting the machining parameters of the EDM process can ensure that the process is highly efficient and highly precise. Many researchers studied with different electrode material such as copper, brass and graphite, aluminum and etc. for determining the effect of control parameters [10-13]. There are various machining parameters of EDM i.e. current, pulse on time, pulse off time, servo voltage, flushing pressure, duty cycle, polarity and etc. and many types of techniques and models such as: ANN (Artificial Neural Network), linear Regression model, response surface methodology, entropy method, mixed factorial etc. to find out the MRR, TWR and SR in EDM [14-17].The experimental studies using fractional design of experiment approach and full factorial design of experiment approach are conducted using the Taguchi experimental method to determine systemically EDM performance in many investigations [18–25]. From most of the studies done earlier, it is found that the three essential machining parameters of the EDM process:

current (I), pulse on time (T_{on}) and servo voltage (V) are significant and needs to be explored for their impact on MRR in heat treated carbon tool steel experimentally, using the Taguchi method.

3. MATERIALS AND METHODS

A series of experiments is carried out to generate data related to machining parameters and output parameter MRR on the EDM available in the lab. The experimental data are then statistically analyzed using analysis of variance (ANOVA) to determine the significant parameters associated with each machining parameter i.e. MRR[26, 27]. Moreover, the optimal combination levels of machining parameters that optimized each machining are determined.

3.1 Electric Discharge Machine

According to the required objective of the present work an electric discharge machine ZNC-250 is used to perform the experiments for MRR. The current values are selected at three level of 4, 8 and 12 A and pulse on time and servo voltages are also selected at three levels at 20, 60 and 100 µs and 3, 4 and 6 V respectively, which are available on the selected machine shown in Fig 1.

Figure 1: EDM Machine

3.2 Work piece Material

SK2MCr4 carbon tool steel is the workpiece material for the study with a hardness of 58 HRC. The composition and mechanical properties of SK2MCr4 carbon tool steel is given in Table 1 & 2 respectively and the pictures of workpiece used (before and after) for the experimental work are shown in [Fig 2 & 3].

Fig-2: SK2MCr4 carbon tool steel used for experiment

Fig-3: SK2MCr4 carbon tool steel used for experiment for Ton (20µs)

Table 1: Chemical Composition of Carbon Tool Steel (SK2MCr4)

Element	C	Si	Mn	P
Composition %	1.10-1.30	0.35 Max	0.50 Max	0.030 Max
Element	S	Cu	Ni	Cr
Composition %	0.030 Max	0.25 Max	0.25 Max	0.40-0.50

(Source: Daewon Steel Co., Ltd)

Table 2: Mechanical properties of Carbon Tool Steel (SK2MCr4)

Grade	Finishing condition	Hardness test	Tensile test	
		HV	Tensile strength (N/mm^2)	Elongation
SK2MCr4	Annealed	170-210	520-685	30-32
	Skin passed	190-230	570-715	10-28
	Rolled	250-290	735-980	2-15
	Full hardened	280-320	835-1080	1-3

(Source: Tokushu Kinzoku Excel Co., Ltd)

3.3 Electrode (Tool) Properties

Due to favorable properties, Copper is used as -a heat conductor, -an electrical conductor, as -a building material and as -a constituent of various metal alloys. It is ductile in nature with excellent electrical conductivity and also has good EDM wear resistance and hence it is generally used for better material removal rate from the workpiece. The diameter of copper electrode selected is 8 mm with a length of 80 mm. The photographic view of copper electrode is shown in Fig 4.

Fig-4: Copper electrode used for experiment

3.4 Dielectric Fluid

The dielectric fluids, generally used in EDM are: EDM oil, kerosene (paraffin oil) and de-ionized water. Tap water cannot be used because of the presence of salts as impurities as it ionizes too early and therefore the breakdown occurs. Dielectric medium is usually flushed around the spark zone. Divyol spark errossion oil- 25 is used as a dielectric medium in this study. The technical specifications are given in Table 3.

Table 3: Technical specification of Divyol Spark Errossion Oil-25

S. No.	**Physical Property**	**Test Method**	**Specification**	**Test Result**
1.	Appearance	Visual	Bright & clear	Bright & clear
2.	Colour	ASTM D-1500	0.0	0.0
3.	Specific Gravity @ 29.5°C,Min.	ASTM D-1298	0.750	0.755
4.	Kinematic Viscosity @ 40°C cSt	ASTM D-445	2.0 to 2.5	2.19
5.	Flash Point°C (COC), Min.	ASTM D-92	100	104
6.	Pour Point °C, Max.	ASTM D-97	-3	<-3

(Gandhar Oil Refinery India Ltd.)

