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Analysis of EDM Process Parameters for Maximizing Material Removal Rate in SK2MCr4 Steel Machining

Deepa Singh[1] *, Birendra Singh Karki [1], Durgesh Shukla [2], Aavesh Kumar [3], Neeraj Bisht [1]

[1]*Department of Mechanical Engineering, College of Technology, G.B. Pant University of Agriculture & Technology, 263145, Pantnagar, India*

[2]*Department of Agriculture Zoology & Entomology, Baba Raghavdas Post Graduate College, D.D.U Gorakhpur University, 273009, Gorakhpur, India*

[3]*Department of Information Technology, Ajay Kumar Garg Engineering College, Dr. A.P.J. Abdul Kalam Technical University, 201001, Lucknow, India*

**Corresponding author, Email address: deepasingh092@gmail.com*

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Abstract: This study examines the effects of key machining parameters—current (I), pulse-on time (T_{on}), and servo voltage (V)—on the Material Removal Rate (MRR) during the Electrical Discharge Machining (EDM) of SK2MCr4 carbon tool steel. Employing a full factorial design of experiments and Taguchi's "larger is better" approach, experiments were conducted to assess the impact of each parameter. Analysis of Variance (ANOVA) indicated that current (I) was the most significant factor, accounting for 62.05% of the variation in MRR, with an F-value of 59.14. Pulse-on time (T_{on}) also demonstrated a considerable influence, contributing 26.39% to the variation, with an F-value of 25.12. Conversely, the servo voltage (V) exhibited a minimal impact, contributing only 1.09% to the MRR variation. The experimental model exhibited high reliability, with an R-squared value of 89.51%. A regression equation, MRR = -2.70 + 1.191 I + 0.0516 T_{on} − 0.413 V, was developed to predict the MRR based on the studied parameters. These findings underscore the critical importance of optimizing the current and pulse-on time to maximize the MRR in EDM operations.

1. Introduction

Solid in electrical discharge machine (EDM), machining process involves many parameters which directly or indirectly influence the material removal rate in the process. Improper selection of the electrode material and other parameters will be a reason for poor machining rate or performance requiring lower material removal rate (MRR) results more time for machining process and hence not good for production. In order to extend the machining efficiency, erosion of the work piece should be maximized and that of the electrode minimized in EDM process (Uhlmann, *et al.*, 2022). Therefore, finding out the material removal rate and its influencing parameters would be effective to enhance the machining productivity and process reliability.

The choice of electrode material greatly influences the surface characteristics and machining efficiency. For instance, when machining Ti-5Al-2.5Sn titanium alloy, copper electrodes produced the lowest surface roughness, while graphite electrodes resulted in the highest (Khan and Rahman, 2017). In another study, aluminum electrodes were found to be suitable for machining Ti-6Al-4V alloy, with optimal parameters identified for material removal rate (Phan *et al.,* 2020). Interestingly, the effectiveness of electrode materials can vary depending on the workpiece material and desired outcomes. For example, in powder mixed EDM (PMEDM) of die steel, graphite electrodes were found to be optimal when combined with titanium powder (Huu, 2020). This highlights the importance of considering the interaction between electrode material, workpiece material and other process parameters.

Peak current and pulse-on time are the most influential electrical parameters affecting surface roughness. For stainless steel 304, optimal EDM parameters were identified as 10A current, 60µs pulse-on time, and 35µs pulse-off time, with pulse-off time and current being the most significant factors (Ubaid *et al.,* 2017). Researchers have employed various optimization techniques, such as Taguchi method, Grey Relational Analysis and Response Surface Methodology, to determine the best combination of parameters for different materials and desired outcomes (Aliakbari & Baseri, 2012; Eljai *et al*., 2015; Juliyana *et al*., 2023; Singh *et al*., 2018 & Singh *et al*., 2019). These studies emphasize the complexity of EDM parameter optimization and the need for systematic approaches to achieve the best results in terms of material removal rate, surface roughness and other quality indicators.

The main goal of EDM manufacturers and users are to achieve a better stability and higher productivity of the EDM process. As newer and more exotic materials are developed and more complex shapes are presented, conventional machining operation has reached to their limitations whereas manufacturing continues to grow at an accelerated rate (Singh and Sharma, 2017).

Current and previous studies are basically reviewed to analyze the gap between conventional technologies and non-conventional technologies (El Magri and Vaudreuil, 2023). By in depth analysis of these studies it can be easily judged that how the technology is moving ahead and still what is the research gap that can be a step ahead towards future extension of that particular work. Thus, the previous work and literature provide a path and guidance for future work so that objectives can be planned.

