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Parameter Optimization of Electric Discharge Machining on AISI M2 High Speed Steel

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Abstract-In this investigation, electric discharge machining was carried out for the AISI M2 high speed steel. The aim of this research was to evaluate the impact of process parameters viz. gap voltage, discharge current and duty cycle on the process performance measures in the form of material removal rate, surface roughness and electrode wear. The machining was carried out according to Taguchi L27 orthogonal array followed by analysis with the help of Taguchi approach. The consequences of this study revealed that ANOVA results revealed that input parameters such as discharge current, gap voltage and duty cycle are significant parameters for each response. For surface roughness, duty cycle and gap voltage are most contributing factors. However, discharge current indicates the highest contribution for minimum tool wear followed by duty cycle. Moreover, duty cycle is the largest contributing to achieve maximum MRR followed by discharge current and gap voltage. According to Taguchi approach, the suggested best combination of the controllable input parameters for Ra, EWR and MRR are $v_3f_1a_1$, $v_1f_1a_1$ and $v_3f_3a_3$ by employing Taguchi approach Confirmatory experiments have been conducted and significant improvement is observed.

Keywords-Electric Discharge Machining, AISI M2 Steel, Taguchi Method, Process Optimization, Confirmatory Experiments.

I. INTRODUCTION

Manufacturing constitutes the economic backbone of an industrialized nation and in general, the economic position of a country is based on the level of manufacturing activity. Merchant (1960) emphasized the need for the newer concepts in metal machining [1]. From the 1960s onwards, non-traditional machining processes like electrical discharge machining (EDM), laser machining, and ultrasonic machining gained prominence. These methods expanded the possibilities for machining materials that were difficult to machine conventionally [2].

Electric Discharge Machining (EDM), stemming from Joseph Priestley's 1770 discovery of electrical discharge erosive effects, evolved significantly over time. Early attempts in the 1930s involved high electrical currents causing intermittent arc discharges, but overheating limited progress. During world war-II, Russian scientists Lazarenko harnessed controlled sparking, laying groundwork for controlled material machining. The 1950s saw the introduction of the R-C circuit, enhancing process reliability. Concurrently, Americans explored similar methods. In the 1980s, CNC integration revolutionized EDM. It's a non-contact, precise process submerged in dielectric fluid, ideal for intricate shapes and various conductive materials like dies and molds. Traditional machining pales in comparison due to EDM's precision and versatility, crucial in modern manufacturing for economic production and high-quality output [3,4]. The EDM process removes material from the work piece surface through rapid, repeated spark discharges between the tool electrode and the work piece, driven by an electric potential and controlled by a servo system to maintain a tiny spark gap of about 0.025mm. Both electrodes are immersed in a dielectric fluid, typically EDM oil, kerosene, or deionized water, creating a vacuum environment. While liquid dielectrics like these are commonly used for smooth machining, occasionally gaseous dielectric fluids find application [5-7]. EDM finds diverse applications, crafting intricate profiles, molds, and dies in hard materials, extensively utilized in aerospace for exotic materials, automotive for part finishing, and in surgical components due to its non-contact nature ideal for delicate pieces. Notably popular in die and mold making, it suits limited-run parts despite longer machining times. Its advantages lie in cutting conductive materials without heat treatment, enabling complex profile programming via X, Y, and Z axes movements, achieving accurate and faster mold sections with lower costs. Automation allows unattended operation, but limitations exist: only electrically conductive materials are machinable, barring insulators except diamond and certain semiconductors. Predicting gap dimensions, tool wear affecting geometry, low material removal rate, and process dependency on tool-workpiece material pairing are critical constraints in EDM. Several factors significantly impact the EDM (Electrical Discharge Machining) process. Material conductivity plays a pivotal role, as only electrically conductive materials can be machined efficiently, except for some exceptions like diamond and specific semiconductors [8]. Electrode and workpiece materials, along with their combination, dictate the electrical parameters influencing machining effectiveness. The gap between the electrodes and the dielectric fluid used are critical; a smaller gap enhances accuracy but can lead to instability. Additionally, tool wear affects precision, and intricate geometries pose challenges in predicting gap dimensions, impacting achievable accuracy[9]. Factors like flushing conditions, power settings, and environmental temperature can also influence the process stability and machining performance [10].

