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Investigation and optimization of the electro-discharge machining parameters of 2024 aluminum alloy and Al/7.5% Al₂O₃ particulate-reinforced metal matrix composite

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Abstract: Being newly advanced materials, metal matrix composites enjoy the properties of high service temperature, light weight, high specific strength, good wear resistance, high stiffness, and a low thermal expansion coefficient. However, machining these materials by conventional methods is difficult. A key machining process for difficult-to-machine materials like composites is electro-discharge machining, which is widely used in non-conventional material removal processes. The current work aims to identify different parameters, such as voltage, current, pulse on-time, and pulse off-time, which influence the material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR). By applying regression equations, a mathematical model is adopted to estimate MRR, TWR, and SR. The optimum machining parameters are investigated using the Taguchi method with L9 orthogonal array. The optimum values are also analyzed by multi-objective Taguchi method with calculation of total normalized quality loss (TNQL) and multi-signal to noise ratio (MSNR) included. Analysis of the Taguchi method introduced voltage and pulse off-time as the two main significant factors that influence the value of the material removal rate. The discharge current and pulse off-time also have a statistically significant impact on both tool wear rate and surface roughness.

Keywords: Al2024/Al₂O₃ metal matrix composite; electro-discharge machining; optimization; surface roughness; Taguchi method.

1 Introduction

As one of the consequential metal matrix composites (MMCs) with diverse properties like lower density, light weight, high strength, heat resistance, stiffness, and significant wear resistance, Al₂O₃ particle-reinforced aluminum matrix composites may be used in automobile, aerospace, and defense industries. Combining the metallic properties of matrix alloys with the ceramic properties of reinforcements, these composites lead to greater strength in shear and compression as well as higher service-temperature capabilities [1]. Aluminum oxide is chemically consistent with aluminum and creates an adequate bond with the matrix, which is free from developing intermetallic phases. Owing to greater hardness and reinforcement strength, composite materials are difficult to be machined by traditional techniques and, accordingly, the electro-discharge machining (EDM) process is a viable method to process these kinds of materials [2]. EDM of composite materials has been already studied by some researchers. An attempt in this connection has been made to develop mathematical models for optimizing EDM characteristics, such as material removal rate (MRR), tool wear rate (TWR), and surface roughness (SR).

The effects of current, pulse on-time, and flushing pressure on responses, like MRR, TWR, and SR were investigated by Singh et al. [3]. To machine LM 25 Al alloy-SiC composites, Karthikeyan et al. used copper electrode and investigated the effects of volume percent of SiCP, pulse duration, and current on TWR, MRR, and SR [4]. The mathematical models seek to achieve higher MRR and lower TWR with much accuracy and SR. To estimate the cutting speed and surface finish, neural network system was used by Tarng et al. to determine the settings of pulse duration, pulse interval, peak current, open circuit voltage, servo reference voltage, electric capacitance, and table speed [5]. Based on the analysis of variance, factorial design method was used to identify the optimal combination of control parameters in wire EDM, demonstrating that pulse frequency, discharge current, and pulse duration are

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significant control factors for both the MRR and SR [6]. In order to determine the optimal setting of EDM parameters, the Taguchi method was adopted, whereas George et al. studied the machining of carbon–carbon composites, in which the input parameters were current, voltage and pulse on-time, and MRR and electrode wear rate served as the responses [7]. By examining the surface profile of 2080 tool steel that was machined under varying machining parameters, Cogun et al. found that a rise in discharge current, pulse duration, and dielectric flushing pressure cause SR to increase [8]. To optimize the process parameter of powder-mixed EDM, Kansal et al. employed the empirical relation of the machining responses and adopted the response surface methodology technique [9]. This review selected pulse on-time, duty cycle, peak current, and concentration of SiC powder as variables. The combination of high peak current and high concentration brings higher MRR and smaller SR. They also reported the error between experimental and predicted values of MRR and SR within 7.8% and 7.85%–3.15%, respectively. Then, Sharif et al. established the empirical relation of the machining responses by response surface methodology technique [10] as well as studied the effect of SiC powder in dielectric on the machining of the Ti-6246 work piece. The result indicated that MRR, TWR, and surface quality were greatly influenced by the current, voltage, and pulse on-time, and that the SR was highly affected by the presence of SiC additives. Meanwhile, Tantra et al. tested the evaluation of model set forth by Heuvelman on the erosion strength of the material to predict tool wear and their applicability to EDM process [11]. Based on the experimental results, no direct correlation with the observation was demonstrated by the Heuvelman model.