In the present study experiments are performed on ZNC-250 electric discharge machine available in the workshop of Mechanical Department, College of Technology and Engineering, Udaipur. It is a die sinking type EDM machine. Die-sink EDM is used to machine extremely hard materials which are difficult to machine such as: tool steels, alloys, tungsten carbides and etc. Also, the effect of machining parameters with copper electrode and SK2MCr4 as a work piece is studied for calculating the material removal rate by changing the values of different parameters such as: current, servo voltage, pulse on time and pulse off time. **Table 1** and **Table 2** describes the chemical and mechanical properties of the carbon tool steel (SK2MCr4).

Table 1. Elemental Composition of Carbon Tool Steel (SK2MCr4)

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

(Source: Daewon Steel Co., Ltd)

Table 2: Properties of Tool (SK2MCr4)

Grade	Finishing Condition	Hardness test	Tensile test	
		HV	Tensile strength (N/mm²)	%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)

2. Methodology

A series of controlled experiments were conducted to generate data concerning various machining parameters and their corresponding effect on the output parameter, Material Removal Rate (MRR), using the Electrical Discharge Machining (EDM) system available in the laboratory. In these experiments, different machining parameters were systematically varied and their impact on MRR was observed and recorded. After the data collection phase, the results were subjected to a statistical analysis method known as Analysis of Variance (ANOVA). This technique helped in determining which machining parameters had a significant effect on MRR, thus identifying the most influential factors (Aichouch *et al*., 2025; El Magri and Vaudreuil, 2021).

Through the use of ANOVA, the researchers were able to identify the parameters that had the greatest influence on MRR and assess the level of interaction between these factors (N. Kumar & Choudhary, 2021). The goal was not only to understand the relationships between the parameters but also to optimize the process. By analyzing the data, the optimal combination of machining parameters for achieving the best possible MRR was determined. This optimization process is crucial for improving machining efficiency and achieving higher quality outcomes in EDM operations, ensuring that each machining setup is as effective as possible for the desired results (Mohankumar *et al*., 2024).

The analysis also provided insights into how different factors such as discharge current, pulse duration and voltage could be adjusted to improve performance, making it easier for operators to fine-tune the machine settings for specific applications. Ultimately, this process of experimentation, statistical analysis and optimization ensures that the EDM process operates at its highest potential efficiency while producing high-quality machined parts (Pourasl *et al*., 2022).

2.1 Electric Discharge Machine

In the context of the present study, the Electric Discharge Machine (EDM) plays a crucial role in performing the experiments aimed at determining the Material Removal Rate (MRR). For this research, the ZNC-250 model EDM is employed, which is a versatile machine widely used for precise machining operations, especially in cases where high accuracy is required for intricate shapes or hard-to-machine materials (Imran *et al*., 2021). The ZNC-250 is equipped with advanced features and allows for precise control over machining parameters, making it an ideal choice for the experiments designed to investigate the relationship between different machining parameters and MRR (Shastri *et al*., 2022). For this experiment, three key machining parameters are varied to understand their influence on MRR. These parameters include:

- Current (A): The current supplied during the machining process directly influences the energy delivered to the work piece, which affects the material removal rate. Three levels of current are selected for experimentation: 4 A, 8 A and 12 A. These levels provide a broad range of energy inputs, enabling the study of how different current intensities affect the MRR.

- Pulse on Time (μs): Pulse on time refers to the duration for which the electrical discharge is applied to the work piece. It determines the heat generated during each discharge and, consequently, the material removal efficiency. Three distinct pulses on times are selected: 20 μs, 60 μs and 100 μs. These varying time settings allow for a thorough exploration of how the duration of the electrical pulse impacts the overall material removal process.
- Servo Voltage (V): Servo voltage controls the gap voltage between the tool and the workpiece during the EDM process, influencing the accuracy and stability of the discharge process. The levels chosen for servo voltage are 3 V, 4 V and 6 V, providing different control over the discharge stability and its impact on MRR.

Figure 1. EDM Machine

The ZNC-250 EDM, shown in **Figure 1,** is designed to allow for precise adjustments of these parameters, ensuring that the experiment can be conducted under controlled and repeatable conditions. The selected parameter levels span a practical range typically encountered in real-world machining scenarios, making the findings of this experiment applicable to various industrial applications where EDM is used for machining complex materials. The combination of these three variables—current, pulse on time and servo voltage—are systematically tested to determine their influence on the Material Removal Rate (MRR), which serves as the key performance indicator for the EDM process in this study. By varying these parameters at their specified levels, the experiment aims to establish a comprehensive understanding of the optimal conditions required to maximize the MRR while ensuring the quality and precision of the machining process.