Certainly, these studies delve into diverse aspects of material behavior and processing methods related to steel and coatings, providing valuable insights into their properties and performance in various applications. Erden et al. [11] Investigated impurities in dielectric liquids used in EDM processes highlights the importance of understanding how contaminants can affect EDM performance. This sheds light on improving breakdown characteristics and addressing natural liquid contamination for enhanced EDM efficiency. Rocha et al. [12] Analyzed the effects of plasma nitriding parameters on M2 tool steel helps comprehend structural changes in the compound layer and diffusion zone. The study's methodology, varying temperatures and gas atmospheres, provides insights into understanding the material's characteristics under different conditions. Dydra and Sayer [13] developed a robust scratch tester for evaluating PVD Titanium Nitride coatings on M2 tool steel offers a practical approach for industrial testing. Correlating critical load with coating failure and elucidating factors influencing the ploughing and adhesion forces strengthens the understanding of coating behavior.Akbari et al. [14] Studied the nitriding behavior of AISI M2 steel samples with different heat treatments reveals insights into microstructural changes and hardness variations in the nitride layer. The use of various characterization techniques like XRD, microscopy, and micro-hardness testing aids in understanding the material's response to plasma nitriding.Alves et al. [15] Investigated the corrosion behavior of M2 high-speed steel under different heat-treatment conditions provides critical information about its resistance in Potassium Chloride solutions. Linking corrosion properties with microstructural analyses through XRD, EDX, and SEM offers a comprehensive understanding of how different treatments impact corrosion resistance.Each study contributes valuable data and insights relevant to material behavior, processing techniques, and performance evaluation, benefiting industries relying on these materials for various applications, from EDM efficiency improvements to corrosion resistance enhancements.

AISI M2, a high-speed tool steel, boasts exceptional wear resistance, toughness, and the ability to maintain sharp cutting edges[16,17]. Heat-treatable to a Rockwell C hardness of 62-65, it excels in maintaining its edge integrity crucial for cutting tools. Its standout wear resistance ensures prolonged high-speed use without compromising cutting efficiency, resulting in longer tool life and cost savings. With good toughness, it withstands impact and shock loading without chipping [18]. Notably, its high red hardness retains cutting capability even at elevated temperatures, vital for high-speed operations. Additionally, it offers heat resistance, preventing premature tool failure in high-temperature applications. Despite its hardness, M2 steel is machinable, enabling efficient production of intricate tool shapes. Overall, AISI M2 steel's blend of hardness, wear resistance, toughness, and high-temperature performance enhances tool life, precision, and efficiency across various industries [19,20].

The Taguchi method, developed by Dr. Genichi Taguchi, is a statistical approach aimed at improving the quality and performance of products and processes while minimizing variability and cost. It focuses on optimizing product or process design by systematically identifying and controlling sources of variation that affect quality. In essence, the Taguchi method aims to improve quality by optimizing designs and processes to be more robust against variations, leading to higher performance, reliability, and cost-effectiveness [21,22].

In this investigation, electric discharge machining was carried out for the AISI M2 steel. The aim of this research was to evaluate the impact of process parameters viz. gap voltage, discharge current and duty cycle on the process performance measures in the form of material removal rate, surface roughness and electrode wear. The machining was carried out according to Taguchi L27 orthogonal array followed by analysis with the help of Taguchi approach.

II. MATERIALS AND METHODS

1. Materials

M2 tool steel is selected for the present experimental research as work piece material with size ϕ 100 × 4 mm is used for electric discharge machining. This material is a very laborious due to its hardness and difficult to cut by conventional machining methods because of its toughness, high abrasion, high corrosion resistance and its compressive strength [23]. This grade of steel is commonly used in applications where high-speed cutting tools are required, such as milling cutters, drills, reamers, and broaches. It is also used in metal-forming tools like punches and dies [24]. The alloying elements in M2 steel, such as tungsten, molybdenum, and vanadium, contribute to its exceptional performance properties. the chemical composition of this steel by weight percentage is shown in Table 1

Table 1 Chemical composition of M2 tool steel (wt. %)

Elements	C	Cr	W	Mo	Va
Wt%	0.87	4.2	5.50	4.9	1.95
Elements	Ma	Si	S	P	Fe
Wt%	0.23	0.32	0.31	0.30	balance

The tool electrodes material selected for the present experimental investigations are conventional copper (Cu) [25].

