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Optimization of Multi-Performance Parameters in EDM through Grey Relational Analysis using Deionized Water

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Abstract

This study includes an experimental study of the effect of input process parameters on output parameters during the EDM of C-20 mild steel. Deionized water is being investigated as a sustainable alternative to Electrical Discharge Machining (EDM) oil, reducing toxic emissions and enhancing process sustainability. ANOVA results revealed that current and voltage had the largest impact on MRR, while TON significantly affected TWR and TON had the greatest influence on surface roughness. The study found that increasing the current and voltage resulted in significant increases in MRR (164.78% and 99.49%, respectively) and TWR (21.19% and 26.02%, respectively). However, an improve in TON led to a decrease in TWR (by 66.7%) but an increase in MRR (by 59.57%). Increased current, voltage, and TON result in a 74.34%, 72.14%, and 108.15% improvement in surface roughness, respectively. The Grey relational analyses were used for best optimum result which comes on parameters current 12 amps, voltage 20 volts and TON 200 µs.

Keywords: EDM, GRA, MRR, Optimization, Surface Roughness

1.0 Introduction

EDM is adaptable and precise machining process that can be used to fabricate intricate geometries and features in a wide range of materials, such as metals, alloys, and composites. Its applications are diverse and it is a valuable tool for many manufacturing industries like aerospace, medical, and automotive industries that require tight tolerances and intricate shapes[1]. Electrical sparks are used in the unconventional machining technique known as EDM to degrade the substance of the workpiece. EDM machining, also known as spark erosion, is a non-traditional machining process that uses a series of electrical discharges or sparks to remove material from a workpiece[2]. The process begins with a tool, known as an electrode, being brought into close proximity to the workpiece, which is immersed in a dielectric fluid, usually deionized water. When a high voltage electrical pulse is applied to the electrode, an electrical discharge occurs, ionizing the dielectric fluid and creating a spark that erodes the workpiece material at high temperature 8,000-12,000°C[3]. Figure 1 depicts the creation of plasma during the machining process. This process is repeated millions of times per second, creating a series of craters or pits on the workpiece surface, until the desired shape or feature is achieved. The dielectric fluid serves to cool the machining zone, flush away the eroded material, and prevent arcing between the electrode and workpiece. EDM machining is a precise method that can create complex shapes on various materials, including hardened steels, titanium,

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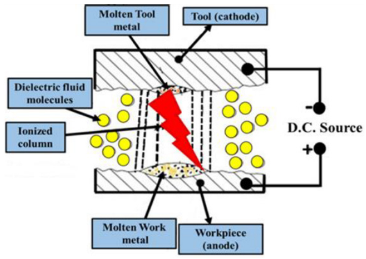

Figure 1. Plasma generation during EDM process.

and ceramics. C-20 mild steel is a popular engineering material due to its low cost, excellent machinability, and weldability. C-20 Mild Steel machined by EDM is the production of precision components for the automotive industry such as engine blocks, transmission gears, and valve seats, etc. It also used in production of molds and dies for plastic injection moulding[4].

Dielectric is important in machining, and hydrocarbon oil is commonly used for this purpose. In addition to hydrocarbon oil, treated water is employed as a dielectric fluid in EDM[5]. Jeswani EDM utilised distilled water for the first time[6]. Kumar *et al.*[7] studied the impact of control variables on performance indicators such as MRR, TWR, and surface roughness during machining using deionized water. The combination of EDM and was utilised to machine Ti-6Al4V using kerosene and distilled water[8]. To decrease the emissions produced by hydrocarbon oil, water was used as the dielectric instead of hydrocarbon oil[9]. As a dielectric, tap water, DI water, and mixtures of tap and DI water are all used. When compared to hydrocarbon oil, it was found that a blends of tap and deionized water displayed favourable MRR and TWR. Deionized water is commonly used as a dielectric in EDM because it has high electrical resistance, making it an effective insulator to prevent electrical arcing and short circuits between the workpiece and electrode. Moreover, DI water is preferred as a dielectric fluid because it is free from impurities such as minerals and salts, which can cause chemical reactions, corrosion, and affect the surface finish of the machined part[10]. The high purity of deionized water also ensures that it does not leave any residue or contaminants on the machined surface, which is crucial for precision machining applications. The using deionized water is its low cost and availability. It is a common industrial chemical that can be easily obtained and recycled for reuse, reducing the overall cost of machining operations[11].