Less comparison has been made in the past between EDM of Al/Al₂O₃ MMCs and 2024 alloys. This gap in the literature highlights the need to study the issue with the purpose of achieving mathematical models to enhance the performance. The current attempt investigated the impacts of reinforcement volume (5% Al₂O₃) in the metal matrix alloy (Al/5% Al₂O₃ MMCs) on the MRR and TWR of EDM. Moreover, SR measurements were examined on the machined surfaces. The machining of Al/5%Al₂O₃ MMCs was compared with that of 2024 alloy within the same machining conditions. Furthermore, the effects of the input parameters of voltage gap, pulse current, pulse on-time and pulse off-time on output parameters, such as MRR, TWR, and SR were investigated on both the abovementioned materials by using the Taguchi method to achieve the highest MRR and the lowest SR and TWR. Accordingly, the quantitative mathematical models were employed to examine the effects of voltage, discharge

current, pulse on-time, and pulse off-time on the performance characteristics of MRR, TWR, and SR.

2 Materials and methods

2.1 Equipment used and experimental procedure

The machine used to perform the experiments was a die-sinking EDM of M204H manufactured by Tehran-Ekram Co. The experiments were conducted on 2024 aluminum alloy composites, which are reinforced with 5% Al₂O₃ particulates and the 2024 alloy with densities of 2.826 and 2.77 gr/cm³, respectively. The materials used in the present work were shaped in the form of plate and ground by milling machine; the dimensions of the workpiece and electrode were 69×32×7 mm and 8.4×55 mm, respectively. The physical and mechanical properties of the copper electrode as well as the 2024 Al alloy composites reinforced with 5% Al₂O₃ particulate are shown in Tables 1 and 2, respectively.

2.2 Tests method used

The experiments were performed on two different materials of 2024 aluminum alloy composites, which were

Table 1: Physical and mechanical properties of 7.5% Al₂O₃ Al-MMCs.

Density (g/cm ³)	2.854
Tensile strength, ultimate (MPa)	475
Tensile strength, yield (MPa)	325
Modulus of elasticity (Gpa)	73.2
Thermal conductivity (W/m-k)	120
Melting point (°C)	638–502
Cu	3.8%–4.9%
Mn	0.3%–0.9%
Mg	1.2%–1.8%

Table 2: Physical and mechanical properties of copper electrode.

Density (g/cm ³)	8.94
Melting range (°C)	1065–1083
Thermal conductivity (W/m-K)	388
Specific heat capacity (J/g°C)	0.385
Electro resistivity (Ω cm)	1.7×10 ⁻⁶
Thermal expansion coefficient (1/°C)	1.7×10 ⁻⁵

Table 3: Machining conditions and machine tool settings.

Parameters	Specifications
Workpiece (–)	Al/5%Al ₂ O ₃ MMC and 2024 alloy
Electrode (+)	Copper
Electrode diameter	10 mm
Time of machining	10 min
Dielectric	Kerosene

Table 4: Input parameters of EDM and designated levels.

Factors	Levels		
Gap voltage (V)	–	80	250
Discharge current (A)	10	15	20
Pulse on-time (μs)	35	50	100
Pulse off-time (μs)	30	70	200

reinforced with 5%Al₂O₃ particulates and the 2024 alloy in order to examine the effects of reinforcement volume (5%Al₂O₃) in metal matrix alloy (Al/5%Al₂O₃ MMCs) on MRR, TWR, and SR.

2.3 Design of experiments

Experiments were conducted according to L9 Taguchi orthogonal array, which had nine numbers of experimental run. The repetitive-level technique applying a repeated voltage level of 80 V were used to optimize the number of experiments, because the electro discharge machine used in this study only had two voltage levels. Conditions and setting of EDM are shown in Table 3. The relation between the parameters was identified using MiniTab® 16.1.1 software. The essential parameters of the experiment are given in Table 4. Changes in electrode weight and material weight were measured by AND GR-300 balance before and after the process; the elapsed times were recorded after each machining test [12]. The SR of the Al/5%Al₂O₃ MMCs and 2024 alloy was measured by Mahr M300-RD18 roughness measurement device. MRR and TWR are calculated by using Equations 1 and 2 [13]