2. Experimentation

The machining was performed at Central Institute of Hand Tools, Jalandhar City, Punjab, India. An Agie-Charmilles FORM 300 (die-sinking type) Electric Discharge Machine was used and the setup is shown in Figure1. As a dielectric fluid, commercial grade EDM oil with a specific gravity of 0.763 and a freezing point of 94°C was employed. The present investigation is to find the optimal parameter setting for minimizing the surface roughness, electrode wear and maximizing the material removal rate[26]. For this purpose, discharge current, gap voltage and duty cycle were elected as input parameters. Table2 shows the variable input parameters with their corresponding symbols and ranges.

Figure1 EDM used during machining of AMMCs

Table 2 Levels of Machining parameters

Factor	Symbol	Level-I	Level-II	Level-III
A	A	5	7	9
V	V	35	50	65
DC	DC	50	65	80

Apart from variable controllable input parameters, constant parameters are sparkinggap of 0.02 mm, depth of cut of 0.50 mm, EDM Oil as dielectric fluid, with square wave form of current

The test samples were machined with the help of EDM process with an aim to explore the machining performance of composites in form of surface roughness (Ra), Electrode Wear Rate (EWR) and Material Removal Rate (MRR). Many EDM researchers are aware of the Material Removal Mechanism (MRM), which Roethel et al. [27] described as the process of changing material elements between the workpiece and electrode. The transformation is transported in a solid, liquid, or gaseous state before reacting in a solid, liquid, or gaseous phase to produce an alloy with the contacting surface.The material MRR is expressed as the ratio of the difference of weight of the workpiece before and after machining to the machining time and density of the material as expressed in Equation 1.

$$MRR = (W_{jb} - W_{ja})/(t^*\rho) \qquad (1)$$

Whereas

W_{jb} = Weight of workpiece before machining.

W_{ja} = Weight of workpiece after machining.

t = Machining time =Five minutes.

ρ = Density of particular AISI M2

Table 3 Experimental layout and observations

Exp. No.	A	V	DC	Ra (µm)	EWR (mg/min)	MRR (mg/min)
1	5	35	50	2.47	0.022	0.162720
2	5	35	65	2.63	0.023	0.236275
3	5	35	80	2.90	0.025	0.312820
4	5	50	50	2.67	0.021	0.279555
5	5	50	65	2.96	0.024	0.367110
6	5	50	80	3.57	0.023	0.493385
7	5	65	50	2.88	0.021	0.294440
8	5	65	65	3.32	0.023	0.372510
9	5	65	80	3.35	0.029	0.686885
10	7	35	50	1.69	0.021	0.354620
11	7	35	65	2.67	0.028	0.431720
12	7	35	80	2.25	0.031	0.505330
13	7	50	50	2.41	0.030	0.259660
14	7	50	65	2.55	0.031	0.436750
15	7	50	80	3.16	0.033	0.508830
16	7	65	50	2.55	0.032	0.338750
17	7	65	65	2.74	0.031	0.560550
18	7	65	80	3.45	0.027	0.801250
19	9	35	50	1.45	0.025	0.466650
20	9	35	65	2.49	0.033	0.455110
21	9	35	80	2.35	0.039	0.516250
22	9	50	50	2.18	0.037	0.402350
23	9	50	65	2.25	0.036	0.448150
24	9	50	80	2.39	0.039	0.857450
25	9	65	50	2.55	0.035	0.458150
26	9	65	65	2.45	0.037	0.491950
27	9	65	80	3.45	0.039	0.898883

Tool wear is a significant factor since it has an impact on the resulting form and dimensional accuracy. Tool wear is influenced by the materials' melting points. Tool wear is affected by the carbon that builds up on the electrode surface during sparking from the hydrocarbon dielectric. The electrode edge quickly wore out because carbon didn't precipitate in hard-to-reach areas of the electrode [28]. EWR is defined as the ratio of the weight difference between the electrode before and after machining to the amount of machining time as explained in Equation 2.

$$EWR = (W_{eb} - W_{ea})/t \quad (2)$$

Where

W_{eb} = Weight of the tool before machining.
W_{ea} = Weight of the tool after machining.
t = Machining time (In this experiment the machining time is five minutes).

Mitutoyo surface roughness tester was used to measure the Ra of machined surface. The Figure 2 shows the surface roughness tester. Three reading for each machined surface were recorded and their average was taken for analysis purpose.

3. Analysis

In this investigation, the Taguchi Method is used to optimize each response for the electric discharge machining of M2 high speed steel. analysis was carried out to evaluate the influence of input parameters on the machining behaviour and to optimize the electric discharge machining process for AISI M2 HSS.