Tang and Du[12] utilized GRA to enhance MRR, TWR, and SR. The optimization led to an increase in MRR from 1.28 to 2.38 mm^3min^{-1}. However, the optimization also resulted in a decrease in EWR from 0.14 to 0.10 mm^3min^{-1} and a decrease in SR from 2.37 to 1.93µm. Optimization with multiple objectives was utilized to enhance the process variables for Ti6Al-4V electro-discharge machining in tap water, resulting in a 2% rise in MRR and a 59% reduction in TWR, with a corresponding 4% decrease in SR. The ideal parameter values yielded an MRR of 6.02 mm^3/min, TWR of 0.17 mm^3/min, and SR of 2.07 micron, up from 5.90 mm^3/min, 0.41 mm^3/min, and 2.15 micron, respectively.

Jagadish and Ray[13] enhanced process parameters, including maximum current, Ton, dielectric level, and flushing pressure, using various techniques to develop a green EDM. The optimal values for Ton, peak current, flushing pressure, and dielectric level were determined to be 261 µs, 4.5 A, 0.3 kg/cm^2, and 80 mm, respectively. These values reduced the machining time, relative TWR, process energy, aerosol concentration, and dielectric usage. Zan *et al.*[14] studies that low-porosity graphite electrodes reduce tool wear in water-based dielectrics. Impregnated graphite weakens electrolysis during machining. Electrolysis thins the electrode, making the bottom margin susceptible to discharge damage. Carbon deposition minimizes tool wear in machining. Guo *et al.*[15] studied the effectiveness of ED machining and dielectric fluid conductivity. Gas bubbles created during milling greatly aided in removal material from the workpiece. The crater that developed on the Ti surface was less in diameter than the crater that developed on the surface of the steel. Ti alloy was green ED milled by Kou and Han[16] using a moving arc method and a water-based dielectric. Comparing the MRR obtained to the traditional EDM, it was five times greater. For this dielectric medium, Muthuramalingam[17] combined tap and deionized water to manufacture Titanium. It was discovered that the MRR is determined by the dielectric medium's electric conductivity. Erden and Temel[18] compared control parameters' effects on performance measures (MRR, TWR, and SR) during machining. The measures showed lower desirable values than hydrocarbon oil. They also compared MRR and EWR after EDM machining using kerosene and distilled water. The results revealed that distilled water had higher MRR and lower EWR, which is favourable. Lin *et al.*[19] performs ED machined Ti-6Al4V with a Cu tool using distilled water resulted in higher MRR but lower TWR and SR compared to kerosene. Additionally, there was no carbon build-up on the work surface when using distilled water. Konig and Siebers[20] stated that using water-based dielectrics under critical conditions enables the application of higher power input due to their exceptional thermal stability. Consequently, these favourable circumstances contribute to a significant increase in the MRR.

Dong *et al.*[21] observed that when using DI water as the dielectric fluid, the process of EDM drilling for micro-holes on C17200 beryllium copper alloy was significantly more efficient compared to the machining effect achieved when using kerosene. Gugulothu[22] studies the effects of three dielectric fluids (DI water, drinking water, and a 25% DI water and 75% drinking water mixture) on the optimization of titanium alloy (Ti-6Al-4V) in die sinking EDM using the Taguchi method. The results emphasized the importance of drinking water, discharge current, TON, and TOFF in EDM operations. Modica *et al.*[23] found that EDMed surfaces in kerosene have reduced roughness, while E365 and E206, machined using DI water and hydrocarbon oil, respectively, reveal more surface craters among the dielectrics. Debnath *et al.*[24] investigates the replacement of hydrocarbon oil with tap water to reduce toxic emissions and promote sustainability. The impact of varying input variables on response measures is studied. Increasing current leads to rise in MRR and TWR, while higher TON results in increased MRR but decreased TWR. Both current and TON contribute to increased surface roughness. Kumar and Mandal[25] investigate the Al_2O_3 nanoparticles in deionized water enhance machining of Inconel 825 in Nano-Powder mixed EDM. They widen the tool gap, promote uniform sparking, prevent arcing, and improve MRR, surface finish, and surface integrity.