3.5 Material Removal Rate (MRR)

The MRR is expressed as the ratio of the difference of weight of the work piece before and after machining to the product of machining time and the density of the material.

$$MRR = \frac{(Wi - Wf)}{t \times \rho}$$

Where, MRR is material removal rate (mm^3/min); Wi is work piece weight before machining (g); Wf is work piece weight after machining (g); t is machining time (min) and ρ is density of the work piece material (g/cm^3).

3.6 Taguchi Methodology

The Taguchi method is a commonly adopted approach for optimizing process parameters. Since experimental procedures are generally time consuming and expensive, the need to satisfy the design objectives with the least number of tests is clearly an important requirement.

While analyzing through Taguchi method, there are three approaches for analysis of signal to noise (S/N) Ratio i.e. the smaller is better, the larger is better and the nominal is best. The term 'signal' represents the desirable value which is given by the mean of the output characteristics while the 'noise' represents the undesirable value which is the squared deviation of output characteristics.

The following equations are used to calculate the S/N ratio [Minitab-17 Free Trial, 2018]:

1) The smaller is better :

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} yi^2\right)$$

2) The larger is better:

$$\eta = -10\log_{10}\left(\left(\sum_{i=1}^{n}\frac{1}{yi^2}\right)/n\right)$$

3) The nominal is best:

$$\eta = 10\log_{10}\sum_{i=1}^{n}\frac{yi^2}{s^2}$$

Where,

η = indicates Signal to Noise ratio
n = No. of repetitions of the experiment
yi = Measured value of the quality characteristics
s = Variance

For the present experimental analysis, the second approach, i.e. 'The larger is better' is chosen to apply while calculating the values of S/N ratio using MiniTab-17. The second approach is chosen to obtain the optimum conditions for maximization of material removal rate which is a desired condition for machined parts. Regardless of the approach, the larger S/N ratio is always recommended for better performance. Thus, the optimal parameter for any factor is the level having a highest S/N ratio.

3.7 Experimental Parameters

The experiments are conducted with following settings:

- The machining is done keeping positive polarity of the copper electrode. The diameter and length of the electrode is 8 mm and 80 mm respectively.
- The initial mass and final mass of the test work piece is measured using Shimadzu portable electronic balance model ELB300, in grams.
- The parameters of the experiment are set at five levels i.e. level 1, level 2, level 3, level 4 and level 5.
- A constant thickness of 1 mm is used for the machining of all work pieces.
- The Taguchi Methodology with "larger is better" criteria is used for optimization of the process parameters.

4. RESULTS AND DISCUSSION

The experiment is started with three independent parameters, each at five levels: current (I), Pulse on time (T_{on}) and Servo voltage (V) which are varied alternatively while Pulse off time (T_{off}) is kept as a constant. During the experiments, the dependent variable Material Removal Rate has been noted down. From the plots of these relationships, two levels of each parameters are identified which are redundant. After dropping these redundant data, L9 orthogonal array was formed with three parameters and three levels as given in Table 4 and Table 5.

Table 4: Experimental levels of Independent parameter

S. No.	Symbols	Independent Parameters	No. of Levels	Levels					Units
				1	2	3	4	5	
1.	Ton	Pulse on time	5	20	40	60	80	100	µs
2.	V	Servo voltage	5	3	4	5	6	7	V
3.	I	Current	5	4	6	8	10	12	A

Table 5 indicates the values of MRR taken for various values of current, pulse on time and servo voltage for SK2MCr4. Pulse of time was kept as constant i.e. 6 µs. Three levels of current, pulse on time and servo voltage are used here. For current 4, 8 and 12 A are taken and for pulse on time 20, 60 and 100 µs are taken and for servo voltage 3, 4 and 6 V which are shown in Table 5.