2.2 Work piece Material

The work piece material used in this study is SK2MCr4 carbon tool steel, which has a hardness of 58 HRC. Interestingly, different machining techniques and tool materials have been explored for high-hardness steels. For example, CBN (cubic boron nitride) tools have shown promise in hard turning of

AISI H13 die tool steel at hardness levels of 45-55 HRC (Kumar *et al.*, 2019). Additionally, cryogenically treated and untreated uncoated carbide cutting tools have been used for turning hardened DIN 1.2344 hot work tool steel (54 HRC) (Nas and Özbek, 2019). The material's composition and mechanical properties are detailed in **Tables 1 and 2**, respectively. Additionally, images of the work piece, both before and after the experimental procedures, are presented in **Figure 2 and 3.**

Figure 2. SK2MCr4 carbon tool steel used for experiment

Figure 3. SK2MCr4 carbon tool steel used for experiment for T_{on} (20μs)

2.3 Electrode (Tool) Properties

Copper is widely recognized for its excellent properties, making it a highly suitable material for use in Electrical Discharge Machining (EDM) electrodes. Its superior thermal conductivity and electrical conductivity play a crucial role in enhancing the efficiency of the EDM process (Skiba *et al.*, 2023). These properties ensure that copper electrodes can effectively transfer electrical energy during the discharge process, facilitating efficient material removal from the work piece (Ulhakim *et al.*, 2025). Additionally, copper is ductile in nature, which means it can undergo deformation without breaking, ensuring durability and maintaining its shape throughout the machining process (Shi *et al.*, 2021).

One of the significant advantages of using copper electrodes in EDM is their resistance to wear during machining (Satija *et al.*, 2023). Copper exhibits relatively low wear rates compared to other materials, which ensures consistent performance and longevity of the electrode, even under the intense conditions of electrical discharge (Mhahe *et al.*, 2024). This wear resistance allows the electrode to maintain its precise geometry, ensuring high-quality machining results and better Material Removal Rate (MRR) (Ramabalan *et al.*, 2024).

Given these properties, copper is often chosen as the preferred material for electrodes in EDM processes, particularly when high efficiency and material removal rates are desired (Selvarajan *et al.*, 2021). The electrode selected for this study has a diameter of 8 mm and a length of 80 mm. These dimensions are optimal for the machining tasks at hand, allowing for controlled energy delivery and effective material removal from the work piece (Ahmed, 2024). The photographic view of the copper electrode, as shown in Figure 4, provides a clear representation of its design and size, which are critical for ensuring consistent and efficient performance during the EDM process. The electrode's geometry and material properties make it an ideal tool for the experiments focused on optimizing machining parameters and improving the MRR in EDM operations.

Figure 4. Copper electrode used for experiment

2.4 Dielectric Fluid

In Electrical Discharge Machining (EDM), the dielectric fluid plays a critical role in maintaining the stability and efficiency of the machining process. The dielectric fluid serves several functions, including insulating the electrode and the workpiece, controlling the temperature by absorbing the heat generated during the electrical discharge and flushing away the debris produced by the spark erosion process (Zhu *et al.*, 2023). Common dielectric fluids used in EDM include EDM oil, kerosene (paraffin oil) and deionized water. Each of these fluids has distinct properties that make them suitable for different types of machining operations (Biswas *et al.*, 2023). For the current study, the Divyol Spark Erosion Oil-25 is selected as the dielectric medium. This oil is specifically designed for use in EDM operations, offering excellent insulating properties and effective heat dissipation, which are crucial for ensuring smooth and efficient machining (Singh *et al.*, 2018). The Divyol Spark Erosion Oil-25 is widely recognized for its ability to improve the overall performance of the EDM process by maintaining stable discharge conditions and optimizing the material removal rate (Prakash *et al.*, 2016). The technical specifications of Divyol Spark Erosion Oil-25 are provided in **Table 3.**

Table 3. Specifications of Divyol Spark Erosion Oil-25

S. No.	Properties	Methods	Specifications	Results
1.	Appearance	Visual	Bright and clear	Bright and 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.)

2.5 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 is given **Eqn.1** *(Kumar et al.*, 2022).

$$MRR = \frac{Wi - Wf}{t \times \rho} \qquad \textbf{Eqn. 1}$$

Where, MRR is material removal rate (mm^3/min);

Wi is work piece weight before machining (g);
W_f is work piece weight after machining (g); it is machining time (min) and ρ is density of the work piece material (g/cm^3).

2.6 Taguchi Methodology

The Taguchi method is used to optimize process parameters for better product quality, while minimizing the cost and time involved in experimentation (Okolie *et al.*, 2021). It achieves this by focusing on the Signal-to-Noise (S/N) ratio, which helps measure the effect of desirable values (signal) compared to undesirable variations (noise) in the output. The method aims to find the best combination of factors that minimizes or maximizes the performance of the process (Li *et al.*, 2019).