According to a literature review, C-20 mild steel have good machinability when employing EDM and deionized water to get improved performance. However, there was very limited research done on ED machining of C-20 mild steel in deionized water. This research investigates the EDM of C-20 mild steel using DI water as the dielectric. It explores the impact of varying current, voltage, and Ton on performance indicators such as MRR, TWR, and SR. The RSM methodology was employed to create the experimental designs. ANOVA is used to investigate the impact of input factors on output parameters using main effects plots. The Grey relational analyses were used for best optimum result between the 20 experiments, respectively.

2.0 Materials and Methods

2.1 Experimental Setup

In this paper, experiments are performed on an Electrical discharge machine (ZNC, 500×300, Electronica India limited), The purpose of a tank is to optimize the use of dielectric in an experiment, while a pump is used to extract the dielectric fluid. The materials used in the experiment are a C-20 mild steel workpiece and a copper electrode, and the dielectric used is deionized water. A precision analytical balance (Wensar ANI ISO 9001:2015) was used to weight the tool and workpiece. The workpiece dimensions are 40 mm x 23 mm x 6 mm, while the tool measures 12.50 mm in diameter and 130 mm in length. The experimental configuration of an EDM machine is depicted in Figure 2. In the present study different parameters such as peak current, voltage, and TON with their levels are considered as shown in Table 1. RSM was used to design 20 experiments for conventional EDM, with DI water as the dielectric medium in the first set of experiments. Investigation the impact of different parameters on the response measures is done using ANOVA. The Figure 2 depicts the image of work pieces after machining. The most effective optimal parameter is chosen using the GRA analysis.

2.2 Grey Relational Analysis (GRA)

GRA is a decision-making technique that is used to evaluate and prioritize a set of options or alternatives based on multiple criteria or factors. GRA is a variation of grey system theory, which is a mathematical framework for dealing with systems that are characterized by incomplete or uncertain information[26]. The GRA method is commonly employed to assess the strength of the relationship between sequences. A number of scholars have utilized grey relational analysis to improve the control parameters in cases involving multiple responses, using grey relational grades[27]. The GRA method is commonly employed to combine various performance measures into a single metric, which can be utilized as the sole parameter for optimization purposes.

This method involves a number of steps. The first phase was normalizing a variety of replies, which ranged from 0 to 1. The GRC co-efficient, which defines the

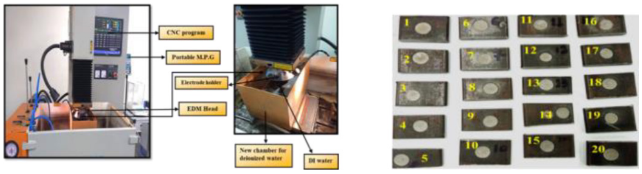

Figure 2. **(a)** Experimental setup for EDM **(b)** Images of the machined samples.

Table 1. Input variables and their levels

Variables	Level	Values
Current (A)	5	8, 12, 16, 20, 24
Voltage (V)	5	15, 20, 25, 30, 35
Pulse on time (μs)	5	100, 200, 300, 400, 500
Dielectric type	-	Deionized water

relationship between the ideal and real normalization values, is then determined using the normalized data. The average of the GRC for each experiment is then used to calculate the GRG. As a result, the single response optimization problem replaces the multi-response optimization problem[28]. The ideal parameter setting is thought to be the factor setting that results in the highest GRG. Following are the steps.