Table 5: Independent parameters and response data for individual experimental run

Independent Parameters				Response		
S. No.	Current	Pulse on time	Servo voltage	MRR	Mean	S/N ratio
1.	4	20	3	2.2504	2.2504	7.0452
2.	4	60	4	4.5065	4.5065	13.0768
3.	4	100	6	3.0415	3.0415	9.6618
4.	8	20	4	5.5978	5.5978	14.9603
5.	8	60	6	10.4470	10.4470	20.3798
6.	8	100	3	8.1070	8.1070	18.1772
7.	12	20	6	6.4286	6.4286	16.1623
8.	12	60	3	16.2440	16.244	24.2139
9.	12	100	4	14.2830	14.283	23.0964

Table 6: Rank Table for S/N ratios of MRR with control machining parameters

Level	I	Ton	V
1	3.266	4.759	8.867
2	8.051	10.399	8.129
3	12.319	8.477	6.639
Delta	9.052	5.640	2.228
Rank	1	2	3

Fig. 5 illustrates the interaction plot of MRR between current and pulse on time at different levels of peak current. The plot exhibits that the material removal rate increases with current and pulse on time at initial two levels. Although at higher value of current, the MRR tends to get reduced with increase in the value of pulse on time.

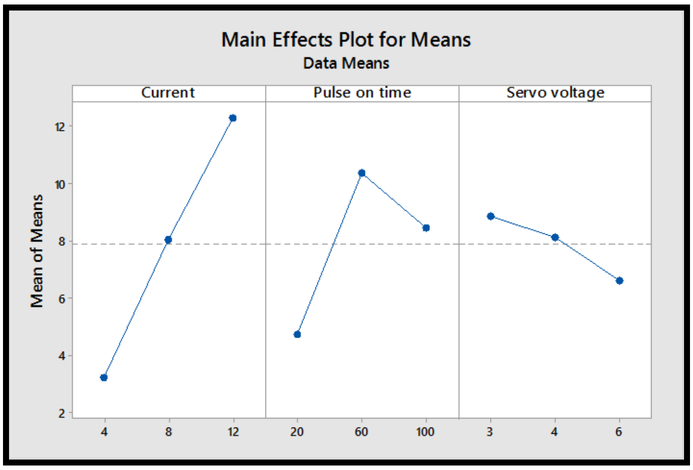

Fig- 5: Means V/s Control parameters (current, pulse on time and servo voltage)

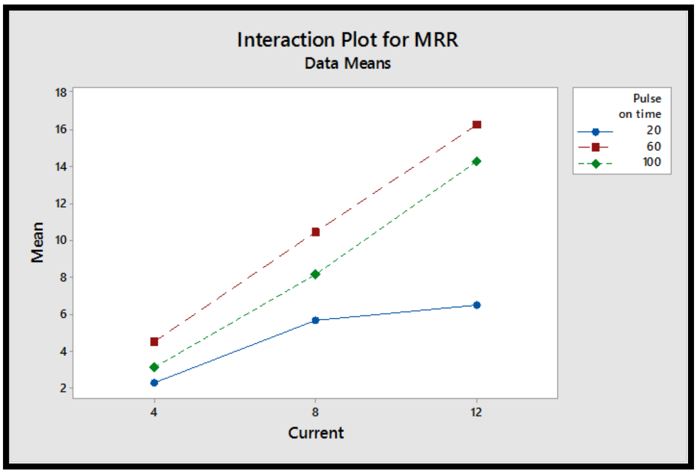

Fig-6: Interaction graph of MRR between current and pulse on time

4.2 Analysis of Variance

It can be seen from the collected data that all the controlled parameters i.e. current, pulse on time and servo voltage with pulse off time as a constant affects MRR. Table 6 shows variation of actual values of each input parameter with experimental results obtained. Average value of MRR was statistically analyzed using Minitab-17 Software. Analysis of variance was performed to study the significance of input machining parameters on MRR.