There are three common approaches for analyzing the S/N ratio in the Taguchi method. The Smaller is Better approach is used when the goal is to minimize the output, such as reducing defects or failures. The Larger is Better approach is applied when maximizing the output is desired, for example, increasing strength or efficiency. Lastly, the Nominal is best approach is used when a specific target value is ideal, and any deviation from that value, whether larger or smaller, is undesirable. Each method helps optimize the process to achieve consistent and high-quality results (Rashid, 2024). The following equations are used to calculate the S/N ratio [Minitab-17 Free Trial, 2018] (Alafaghani & Qattawi, 2020):

a. The smaller is better: $\eta = -10 \log 10(\sum_{i=1}^{n} yi^2)$ **Eqn. 2**

b. The larger is better: $\eta = -10 \log 10 \sum_{i=1}^{n} \frac{1}{yi^2})/n)$ **Eqn. 3**

c. The nominal is best: $\eta = 10 log 10 \sum_{i=1}^{n} \frac{yi^2}{s^2}$ **Eqn. 4**

Where,

η = indicates Signal to Noise ratio

n = No. of repetitions of the experiment

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.

2.6 *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.

3. Results and Discussion

The experiment was designed to study the effect of three independent parameters—current (I), pulse on time (T_{on}) and servo voltage (V)—on the Material Removal Rate (MRR) in the Electrical Discharge Machining (EDM) process. Each of these parameters was varied at five different levels, while the pulse off time (T_{off}) was held constant during the experimentation. The dependent variable, MRR, was recorded for each experimental condition. The three independent parameters and their corresponding levels were chosen based on practical EDM machining conditions. Initially, experiments were performed with five levels for each parameter. However, after analyzing the data and plotting the relationships, two levels for each parameter were found to be redundant. Consequently, the redundant data were discarded and an L9 orthogonal array was developed, reducing the parameters to three levels. The experimental levels for each parameter are presented in Table 4.

Table 4. Levels of Independent Parameters

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

After reducing the levels, a combination of three levels for each parameter was used for the L9 orthogonal array to optimize the results. **Table 5** shows, the independent parameters and the response data for each experimental run conducted on SK2MCr4 material, with pulse off time fixed at 6 µs. From **Table 6**, it is evident that current (I) has the highest impact on the MRR, as indicated by the highest Delta value (9.052), followed by pulse on time (T_{on}) with a Delta of 5.640. The servo voltage (V) has the least impact, with the smallest Delta of 2.228. Based on the S/N ratios and their ranks, the most significant parameter influencing the material removal rate is the current, followed by pulse on time and lastly, servo voltage.

Table 5. Independent Parameters and Corresponding Response Data

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

2.	4	60	4	4.5065	4.5065	13.0768
3.	6	100	4	3.0415	3.0415	9.6618
4.	4	20	8	5.5978	5.5978	14.9603
5.	6	60	8	10.4470	10.4470	20.3798
6.	3	100	8	8.1070	8.1070	18.1772
7.	6	20	12	6.4286	6.4286	16.1623
8.	3	60	12	16.2440	16.244	24.2139
9.	4	100	12	14.2830	14.283	23.0964

Table 6. Rank Table for S/N ratios of MRR with Control Machining Parameters

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

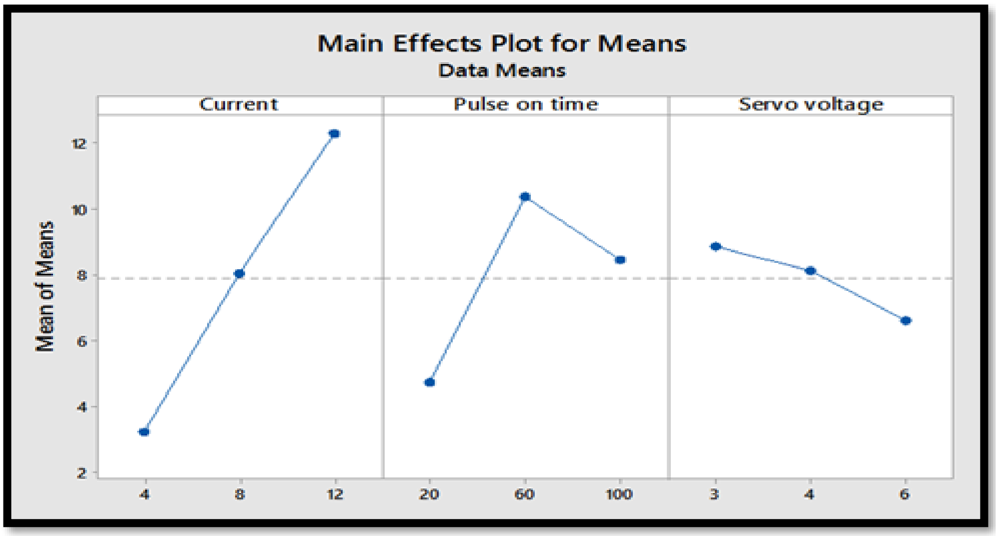

Figure 5. Means V/s current, pulse on time and servo voltage

As shown in **Figure 5**, MRR increases with both current and pulse on time at the initial two levels of each parameter. However, at higher values of current, the MRR begins to decrease with an increase in pulse on time.