Step 1

The given equation is used to standardize the response data in order to greater is better condition of the data

$$X_i(k) = \frac{P^*_{ab} - Min\left(P^*_{ab}\right)}{Max\left(P^*_{ab}\right) - Min\left(P^*_{ab}\right)} \tag{1}$$

The following equation is used to convert the response data in order to normalize the smaller is better condition.

$$X^*_{qr} = \frac{Max(P^*_{ab}) - P^*_{ab}}{Max\left(P^*_{ab}\right) - Min\left(P^*_{ab}\right)} \tag{2}$$

where, stands for the response parameters, for the largest value, for the lowest value, a for the outcome variables, and b the quantity of experiment runs.

Step 2

The subsequent equation identifies the maximum values obtained from the standardized responses of multiple non-experimental trials

$$PS = Max\left(X^*_{qr}\right) \tag{3}$$

Step 3

The difference between each normalized value and the S value of the reference sequence is provided by.

$$\Delta^*_{qr} = \left|\left(X^*_{qr} - PS\right)\right| \tag{4}$$

where, PS is the predicted sequence, i is the compatibility sequence value, and is the difference between them.

Step 4

For each number of normalized responses, the GRC (ξ^*) is calculated using the equation below.

$$\xi^*_{qr} = \frac{Min\left(\Delta^*_{qr}\right) - \zeta Max\left(\Delta^*_{qr}\right)}{\Delta^*_{qr} - \zeta Max\left(\Delta^*_{qr}\right)} \tag{5}$$

where, ζ is the differentiating co-efficient, has a value between 0 and 1. It is assumed that ζ is equal to 0.5.

Step 5

Equation presented is used to calculate the GRG for each number of an experiment.

$$Y^* = \sum_{j=1}^{n} \frac{\xi^*_{qr}}{n} \tag{6}$$

where, n is the quantity of respond variable.

3.0 Results and Analysis

The results show that by using EDM with deionized water on C-20 mild steel, different levels of MRR, TWR, and surface roughness can be achieved, and these results are presented in Table 2.

3.1 Influence of Process Variables on MRR

Increasing the current, voltage, and TON between the tool and workpiece leads to an increase in MRR. This is because a higher current and voltage leads to a higher electric field strength, which in turn increases the rate of MRR. The main effect method was used to display the impact of various parameters on the MRR effect, and Figure 3 was shows MRR response to input parameters. The MRR exhibits an increment of 164.78% when the current is raised from 8 to 24 amperes. Similarly, an increase of 99.49% in MRR is observed with a voltage rise from 15 to 35 volts, while a pulse-on time extension from 100-500 µs leads to a 59.57% rise in MRR.

3.2 Influence of Process Variables on TWR

Similar to MRR, the results of the input parameters for TWR are depicted in Figure 4, and TWR grows as current increases because the electrode workpiece gap absorbs more heat energy. The volume of tool material that melts as a result increases, increasing TWR. Plasma channel expansion occurs as pulse on time increases, though. Energy density delivered to the tool gap in the workpiece decreases as a result. In turn, this results in a drop in TWR as the rate of material removal from the tool slows. The TWR increases by 21.19% and 26.02% when current increase by 8 to 24 ampere and voltage 15 to 35 volts. Furthermore, When the TON is increased from 100 to 400 µs, there is a 66.7% decrease in TWR. However, when the pulse on time is further increased to 500 µs, there is a 22.73% increase in TWR.