Table 7: Analysis of Variance for MRR

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F value	P value	Percentage contribution
I	2	123.052	123.052	61.526	10.91	0.084	64.29%
Ton	2	49.332	49.332	24.666	4.37	0.186	25.78%
V	2	7.729	7.729	3.865	0.69	0.593	4.04%
Error	2	11.282	11.282	5.641			5.89%
Total	8	191.395	191.395				100%
S = 2.37503 R-sq = 94.11% R-sq (adj.) = 76.42%							

It is clear from Table 7 that the effect of current, pulse on time and servo voltage on MRR is 64.29%, 25.78% and 4.04% respectively which is same as obtained from response table for S/N ratio. R-sq represents the significance of experimental work which is 94.11%. In Analysis of variance, F value is also an indication of more and less affecting parameter. Parameter which has more or less F value indicates most and least affecting parameter. From Table 7 it is seen that the current is most significant parameter as it has high F value and pulse on time and servo voltage are lesser significant parameter as it has less F value.

$$MRR = -0.74 + 1.132\, I + 0.0465\, T_{on} - 0.743\, V \quad (1)$$

This equation is used to obtain the predicted values of material removal rate using the data of experimental run. Initially, the equation was applied to experimental data for each run as shown in Table 4 to predict the material removal values for given input as used in predictive equation.

$$SNRA1 = 3.73 + 1.404\, I + 0.0532\, T_{on} - 0.425\, V \quad (2)$$

Fig. 8 illustrates the interaction plot of S/N ratio between current and pulse on time at different levels of current and pulse on time.

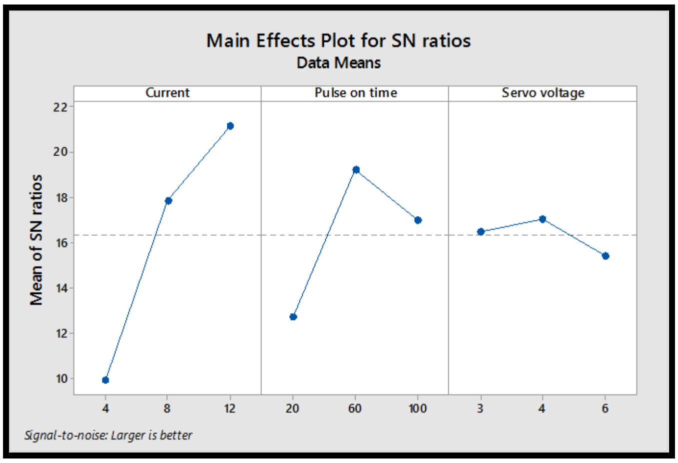

Fig- 7: S/N ratios of MRR for current, pulse on time and servo voltage

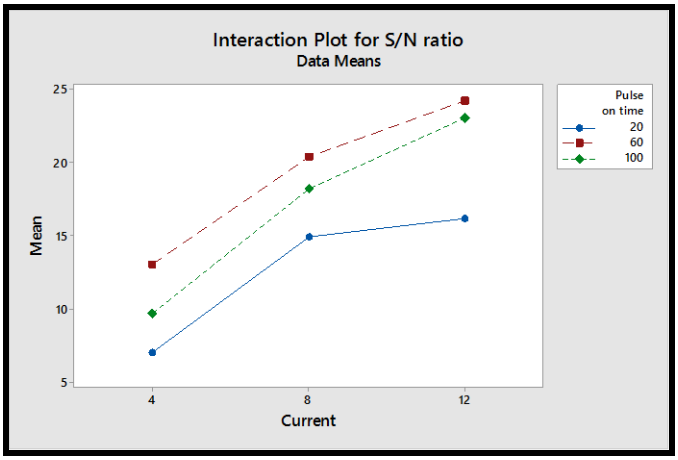

Fig- 8: Interaction graph of S/N ratio of MRR between current and pulse on time

4.30 Full Factorial design of experiment approach: After dropping the redundant data

According to the strategy of the present work, this is an approach after dropping the redundant data with three different parameters and three levels of the experimentation in which a full factorial experimental runs are created.

Table-8: Parameter and Response data for individual experimental run

S. No.	Independent parameters			Dependent Response Variable	
	Current	Pulse on time	Servo voltage	MRR	S/N ratio
1.	4	20	3	2.2504	7.0452

2.	4	20	4	2.237	6.9993
3.	4	20	6	1.9227	5.6782
4.	4	60	3	4.579	13.2154
5.	4	60	4	4.50655	13.0769
6.	4	60	6	3.5282	10.9511
7.	4	100	3	3.662	11.2744
8.	4	100	4	4.20087	12.4688
9.	4	100	6	3.0415	9.6618
10.	8	20	3	6.416	16.1453
11.	8	20	4	5.5978	14.9603
12.	8	20	6	2.674	8.5432
13.	8	60	3	11.775	21.4192
14.	8	60	4	10.6705	20.5637
15.	8	60	6	11.267	21.0362
16.	8	100	3	8.107	18.1772
17.	8	100	4	9.443	19.5022
18.	8	100	6	8.1332	18.2052
19.	12	20	3	9.8214	19.8435
20.	12	20	4	5.252	14.4065
21.	12	20	6	6.4286	16.1623
22.	12	60	3	16.244	24.2139
23.	12	60	4	18.34	25.2680
24.	12	60	6	16.45	24.3233
25.	12	100	3	15.31	23.6995
26.	12	100	4	14.283	23.0964
27.	12	100	6	13.581	22.6586