$$\text{MRR} = \frac{(W_1 - W_2)}{\rho_w \times t} \times 10^3, \quad (1)$$

where for MRR (mm³/min), W_1 is the initial weight of workpiece in gram, W_2 is the final weight of workpiece in gram, t is the machining time in minutes, and ρ_w is the density

of the workpiece. Equation 2 is used also to calculate TWR (mm³/min)

$$\text{TWR} = \frac{(T_1 - T_2)}{\rho_T \times t} \times 10^3, \quad (2)$$

where for TWR (mm³/min), T_1 is the initial weight of electrode in gram, T_2 is the final weight of electrode in gram, t is the period of trials in minutes, and ρ_T is the density of copper. To select an appropriate orthogonal array for the experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that must be made to determine which level is better and specifically how much better it is. Once the degrees of freedom are known, the next step is to select an appropriate orthogonal array to fit the specific task. The orthogonal array selected is based on the freedom degree of process parameters. The DOF were determined using Equation 3.

$$\begin{aligned} &1 + \text{number of factors} \times (\text{number of level} - 1) \\ &= \text{degrees of freedom (DOF)} \end{aligned} \quad (3)$$

$$1 + 4 \times (3 - 1) = \text{DOF}$$

A statistical analysis of variance (ANOVA) was performed to identify the process parameters that were statistically significant.

3 Results and discussion

3.1 Control factors and selection of the Taguchi standard orthogonal array

The output parameters of SR, MRR, and TWR in this study were measured as technological response variables. The machining parameters included the input parameters of the EDM process, namely, voltage, current, pulse on-time, and pulse off-time. Table 4 displays the design factors and selected levels for each experimental parameter. According to Table 5, the L9 orthogonal array was used. The table presents the experimental design matrix and results for MRR, SR, and TWR for both machining conditions in the present study, which are applied to Al/5%Al₂O₃ MMCs and 2024 alloy. The objective of this paper is to present the mathematical models for modeling and analyzing the effects of the machining parameters on the performance characteristics in the

Table 5: Experimental design and results for MRR, SR, and TWR on two different materials used.

Experimental design using L9 orthogonal array										
Experiment number	Control factors levels				Output parameters as a result of machining of Al/5%Al ₂ O ₃ MMCs			Output parameters as a result of machining of 2024 alloy		
	Voltage	Discharge current	Pulse on-time	Pulse off-time	SR (Ra)	MRR	TWR	SR (Ra)	MRR	TWR
1	1	1	1	1	4.360	3.225	0.1235	3.585	6.209	0.101
2	1	2	2	2	6.088	6.263	0.2358	5.444	8.267	0.146
3	1	3	3	3	6.618	9.447	0.3256	6.322	10.613	0.1796
4	2	1	2	3	4.255	2.052	0.0786	3.272	1.805	0.0449
5	2	2	3	1	3.746	14.720	0.3930	4.387	23.465	0.2583
6	2	3	1	2	5.711	7.041	0.2695	5.829	9.241	0.1684
7	3	1	3	2	7.683	5.024	0.1909	4.760	5.198	0.0673
8	3	2	1	3	5.631	0.813	0.0336	5.140	1.227	0.0224
9	3	3	2	1	7.520	19.709	0.4716	4.728	22.599	0.2358

EDM process of 2024 alloy and Al/5%Al₂O₃ MMCs. The mathematical models are developed using the response surface methodology (RSM) to explain the influences of the machining parameters on the performance characteristics in the EDM process. The RSM is an empirical modeling approach for determining the relationship between various process parameters and responses, on the one hand, and the different desired criteria on the other hand. The RSM is also used for searching the significance of these process parameters on the coupled responses. The process design factors with their values on different levels are listed in Table 6.

The effects of voltage, current, pulse on-time, and pulse off-time on MRR in the machining of both materials used are illustrated in Figures 1 and 2. As shown in Figure 2, which is related to EDM of 2024 alloy, increase in current, voltage, and pulse on-time causes increasing MRR, whereas an increase in pulse off-time causes MRR to decrease. In comparison, as shown in Figure 2, an increase in voltage causes MRR to decrease.