Table 2. Experimental outcomes of MRR, TWR, and SR

Exp. No	IP (Amp)	Voltage (volt)	T_{ON} (µs)	MRR (mg/ min)	TWR (mg/ min)	SR (µm)
1	16	25	100	4.5	4.12	3.8
2	12	30	200	4.744	2.75	6.534
3	12	30	400	5.27	2.1	7.68
4	20	30	200	6.96	3.89	5.012
5	16	35	300	7.96	3.433	7.92
6	16	15	300	3.99	2.724	4.6
7	24	25	300	10.3	3.056	8.02
8	16	25	300	4.95	2.48	5.322
9	16	25	300	4.25	2.267	6.4
10	16	25	300	4.75	2.896	8.21
11	12	20	200	4.16	2.56	4.12
12	20	20	400	4.986	2.143	7.042
13	16	25	500	7.181	3.142	7.91
14	20	30	400	8.73	3.2	8.48
15	16	25	300	7.89	2.435	7.42
16	20	20	200	5.99	2.98	7.22
17	12	20	400	6.89	2.878	6.58
18	8	25	300	3.89	2.522	4.6
19	16	25	300	5.96	2.672	6.8
20	16	25	300	5.26	2.317	7.94

3.3 Influence of Process Variables on Surface Roughness

The machining parameters and surface roughness was obtained the higher the current, voltage, and TON, the rougher the surface is created. Surface roughness exhibits an increment of 74.34% when the current is raised from 8 to 24 amperes. Similarly, an increase on 72.17% in SR is observed with a voltage rise from 15 to 35 volts, while a TON extension from 100-500µs leads to a 108.15% rise in SR. The Figure 5 depicts the influence of method variables on TON.

4.0 ANOVA Analysis

The impact of variable parameters on the response measures is examined using an ANOVA. ANOVA can be used to determine the relative impact or influence of each

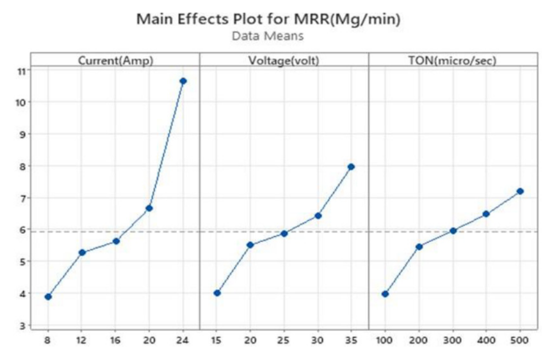

Figure 3. MRR response to input parameters.

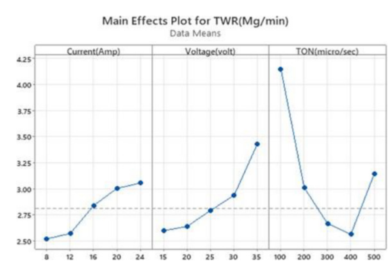

Figure 4. TWR response to input parameters.

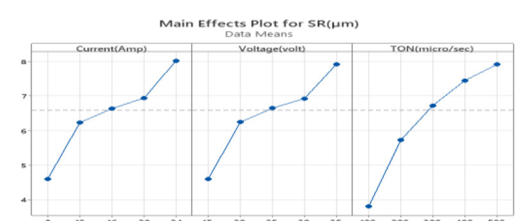

Figure 5. SR response to input parameters.

parameter on the output parameters by calculating their respective percentage contributions. The analysis of the ANOVA is shown in Tables 3-5. According to the ANOVA, the most important factors for MRR are current (31.08%) followed by voltage (25.86%). Pulse on time (87.52%) is the factor that has the greatest influence on TWR. While pulse on time (61.50%) is the largest contributing factor for surface roughness. The inaccuracies observed in the MRR, TWR, and SR measurements (which were 43.06%, 12.48%, and 38.50% respectively) were relatively small compared to the significance of the process parameters that were being studied. This suggests that the impact of the process parameter interaction on these measurements is minimal.