III. RESULTS AND DISCUSSION

1. Analysis of Variance

Table 4 presents the result of Analysis of Variance (ANOVA) conducted on different response variables: surface roughness, electrode wear rate (EWR), and material removal rate (MRR). ANOVA helps assess the significance of various input parameters (such as Discharge Current, Gap Voltage, and Duty Cycle) on these response variables in an Electrical Discharge Machining (EDM) process. Each input parameter's significance is assessed based on their respective p-values ($P < 0.05$ indicates significance at a 95% confidence level). The columns present the Degrees of Freedom (DF), Sequential Sum of Squares (Seq SS), Adjusted Sum of Squares (Adj SS), Adjusted Mean Squares (Adj MS), F-value, P-value, and the percentage contribution of each factor.

From results it is evident that Discharge Current (A), Gap Voltage (V), and Duty Cycle (%) all show significant effects on surface roughness. Also, Discharge Current demonstrates significant influence on EWR, while Gap Voltage and Duty Cycle also show significance but to a lesser extent. For MRR, Discharge Current, Gap Voltage, and Duty Cycle significantly impact MRR.

Table 4 Analysis of Variance for surface roughness

Surface Roughness							
Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Cont.
A	2	18.3178	18.3178	9.1589	9.16	0.009	22.12%
V	2	22.9622	22.9622	11.4811	11.48	0.004	27.73%
DC	2	23.2926	23.2926	11.6463	11.64	0.004	28.13%
DC * V	4	2.3588	2.3588	0.5897	0.59	0.68	2.85%
A * DC	4	0.7834	0.7834	0.1958	0.2	0.934	0.95%
V*DC	4	7.0829	7.0829	1.7707	1.77	0.228	8.55%
Error	8	8.0026	8.0026	1.0003			9.66%
Total	26	82.8002					
Electrode wear rate							
A	2	57.9697	57.9697	28.9849	31.83	0	66.41%
V	2	4.7859	4.7859	2.393	2.63	0.133	5.48%
DC	2	9.0569	9.0569	4.5284	4.97	0.039	10.38%
DC * V	4	2.972	2.972	0.743	0.82	0.549	3.40%
A * DC	4	0.7778	0.7778	0.1944	0.21	0.924	0.89%
V*DC	4	4.4428	4.4428	1.1107	1.22	0.375	5.09%
Error	8	7.2856	7.2856	0.9107			8.35%
Total	26	87.2907					
Material removal rate							
A	2	79.672	79.672	39.836	42.07	0	26.61%
V	2	40.967	40.967	20.4837	21.63	0.001	13.68%
DC	2	127.583	127.583	63.7915	67.36	0	42.62%
DC * V	4	23.098	23.098	5.7744	6.1	0.015	7.72%
A * DC	4	8.496	8.496	2.1239	2.24	0.154	2.84%
V*DC	4	11.984	11.984	2.996	3.16	0.078	
Error	8	7.576	7.576	0.947			
Total	26	299.376					

The percentage contribution indicates the proportion of variance in the response variable attributed to each input parameter. Factors with higher percentage contributions generally have a more significant impact on the respective response variable in the EDM process. The asterisks (*) next to P-values denote statistically significant factors influencing the responses.

Table 5 Estimated Model Coefficients for SN ratios of the responses

Term	Surface roughness		Electrode wear rate		Material Removal Rate	
	Coefficient	P	Coefficient	P	Coefficient	P
Constant	-8.3254	0.000*	30.804	0.000*	-7.38558	0.000*
A 5	-1.0771	0.004*	1.8347	0.000*	-2.25526	0.000*
A 7	0.1544	0.586	-0.0831	0.757	0.34561	0.228
V 35	1.1914	0.002*	0.5952	0.051*	-1.48406	0.001*
V 50	-0.1363	0.630	-0.2856	0.304	-0.04799	0.861
DC 50	1.2111	0.002*	0.7481	0.021*	-2.49097	0.000*
DC 65	-0.1652	0.561	-0.0852	0.751	-0.31473	0.269
A*V 5 35	-0.2893	0.474	-0.5812	0.152	-1.67407	0.002*
A*V 5 50	-0.1311	0.742	0.5525	0.171	1.05182	0.023*
A*V 7 35	0.269	0.505	0.279	0.469	1.1143	0.018*
A*V 7 50	-0.281	0.486	-0.3486	0.370	-1.17064	0.014*
A*DC 5 50	-0.3327	0.413	0.0341	0.928	-0.35549	0.370
A*DC 5 65	0.1517	0.704	0.0888	0.815	0.01792	0.963
A*DC 7 50	0.1836	0.646	-0.1656	0.664	-0.50875	0.211
A*DC 7 65	-0.1359	0.733	-0.1682	0.659	0.84836	0.053
V*DC 35 50	0.7098	0.102	0.7688	0.070	0.89524	0.044*
V*DC 35 65	-0.9853	0.034*	-0.1633	0.668	0.29595	0.452
V*DC 50 50	-0.396	0.334	-0.3834	0.327	-0.30563	0.438
V*DC 50 65	0.4267	0.300*	0.0477	0.900	0.12464	0.748