Table 7 shows the ANOVA results of MRR for 95% confidence levels with p values that are smaller than 0.05, based on analyses of the S/N ratios for the machining of Al/5%Al₂O₃ MMCs. Table 7 indicates that voltage leaves the greatest effect on the TWR followed by current, pulse

off-time, and pulse on-time. Equation 4 shows the regression equation of material removal in the machining of Al/5%Al₂O₃ MMCs.

$$\begin{aligned}
 \text{MRR} = & 2.53036 - (0.0117161 \times \text{Voltage}) \\
 & - (0.520929 \times \text{Current}) + (0.207512 \times \text{On time}) \\
 & + (0.0151512 \times \text{Off time}) \\
 & + (0.0347800 \times \text{Current} \times \text{Current}) \\
 & - (7.19932\text{E-}04 \times \text{On time} \times \text{On time}) \\
 & - (4.86130\text{E-}05 \times \text{Off time} \times \text{Off time}) \\
 & - (0.00655304 \times \text{On time} \times \text{Current})
 \end{aligned} \quad (4)$$

The results of ANOVA for the response functions MRR in the machining of 2024 alloy is given in Table 8. Equation 5 shows the regression equation of material removal in the machining of 2024 alloy.

$$\begin{aligned}
 \text{MRR} = & -33.2591 + (0.0131071 \times \text{Voltage}) \\
 & + (3.44731 \times \text{Current}) + (0.865275 \times \text{On time}) \\
 & - (0.419827 \times \text{Off time}) \\
 & - (0.0683533 \times \text{Current} \times \text{Current}) \\
 & - (0.00479060 \times \text{On time} \times \text{On time}) \\
 & + (0.00150623 \times \text{Off time} \times \text{Off time}) \\
 & - (0.00684348 \times \text{On time} \times \text{Current})
 \end{aligned} \quad (5)$$

Table 6: Machining parameters and their levels.

Experiment levels	Voltage	Discharge current	Pulse on-time	Pulse off-time
Level 01	80	10	35	30
Level 02	250	15	50	70
Level 03	80	20	100	200

As observed from the main effects plots of SR (Figures 3 and 4), pulse off-time has a significant effect on SR followed by current, pulse on-time, and voltage. Table 9

Signal-to-noise: Larger is better

Figure 1: Effects of the input parameters of EDM on MRR in the machining of Al/5%Al₂O₃ MMCs.

Signal-to-noise: Larger is better

Figure 2: Effects of the input parameters of EDM on MRR in the machining of 2024 alloy.

Table 7: Analysis of variance for MRR in the machining of Al/5%Al₂O₃ MMCs.

Source	Degrees of freedom (DF)	Sum of squares (SS)	Mean square (MS)	F	p-Value	Rank
Voltage	1	6.10	6.10	4.34	0.076	*
Current	2	3.61	1.81	0.88	0.462	2
On time	2	1.13	0.57	0.23	0.801	4
Off time	2	2.72	1.36	0.62	0.570	3

*Significant parameter.

Table 8: Analysis of variance for MRR in the machining of 2024 alloy.

Source	DF	SS	MS	F	p-Value	Rank
Voltage	1	0.5	0.5	0.01	0.914	4
Current	2	112.2	56.1	1.74	0.253	2
On time	2	68.5	34.3	0.87	0.467	3
Off time	2	116.9	58.4	1.86	0.235	*

*Significant parameter.

shows the ranking order of input parameters for SR for 95% confidence levels with p values smaller than 0.05, in the machining of Al/5%Al₂O₃ MMCs. The result reveals that pulse off-time is the most significant parameter for SR followed by current, pulse on-time, and voltage. Equation 6 shows the regression equation of SR in the machining of Al/5%Al₂O₃ MMCs).

Signal-to-noise: Smaller is better

Figure 3: Effects of the input parameters of EDM on SR in the machining of Al/5%Al₂O₃ MMCs.

Table 9: Analysis of variance for SR in the machining of Al/5%Al₂O₃ MMCs.

Source	DF	SS	MS	F	p-Value	Rank
Voltage	1	0.5	0.5	0.01	0.914	4
Current	2	112.2	56.1	1.74	0.253	2
On time	2	68.5	34.3	0.87	0.467	3
Off time	2	116.9	58.4	1.86	0.235	*

*Significant parameter.

Table 10: Analysis of variance for SR in the machining of 2024 alloy.