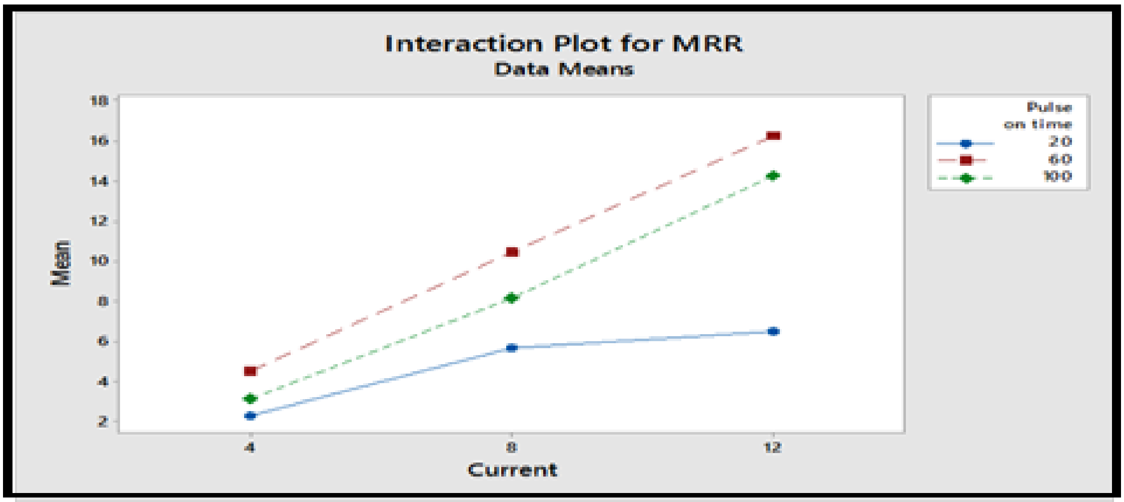

Figure 6: Interaction graph of MRR between current and pulse on time

Figure 6 further explores the interaction between current and pulse on time. The interaction plot indicates that as pulse on time increases, MRR tends to rise with lower current levels. However, beyond a certain threshold, increasing pulse on time at higher currents does not lead to a proportional increase in MRR. This emphasizes the importance of balancing current and pulse on time for optimal EDM performance.

3.1 Analysis of Variance (ANOVA)

The collected data indicates that all the controlled parameters—current, pulse on time, and servo voltage—along with a constant pulse off time, influence the material removal rate (MRR). **Table 6** presents the variation in the actual values of each input parameter alongside the experimental results. The average MRR values were statistically analyzed using Minitab-17 software. An analysis of variance (ANOVA) was conducted to evaluate the significance of the input machining parameters on MRR.

Table 7. ANOVA for MRR

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F Value	P Value	Percentage Contribution
I	2	123.1	123.1	61.5	10.9	0.08	64.29%
T_{on}	2	49.3	49.3	24.7	4.4	0.19	25.78%
V	2	7.7	7.7	3.9	0.7	0.59	4.04%
Error	2	11.3	11.3	5.6	-	-	5.89%
Total	8	191.4	191.4	-	-	-	100%
S = 2.37503 R-sq = 94.11% R-sq (adj.) = 76.42%							

From the results presented in **Table 7,** the effect of each parameter on the Material Removal Rate (MRR) is clearly quantified in terms of their percentage contributions to the total variation observed in the experimental data. The percentage contributions of the three independent parameters—current (I), pulse on time (T_{on}) and servo voltage (V)—are as follows: current (I) accounts for 64.29%, pulse on time (T_{on}) contributes 25.78% and servo voltage (V) contributes 4.04%. These values are consistent with the findings from the response table for S/N ratios, where current had the most significant impact on MRR, followed by pulse on time and servo voltage. This highlights the relative influence each parameter has on the machining process. The R-squared (R^2) value, which represents the goodness of fit of the experimental data to the statistical model, is found to be 94.11%. This indicates that the model explains 94.11% of the total variation in MRR, meaning that the experimental parameters and the statistical model used in the analysis capture the majority of the variation in the output. This high R^2 value suggests that the experimental design is robust and the results are statistically reliable, confirming that the study was well-structured and the findings are meaningful.