4.1 Implementation of GRA

The raw dataset was normalized and standardized using Taguchi's GRA method. The MRR is "larger the better" calculated with the help of equation 1. The TWR and Surface Roughness (SR) "lower the better" sort in this study. Equation 2 is applied to normalize the responses. The deviation from the ideal value represents the fluctuation between the greatest and lowest values in a collection of replies, or the sequence of variations from the expected value. After obtaining the GRC value using Eq. 5, the GRG is computed for each experiment number, and the results are presented in Table 6. According to the earlier discussion, the ideal parametric configuration is represented by the GRG's maximum value. The optimal values were determined at current 12 amps, voltage 20 volts and Ton 200 µs. It has been determined that experiment number 11 reflects the highest value of GRG. Table 7 displays the average GRG value for each machining parameter.

5.0 Conclusion

EDM was used to modify C20 mild steel by adjusting input parameters including current, voltage, and T_{ON} time. The resulting MRR, TWR and surface roughness

Table 3. Analysis of response variance -MRR (mg/min)

Source	DF	SS	MS	Var Comp.	F-Value	P-Value	%of Total	St Dev
Current (Amp)	4	31.0475	7.7619	1.214	3.26	0.041	31.08	1.102
Voltage (Volt)	4	13.9382	3.4845	1.010	0.72	0.594	25.86	1.005
T_{ON} (µs)	6	9.6930	1.6155	-0.055	0.39	0.813	0.00	0.000
Error	5	8.4082	1.6816	1.682	-	-	43.06	1.297
Total	19	63.0868	-	3.905	-	-	-	1.976

Table 4. Analysis of response variance-TWR (mg/min)

Source	DF	SS	MS	Var Comp.	F-Value	P-Value	%of Total	St Dev
Current (Amp)	4	0.5352	0.1338	-0.068	0.47	0.758	0.00	0.000
Voltage (Volt)	4	1.2558	0.3139	-0.111	0.48	0.749	0.00	0.000
T_{ON} (µs)	6	3.1611	0.5269	0.390	2.91	0.058	87.52	0.624
Error	5	0.2781	0.0556	0.056	-	-	12.48	0.236
Total	19	5.2301	-	0.446	-	-	-	0.668

Table 5. Analysis of response variance-SR (µm)

Source	DF	SS	MS	Var Comp.	F-Value	P-Value	%of Total	St Dev
Current(Amp)	4	7.0295	1.7574	-0.216	0.75	0.571	0.00	0.000
Voltage(Volt)	4	9.0928	2.2732	-0.568	0.71	0.597	0.00	0.000
T_{ON} (µs)	6	20.1774	3.3629	1.833	2.22	0.115	61.50	1.354
Error	5	5.7384	1.1477	1.148	-	-	38.50	1.071
Total	19	42.0381	-	2.981	-	-	-	1.727

were measured and found to be impacted by changes in these input parameters.

- The study found varying values for MRR, TWR, and SR, ranging from 3.89 to 10.3 mg/min for MRR, 2.1 to 4.12 mg/min for TWR, and 3.8 to 8.21 µm for SR.
- Due to the higher thermal energy delivered between the tool electrode gap and the increased current and voltage, MRR and TWR both rise.
- By giving the workpiece surface with additional electrical energy, lengthening the T_{ON} can increase the MRR. However, it can also lead to a lower energy density in the electrode and workpiece gap due to the enlargement of the plasma channel, thereby reducing the material exclusion from the tool and resulting in a decrease in TWR.
- Increasing the current and voltage leads to higher MRR and TWR by 164.78% and 21.19% and 99.49% and 26.02% respectively. However, increasing pulse-on time results in a higher MRR by 59.57% but a lower TWR by 66.7%. Increasing all three parameters improves surface roughness by 74.34%, 72.14%, and 108.15%.
- ANOVA analysis revealed that current and voltage had the greatest impact on MRR, accounting for 31.08%