Source	DF	SS	MS	F	p-Value	Rank
Voltage	1	0.50	0.50	0.47	0.513	3
Current	2	4.731	2.365	4.50	0.064	*
On time	2	0.69	0.34	0.29	0.761	4
Off time	2	1.88	0.94	0.94	0.441	2

*Significant parameter.

$$\begin{aligned}
 RA = & -25.3233 + (0.000547144 \times \text{Voltage}) \\
 & + (0.991006 \times \text{Current}) + (1.03126 \times \text{On time}) \\
 & - (0.317551 \times \text{Off time}) + (0.0193733 \times \text{Current} \times \text{Current}) \\
 & - (0.00567347 \times \text{On time} \times \text{On time}) \\
 & + (0.00118177 \times \text{Off time} \times \text{Off time}) \\
 & - (0.0114974 \times \text{On time} \times \text{Current})
 \end{aligned} \quad (6)$$

The results of ANOVA for the response functions of SR in the machining of 2024 alloy are given in Table 10. Meanwhile, Equation 7 shows the regression equation of SR in the machining of 2024 alloy.

$$\begin{aligned}
 RA = & 1.58476 - (0.00266675 \times \text{Voltage}) \\
 & + (0.387061 \times \text{Current}) - (0.0934378 \times \text{On time}) \\
 & + (0.0538198 \times \text{Off time}) \\
 & - (0.00964000 \times \text{Current} \times \text{Current}) \\
 & + (0.000587179 \times \text{On time} \times \text{On time}) \\
 & - (2.18535\text{E-}04 \times \text{Off time} \times \text{Off time}) \\
 & + (0.00125739 \times \text{On time} \times \text{Current})
 \end{aligned} \quad (7)$$

The influence of TWR in the machining of both materials used on each level of control variables are plotted on the graphs shown in Figures 5 and 6. According to these figures, an increase in voltage, current, and pulse on-time cause a decrease in TWR, but an increase in pulse off-time causes TWR to increase.

Table 11 shows the results of ANOVA of TWR for 95% confidence levels with p values smaller than 0.05, based on analyses of the S/N ratios for the machining of Al/5%Al₂O₃ MMCs. Table 11 indicates that current leaves the greatest effect on the TWR followed by pulse off-time, pulse on-time, and voltage. Equation 8 shows the regression equation of TWR in the machining of Al/5%Al₂O₃ MMCs.

$$\begin{aligned}
 TWR = & -0.318663 + (9.49190\text{E-}05 \times \text{Voltage}) \\
 & + (0.00332217 \times \text{Current}) + (0.0176463 \times \text{On time}) \\
 & - (0.00359365 \times \text{Off time}) \\
 & - (0.000899333 \times \text{Current} \times \text{Current}) \\
 & - (1.10205\text{E-}04 \times \text{On time} \times \text{On time}) \\
 & + (1.09622\text{E-}05 \times \text{Off time} \times \text{Off time}) \\
 & - (1.94783\text{E-}05 \times \text{On time} \times \text{Current})
 \end{aligned} \quad (8)$$

Figure 4: Effects of the input parameters of EDM on SR in the machining of 2024 alloy.

Figure 5: Effects of the input parameters of EDM on TWR in the machining of Al/5%Al₂O₃ MMCs.

The results of ANOVA for the response functions of TWR in the machining of 2024 alloy are given in Table 12.

Equation 9 shows the regression equation of TWR in the machining of 2024 alloy.

$$\begin{aligned}
 \text{TWR} = & -0.105147 + (0.000226138 \times \text{Voltage}) \\
 & + (0.0127907 \times \text{Current}) \\
 & + (0.00359620 \times \text{On time}) - (0.00153776 \times \text{Off time}) \\
 & - (3.76000\text{E-}04 \times \text{Current} \times \text{Current}) \\
 & - (3.80684\text{E-}05 \times \text{On time} \times \text{On time}) \\
 & + (3.45514\text{E-}06 \times \text{Off time} \times \text{Off time}) \\
 & + (0.000175826 \times \text{On time} \times \text{Current})
 \end{aligned}
 \tag{9}$$

The mathematical model presented above can be used to predict the values of MRR, EWR, and SR within the limits of the factors studied.

3.2 Interaction plot of MRR, SR, and TWR

Creating an interaction plot matrix can show us the interactions between factors, regardless of whether they exist or not. No interaction is represented within parallel lines in an interaction plot. However, the interaction plot does not reveal whether the interaction is statistically significant or not. Interaction plots usually make the visualization of interactions possible during the design

Signal-to-noise: Smaller is better

Figure 6: Effects of the input parameters of EDM on TWR in the machining of 2024 alloy.