2. Model Coefficients

Table 5 presents the estimated model coefficients for the Signal-to-Noise (SN) ratios of three responses that demonstrate the effects of different input parameters and their combinations on surface roughness, electrode wear rate, and material removal rate in EDM, helping identify critical factors that impact these outcomes.

Term denotes the factor or combination of factors analyzed in the model.Surface roughness Coefficient, Electrode wear rate Coefficient, Material Removal Rate Coefficient: Represents the estimated effect of each factor or interaction on the respective response.P-Value (P) indicates the significance of each factor's effect on the response. If P ≤ 0.05 (as indicated by *), the factor is considered statistically significant in affecting the response.Factors like Cutting Speed, Feed Rate, Duty Cycle (%), and their interactions exhibit varying degrees of significance across the responses.For instance, Cutting Speed at 60 and 90, Feed Rate at 0.07, and specific combinations show significant effects on Surface Roughness, EWR, and MRR.Some interactions between factors also demonstrate significance, highlighting their joint impact on the responses.The asterisks (*) in the table denote statistically significant factors influencing the responses.

3. Main Effects Plot Study

In the main effect plots, the effect of each significant parameter on the responses was easily identified by the sliding of the line in the plot. The optimum level of these parameters can be easily determined by considering the highest points in the main effect plot lines. In the main effect plots, the highest point's plot lines are significant parameters to optimize and it can be easily determined. Figure 3 indicates that surface roughness decreases with increasing the discharge current while an increment in gap voltage and duty cycle shows inverse effect on the surface quality.

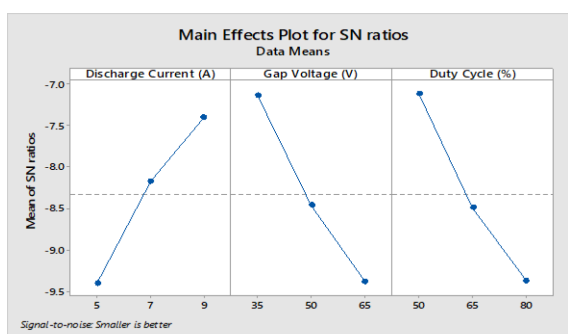

Figure 2 Main effects plot for Ra

The suggested best combination of the controllable input parameters for Ra, EWR and MRR are v3f1a1, v1f1a1 and v3f3a3 by employing Taguchi approach.

Therefore, minimum surface roughness is obtained when machining discharge current of 9 A, Gap voltage of 35 V and duty cycle of 50%. tool wear will be minimum at machining parameters as machining discharge current of 5 A, Gap voltage of 35 V and duty cycle of 50%., while the maximum MRR is obtained at machining discharge current of 9 A, Gap voltage of 65 V and duty cycle of 80%.Figure 4 indicate that minimum tool wear is observed at lower levels of the machining parameters due to less heat at the spark area. Figure 4 shows that maximum MRR is obtained at higher levels of the machining parameters.