In the Analysis of Variance (ANOVA), the F-value is a crucial metric used to determine the significance of each parameter. The F-value indicates the relative impact of each parameter on MRR. A higher F-value suggests that the parameter has a greater influence on MRR, while a lower F-value suggests a lesser impact. From the data in **Table 7,** it is evident that current (I) is the most significant parameter affecting MRR, as it has the highest F-value. This supports the earlier findings that current is the primary factor driving material removal in EDM. On the other hand, pulse on time (T_{on}), while still significant, has a relatively smaller effect than current based on its F-value. Finally, servo voltage (V), while influencing the MRR, has the least effect among the three parameters, as indicated by its lower F-value. The ANOVA results from **Table 7** clearly demonstrate that current (I) is the most influential parameter in controlling MRR, contributing 64.29% to the overall variation. Pulse on time (T_{on}) also plays a significant role, contributing 25.78% to the variation, while servo voltage (V) has the least impact, with only 4.04% of the total variation. The high R-squared value of 94.11% indicates that the experimental model effectively explains the observed data, reinforcing the reliability and significance of the experimental setup. These findings are valuable for optimizing EDM process parameters to achieve better machining efficiency and precision.

$$MRR = -0.74 + 1.132\, I + 0.0465 T_{on} - 0.743\, V \qquad \textbf{Eqn. 5}$$

This equation predicts the material removal rate using experimental data from each run, as shown in **Table 4**, to estimate the values based on the given inputs.

$$SNRA1 = 3.73 + 1.404 I + 0.0532 T_{on} - 0.425\, V \qquad \textbf{Eqn. 6}$$

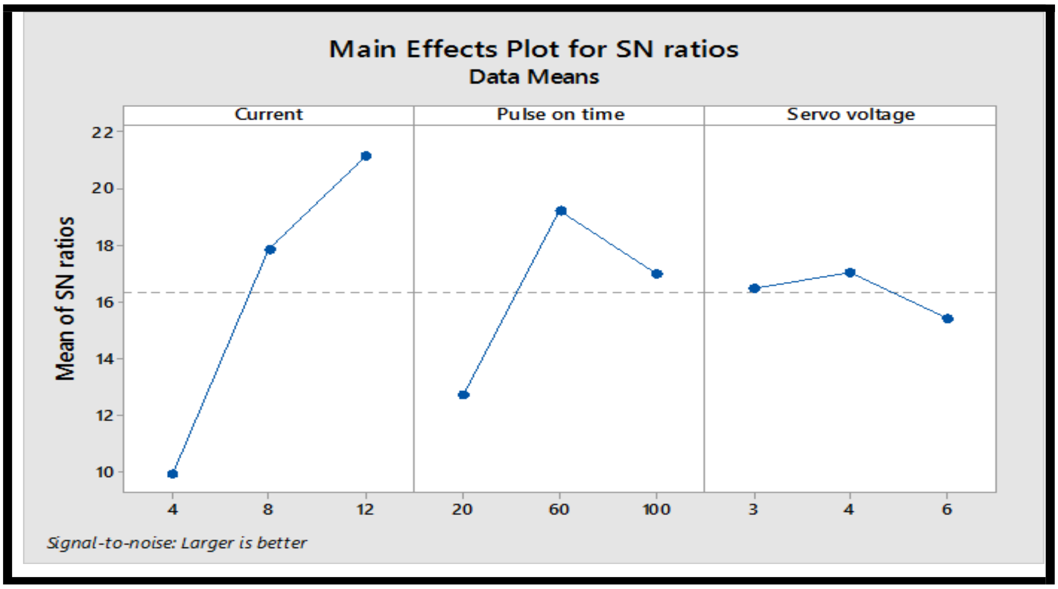

Figure 7. S/N ratios of MRR for current, pulse on time and servo voltage

Figure 8 shows the interaction plot of the S/N ratio between current and pulse on time at various levels of both parameters.

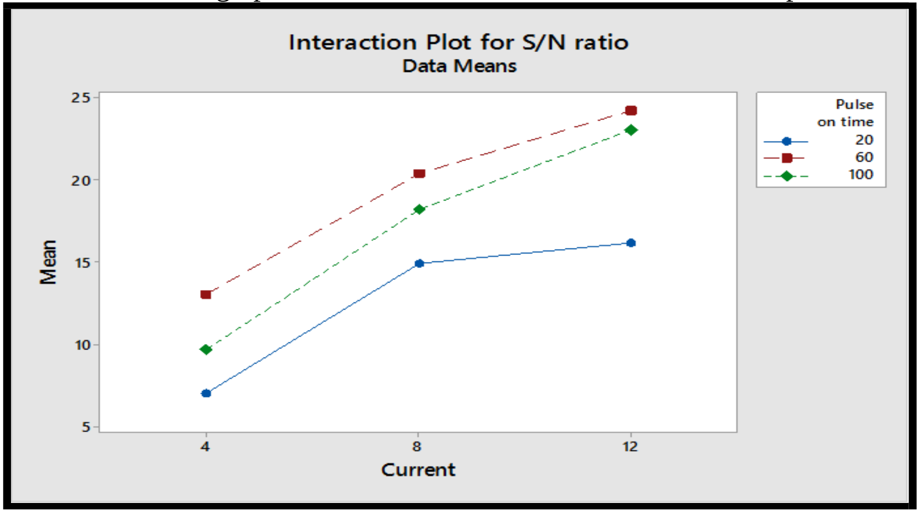

Figure 8: Interaction graph of S/N ratio of MRR between current and pulse on time