Table 6. Grey relational coefficient and grade

S. No.	Normalization			Deviation sequence			Grey relation coefficient			Grade	Rank
	MRR (mg/min)	TWR (mg/min)	SR (µm)	MRR (mg)	TWR (mg/min)	SR (µm)	MRR (mg)	TWR (mg/min)	SR (µm)		
1.	0.0952	0.0000	1.0000	0.9048	1.0000	0.0000	0.3559	0.3333	1.0000	0.5631	9
2.	0.1332	0.6782	0.4158	0.8668	0.3218	0.5842	0.3658	0.6084	0.4612	0.4785	16
3.	0.2153	1.0000	0.1709	0.7847	0.0000	0.8291	0.3892	1.0000	0.3762	0.5885	4
4.	0.4789	0.1139	0.7410	0.5211	0.8861	0.2590	0.4897	0.3607	0.6588	0.5031	12
5.	0.6349	0.3401	0.1197	0.3651	0.6599	0.8803	0.5780	0.4311	0.3622	0.4571	17
6.	0.0156	0.6911	0.8291	0.9844	0.3089	0.1709	0.3368	0.6181	0.7452	0.5667	8
7.	1.0000	0.5267	0.0983	0.0000	0.4733	0.9017	1.0000	0.5137	0.3567	0.6235	2
8.	0.1654	0.8119	0.6748	0.8346	0.1881	0.3252	0.3746	0.7266	0.6059	0.5691	7
9.	0.0562	0.9173	0.4444	0.9438	0.0827	0.5556	0.3463	0.8581	0.4737	0.5594	10
10.	0.1342	0.6059	0.0577	0.8658	0.3941	0.9423	0.3661	0.5592	0.3467	0.4240	20
11.	**0.0421**	**0.7723**	**0.9316**	**0.9579**	**0.2277**	**0.0684**	**0.3430**	**0.6871**	**0.8797**	**0.6366**	**1**
12.	0.1710	0.9787	0.3073	0.8290	0.0213	0.6927	0.3762	0.9592	0.4192	0.5849	5
13.	0.5134	0.4842	0.1218	0.4866	0.5158	0.8782	0.5068	0.4922	0.3628	0.4539	19
14.	0.7551	0.4554	0.0000	0.2449	0.5446	1.0000	0.6712	0.4787	0.3333	0.4944	15
15..	0.6240	0.8342	0.2265	0.3760	0.1658	0.7735	0.5708	0.7509	0.3926	0.5714	6
16..	0.3276	0.5644	0.2692	0.6724	0.4356	0.7308	0.4265	0.5344	0.4063	0.4557	18
17.	0.4680	0.6149	0.4060	0.5320	0.3851	0.5940	0.4845	0.5649	0.4570	0.5021	13
18.	0.0000	0.7911	0.8291	1.0000	0.2089	0.1709	0.3333	0.7053	0.7452	0.5946	3
19.	0.3229	0.7168	0.3590	0.6771	0.2832	0.6410	0.4248	0.6384	0.4382	0.5005	14
20.	0.2137	0.8926	0.1154	0.7863	0.1074	0.8846	0.3887	0.8231	0.3611	0.5243	11

Table 7. Response table for GRG

Machining Parameters	Level 1	Level 2	Level 3	Level 4	Level 5	Max-Min	Grade
Current	0.5946	0.5514	0.5189	0.3956	0.6235	0.2279	1
Voltage	0.5667	0.5448	0.5384	0.5161	0.4571	0.1096	2
T_{ON}	0.5631	0.5185	0.5391	0.5425	0.4539	0.1092	3

and 25.86% of the variance, respectively. T_{ON} was found to affect TWR, explaining 87.52% of the variation. Surface roughness was most significantly influenced by T_{ON} , explaining 61.50% of the variation.

- The Grey Relational Analyses (GRA) were used for best optimum result which comes on parameters current 12 amps, voltage 20 volts and T_{ON} 200μs at experiment number11.

EDM has the potential to produce complex shapes with more precision and accuracy, even on difficult-to- machine materials like hardened steel. Using DI water as a dielectric fluid in EDM can improve machining effectiveness, achieve smoother surface finishes, and minimize negative environmental impact by eliminating the need for harmful fluids. This technology has the potential to revolutionize manufacturing by improving the production of intricate components with higher accuracy and surface finish, while also increasing efficiency and speed.

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