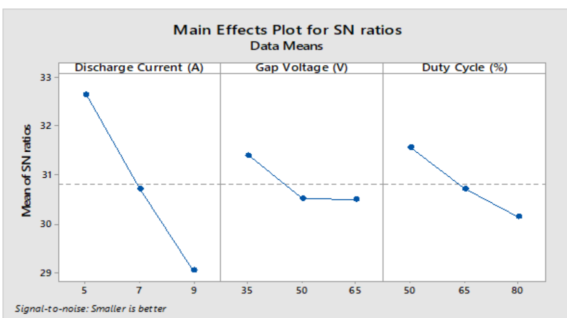

Figure 3 Main effects plot for EWR

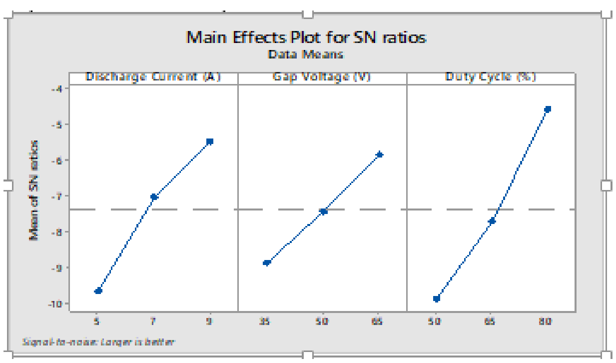

Figure 4 Main effects plot for MRR

4. Interaction Plots Study

Interaction plots for the responses are shown in Figure 5, Figure 6 and Figure 8 for Ra, EWR and MRR respectively.

It has been observed that, surface roughness decreases with increasing the gap voltage and duty cycle at all current values.

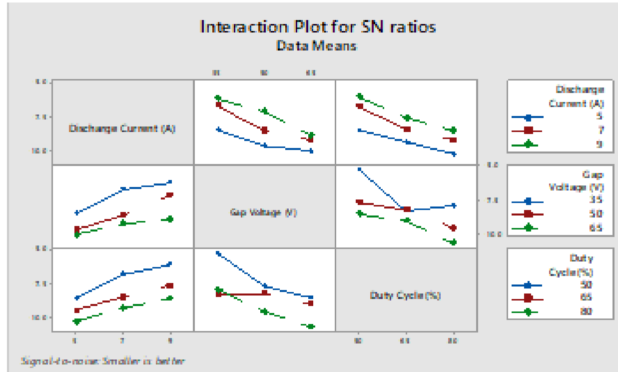

Figure 5 Interaction plot for Ra

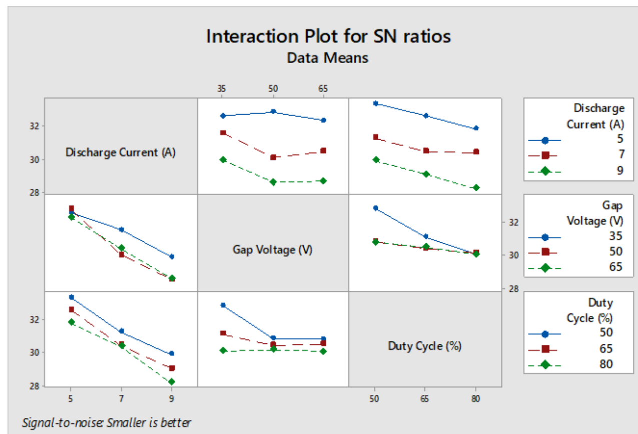

Figure 6 Interaction plot for EWR

Figure 7 Interaction plot for MRR

However, surface roughness increases with increasing discharge current and decreasing gap voltage and duty cycle. Interaction plot for tool wear rate (see Figure 6) shows a reduction in tool wear at high values of discharge current, gap voltage and duty Cycle. However, electrode wear is increased with the reduction in the discharge current at all values of gap voltage and duty cycle. Moreover, interaction plots for MRR shows that it increases with increasing the values of discharge current, gap voltage and duty cycle as shown in Figure 7.

Table 6 Response Table for Responses

Surface roughness			
Level	Discharge Current (A)	Gap voltage (V)	Duty cycle (%)
1	-9.402	-7.134	-7.114
2	-8.171	-8.462	-8.491
3	-7.403	-9.38	-9.371
Delta	2	2.247	2.257
Rank	3	2	1
Electrode wear rate			
1	32.64	31.4	31.55
2	30.72	30.52	30.72
3	29.05	30.49	30.14
Delta	3.59	0.9	1.41
Rank	1	3	2
Material removal rate			
1	-9.641	-8.87	-9.877
2	-7.04	-7.434	-7.7
3	-5.476	-5.854	-4.58
Delta	4.165	3.016	5.297
Rank	2	3	1

Response Table Study

The Response Table for Signal to Noise ratios of Ra, EWR and MRR is shown in Table 6. The signal to noise ratios corresponding to various input parameters and their levels are calculated, then after the difference between the maximum and minimum value of different levels (i.e. delta value) for each factor is determined and all input parameters for each response parameter are then ranked accordingly.