3.2 Full Factorial Design: After removing redundant data

In the present work, after removing the redundant data, a systematic approach was adopted with three independent parameters: current (I), pulse on time (T_{on}) and servo voltage (V). These parameters were tested at three levels each and a full factorial experimental design was used to generate the experimental runs. This design allows for the evaluation of the combined effects of all three parameters on the dependent response variable, the Material Removal Rate (MRR). The S/N ratio was also calculated as part of the analysis to evaluate the signal-to-noise ratio for MRR. The data for the individual experimental runs, including the values for current, pulse on time, servo voltage, MRR and the corresponding S/N ratios, are summarized in **Table 9**. This table provides the results for each of the 27 experimental runs, offering insight into the effects of varying the machining parameters on the material removal rate. The experimental runs include different combinations of the three parameters, with the response variable (MRR) and its S/N ratio recorded for each set of conditions. **Table 8** shows Analysis of variance on MRR versus I, T_{on} and V.

Table 8. ANOVA for MRR with Respect to I, T_{on} and V

Source	DOF	Adj. SS	Adj. MS	Seq. SS	F-value	P-value	Percentage Contribution
I	2	408.92	204.46	408.92	59.14	0.00	62.05%
T_{on}	2	173.68	86.84	173.68	25.12	0.00	26.39%
V	2	7.17	3.58	7.17	1.04	0.373	1.09%
Error	20	69.15	3.46	69.15	-	-	10.49%
Total	26	658.93	-	658.93	-	-	100%
	S = 1.85943 R-sq = 89.51% R-sq (adj.) = 86.36% R-sq (pred.) = 80.87%						

Table 9: Parameter and Response Data for Individual Experimental Runs: MRR and S/N Ratio

Independent Parameters				Response	
S. No.	**Current (A)**	**T_{on} (µs)**	**Servo voltage (V)**	**MRR (mm^3/min)**	**S/N ratio**
1.	4	20	3	2.25	7.04
2.	4	20	4	2.23	6.99
3.	4	20	6	1.92	5.67
4.	4	60	3	4.57	13.21
5.	4	60	4	4.50	13.07
6.	4	60	6	3.52	10.95
7.	4	100	3	3.66	11.27
8.	4	100	4	4.20	12.46
9.	4	100	6	3.04	9.66
10.	8	20	3	6.41	16.14
11.	8	20	4	5.59	14.96
12.	8	20	6	2.67	8.54
13.	8	60	3	11.77	21.41
14.	8	60	4	10.67	20.56
15.	8	60	6	11.26	21.03
16.	8	100	3	8.10	18.17
17.	8	100	4	9.44	19.50
18.	8	100	6	8.13	18.20
19.	12	20	3	9.82	19.84
20.	12	20	4	5.25	14.40
21.	12	20	6	6.42	16.16
22.	12	60	3	16.24	24.21
23.	12	60	4	18.34	25.26
24.	12	60	6	16.45	24.32
25.	12	100	3	15.31	23.69
26.	12	100	4	14.28	23.09
27.	12	100	6	13.58	22.65

The percentage contribution of each parameter to MRR is summarized as follows:

- Current (I): 62.05%
- Pulse on time (T_{on}): 26.39%
- Servo voltage (V): 1.09%
- Error: 10.49%

The R-squared value (R^2) of 89.51% indicates that the experimental model accounts for a substantial portion of the variation in MRR, confirming that the analysis captures most of the influences affecting MRR. The adjusted R-squared (R^2 (adj.)) of 86.36% and predicted R-squared (R^2 (pred)) of 80.87%

suggest that the model is robust and reliable, with minimal over fitting (**Figure 9**). After comparing both of the design approaches the interpretation between them are:

- The ANOVA results clearly demonstrate that current (I) is the most significant parameter affecting the material removal rate (MRR), with a percentage contribution of 62.05%. Pulse on time (T_{on}) also plays a substantial role, contributing 26.39% to the variation in MRR. However, servo voltage (V) has a relatively minimal impact, contributing only 1.09% to the overall variation.

- The F-value and P-value further support these findings. The current (I) parameter has the highest F-value of 59.14, indicating that it is the most influential factor. The pulse on time (T_{on}) also shows a significant effect, with an F-value of 25.12, while servo voltage (V) has the lowest F-value of 1.04, confirming its minor influence on MRR.

- The experimental analysis indicates that optimizing the current (I) and pulse on time (T_{on}) parameters will have the most significant impact on improving the material removal rate in EDM processes. Servo voltage (V), while still contributing to the process, has the least influence and may not require as much focus in optimization. The high R-squared value further validates the robustness of the experimental model and the reliability of the findings.