Table-9: Analysis of variance on MRR versus I, T_{on} & V

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F-value	P-value	Percentage Contribution
I	2	408.925	408.925	204.462	59.14	0.00	62.05%
T_{on}	2	173.681	173.681	86.841	25.12	0.00	26.39%
V	2	7.170	7.170	3.585	1.04	0.373	1.09%
Error	20	69.150	69.150	3.457	-	-	10.49%
Total	26	658.926	658.926	-	-	-	100%
S = 1.85943 R-sq = 89.51% R-sq(adj.) = 86.36% R-sq (pred)= 80.87%							

From the Analysis of variance, the contribution of the current is found to be 62.05%, pulse on time is 26.39% and servo voltage is 1.09% on material removal rate. R-sq value represents the significance of the experimental work which is 89.51%.

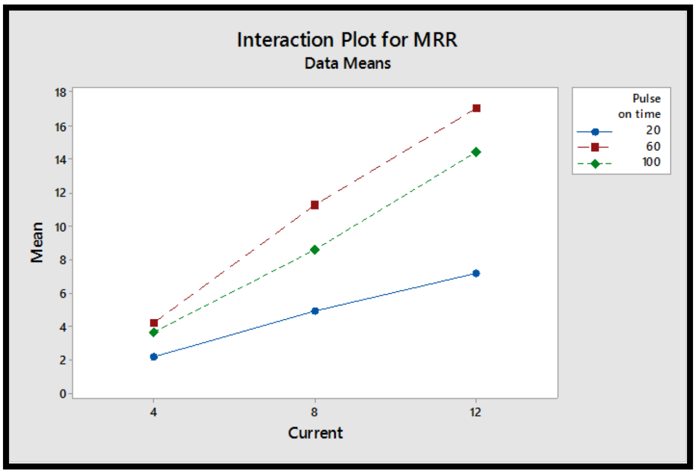

Fig-9: Interaction graph of MRR between current and pulse on time

The regression equation 3 can also be used for finding more values of MRR at different control parameters i.e. current, pulse on time and servo voltage.

$$MRR = -2.70 + 1.191\, I + 0.0516\, T_{on} - 0.413\, V \quad (3)$$

5. CONCLUSIONS

The present investigation aimed at obtaining required material removal rate during EDM drilling of SK2MCr4 work piece with copper electrode by changing the combination of control parameters. The relationship between control parameters and the performance measures are expressed by multiple regression models which can be used to estimate the expressed values of the performance level for any parameter levels and is obtained by fractional design of experiment approach. Main effect plots and interaction graph were drawn which shows relationship among the collected data.

- The effect of machining parameters on material removal rate (MRR) during electric discharge machining is strongly affected by current while the pulse on time and servo voltage has least effect on material removal rate.
- The MRR is mainly affected by current (I) and the other two parameters have least effect on it.
- MRR increased linearly to starting level due to current increment and decreases slightly with pulse on time.
- Optimization of machining parameters for maximum material removal rate (MRR) by Taguchi L9 orthogonal design of experiment and ANOVA analysis, the interactions are found between the parameters.
- The value of maximum material removal is 18.34 mm^3/min and the optimum parameters can be considered for maximize the material removal rate is 12 A current, 60 µs pulse on time and 3 V servo voltage.
- The percentage contribution of the current, pulse on time and servo voltage are found to be 64.29%, 25.78% and 4.04% respectively on material removal rate in fractional design of experiment approach, while in full factorial design of experiment approach, the percentage contributions are 62.05%, 26.39% and 1.09% respectively
- Taguchi Design is a robust model for optimization when experimental runs are to be limited and it does not involve all the parameter combination. Thus rate of error by fractional design approach is found to be 5.89% which is lower in comparison to full factorial design approach where it is found to be 10.49%.

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