Residual Plots Study

The residual plots for S/N ratios for Ra, TWR and MRR are shown in Figure 8, Figure 9 and Figure 10 respectively. From – 0.1 and 0.1. Residual versus fitted values indicate that the variance is constant and a nonlinear relationship exists as well as no outliers are present in the data. The histogram proves that the data are approximately normally distributed. This may be due to the fact that the number of digits is very small.

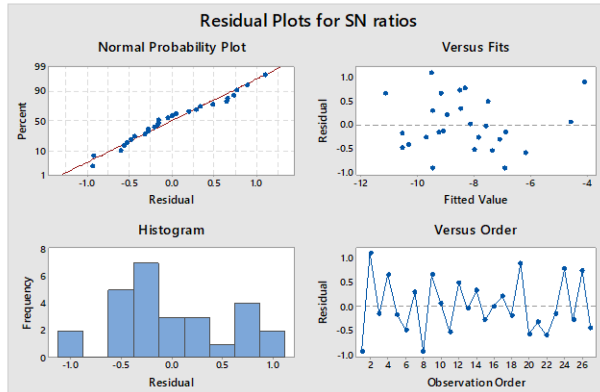

Figure 8 residual plots for surface roughness

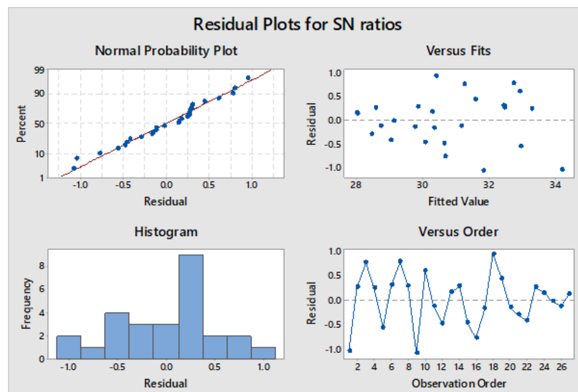

Figure 9 residual plots for EWR

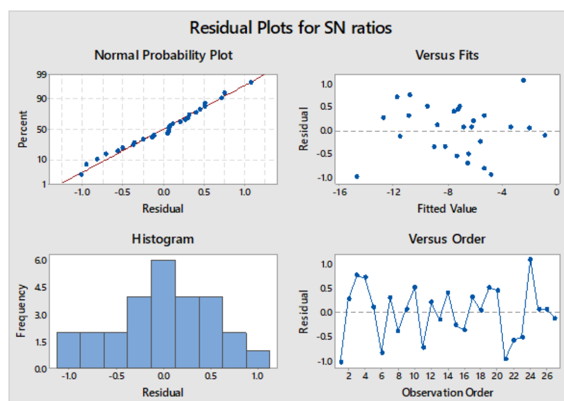

Figure 10 residual plots for MRR

The normal probability plot shows that the data are approximately normally distributed and the variables are influencing the response. A standardized residual range ranges residual versus order of the data indicates that the data have an almost systematic effect.

IV. CONCLUSION

The conclusions based on the input machining parameters (discharge current, gap voltage and duty cycle) on the response parameters (Ra, EWR and MRR) are as follows:

Feasibility of standard EDM process for M2 tool steel using 99% copper tool electrode has been essayed.
ANOVA results revealed that input parameters such as discharge current, gap voltage and duty cycle are significant parameters for each response.

For surface roughness, duty cycle and gap voltage are most contributing factors that contribute 28.13% and 27.73% respectively. However, discharge current indicates the highest contribution (66.41%) for minimum tool wear followed by duty cycle. Moreover, duty cycle is the largest contributing parameters that contribute 42.62% to achieve maximum MRR followed by discharge current (26.61%) and gap voltage (13.68%).

According to Taguchi approach, the suggested best combination of the controllable input parameters for Ra, EWR and MRR are v3f1a1, v1f1a1 and v3f3a3 by employing Taguchi approach. Therefore, minimum surface roughness is obtained when machining discharge current of 9 A, Gap voltage of 35 V and duty cycle of 50%. tool wear will be minimum at machining parameters as machining discharge current of 5 A, Gap voltage of 35 V and duty cycle of 50%., while the maximum MRR is obtained at machining discharge current of 9 A, Gap voltage of 65 V and duty cycle of 80%.
Confirmatory experiments have been conducted and significant improvement is observed.

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