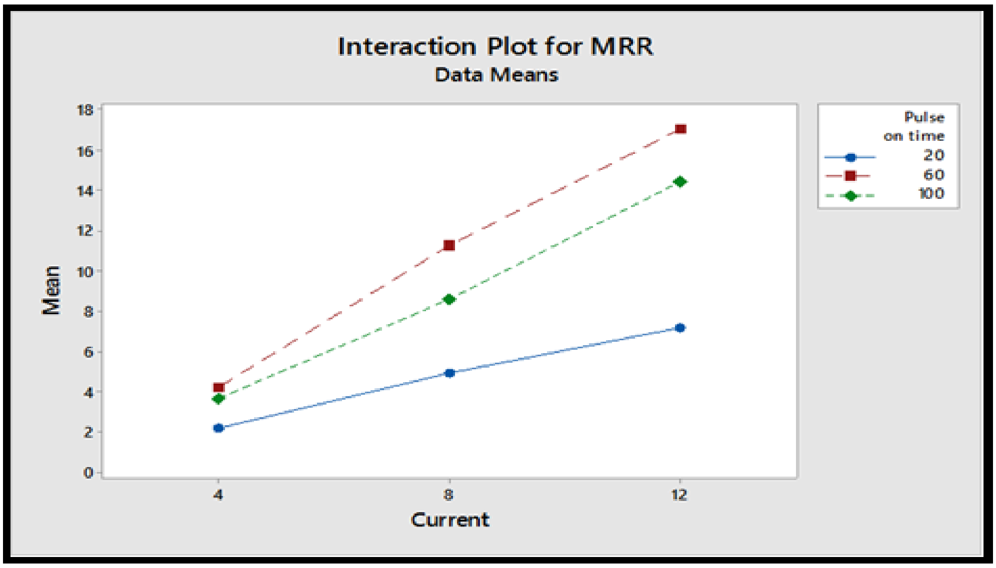

Figure 9. Interaction graph of MRR between I and T_{on}

The regression **Eqn. 8** can also be used for finding more values of MRR at different control parameters i.e. current, pulse on time and servo voltage.

$$MRR = -2.70 + 1.191\, I + 0.0516T_{on} - 0.413\, V \qquad \textbf{Eqn. 7}$$

The regression equation can predict MRR for any combination of current, pulse on time, and servo voltage within the experimental range. This aids in process optimization by identifying the optimal parameter set to maximize MRR.

Conclusion

- The experimental investigation into the Electrical Discharge Machining (EDM) of SK2MCr4 carbon tool steel, utilizing a full factorial design of experiments and Taguchi's "larger is better" approach, yielded significant insights into the factors influencing Material Removal Rate (MRR).

- Analysis of Variance (ANOVA) revealed that current is the most influential parameter, contributing a substantial 62.05% to the variation in MRR. This dominance is further supported by its high F-value of 59.14, indicating a strong statistical significance ($P < 0.001$). The rank table from the Taguchi analysis also confirms that current has the highest delta value of 9.052, emphasizing its crucial role in determining MRR.
- Pulse on time also significantly affects MRR, accounting for 26.39% of the variation. Its F-value of 25.12 demonstrates its considerable influence, though less than that of current. The Taguchi analysis further supports this by showing that pulse on time had the second highest delta value of 5.640, reinforcing its importance in optimizing the EDM process.
- Servo voltage exhibited the least impact on MRR, contributing only 1.09% to the variation. It's low F-value of 1.04 and high P-value of 0.373 suggests its limited statistical significance. The Taguchi analysis confirmed this, showing that servo voltage had the lowest delta value of 2.228, indicating that adjustments to this parameter have minimal effect on MRR.
- The high R-squared (R^2) value of 89.51% and adjusted R-squared (R^2 (adj.)) of 86.36% confirm the robustness and reliability of the experimental model. Additionally, the predicted R-squared (R^2 (pred.)) of 80.87% further strengthens the model's predictive capability, ensuring its accuracy in estimating MRR outcomes.
- The regression equation, $MRR = -2.70 + 1.191\ I + 0.0516\ T_{on} - 0.413\ V$, provides a quantitative tool for predicting MRR based on specific parameter combinations. This equation serves as a valuable resource for optimizing machining parameters to achieve higher material removal rates.
- The experimental data, as shown in Table 8, demonstrates that the highest MRR values were obtained when the current was at its highest level (12 Amps) and the pulse on time was also at the higher levels (60 and 100 microseconds). This trend reinforces the conclusion that current and pulses on time are the key parameters influencing MRR.

The data conclusively demonstrates that current is the primary driver of MRR in the EDM process under the studied conditions, followed by pulse on time. Servo voltage, while still a factor, has a comparatively negligible effect. Therefore, optimizing EDM operations for enhanced MRR should prioritize adjustments to current and pulse on time. The high R-squared values validate the experimental model's accuracy and the regression equation provides a valuable tool for predicting MRR, supporting process optimization efforts.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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