Table 11: Analysis of variance for TWR in the machining of Al/5%Al₂O₃ MMCs.

Source	DF	SS	MS	F	p-Value	Rank
Voltage	1	0.0006	0.0006	0.02	0.882	4
Current	2	0.0767	0.0383	2.47	0.165	*
On time	2	0.0420	0.0210	0.99	0.427	3
Off time	2	0.0505	0.0253	1.27	0.346	2

*Significant parameter.

Table 12: Analysis of variance for TWR in the machining of 2024 alloy.

Source	DF	SS	MS	F	p-Value	Rank
Voltage	1	0.00203	0.00203	0.27	0.621	3
Current	2	0.02307	0.01153	2.16	0.197	*
On time	2	0.00777	0.00388	0.49	0.634	4
Off time	2	0.02055	0.01028	1.78	0.247	2

*Significant parameter.

of experiments. Figures 7 and 8 demonstrate the interaction plots of voltage, current, pulse on-time, and pulse off-time on MRR in the machining of both applied materials; as can be seen, non-parallel lines exist among these four parameters. Figures 7 and 8 also display briefly the combined effects of gap voltage, current, pulse on-time, and pulse off-time on MRR in the machining of 2024 alloy. The rise of MRR and current is due to ease of the melting, vaporization, and dielectric explosion. With an increase in pulse on-time, MRR increases first, and then decreases. This can be attributed to the fact that less vaporization on the workpiece surface takes place because of a very

short pulse on-time, while longer pulse on-time makes the machining process unstable because of the increased short-run circuiting probability. MRR is lower at higher voltages because of the non-flushing of debris, which is entrapped in the spark gap and may not be carried away immediately by the dielectric fluid.

The plots of main factors and interaction graphs for the process parameters on SR in the machining of 2024 alloy and Al/5%Al₂O₃ MMCs are shown in Figures 9 and 10, respectively. The plots show that SR increases with the increase of current. It should be noted that an increase in current and pulse on-time cause SR to decrease in the machining of both materials used. As the pulse off-time varies from 30 to 70 μ s, the SR in the machining of 2024 alloy decreases and the variation of 70–200 μ s leads to an increase in SR as compared to a situation when the machining of Al/5%Al₂O₃ MMCs is performed.

According to Figures 11 and 12, increase in voltage, current, and pulse on-time cause a decrease in TWR. As shown in Figures 11 and 12, which are related to EDM of both materials used, an increase in pulse off-time causes an increase in TWR.

3.3 Signal-to-noise ratio analysis based on the Taguchi method

The ANOVA based on the Taguchi method displays the relationship between the machining parameters and observed values [14, 15]. A comparison of the signal-to-noise (S/N) ratio based on the abovementioned method unveils the optimization of the observed values. Three categories of

Figure 7: Interaction plot for the process parameters on MRR in the machining of 2024 alloy.

Figure 8: Interaction plot for the process parameters on MRR in the machining of Al/5%Al₂O₃ MMCs.

the performance characteristics in the analysis of the S/N ratio are identifiable, including the lower-the-better, the higher-the-better, and the nominal-the-better, respectively. The minimum TWR and SR and the maximum MRR are considered in order to obtain the optimal machining performance. Therefore, the lower-the-better TWR and SR and the higher-the-better MRR are selected. The following equation is used to calculate the S/N ratios:

For smaller the better:

$$\eta_i = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right], \quad (10)$$

where η_i is the S/N ratio at the i th test, y_i is the i th test, and n is the total.

For larger the better:

$$\eta_i = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^n \left(\frac{1}{y_i^2} \right) \right]. \quad (11)$$

The estimated S/N ratio using the optimal machining parameters for SR and TWR, and for MRR can be obtained by using Equations 10 and 11, respectively, and the corresponding SR and TWR as well as the MRR can also be calculated by using Equations 10 and 11, respectively.

Figure 9: Interaction plot for the process parameters on SR in the machining of 2024 alloy.

Figure 10: Interaction plot for the process parameters on SR in the machining of Al/5%Al₂O₃ MMCs.

The larger the better and the smaller the better principles are used in the present study to maximize the MRR and minimize the SR and TWR, respectively. Those factor levels that maximize the appropriate S/N ratio are deemed optimal. This research aimed at achieving maximum MRR and minimum SR (Ra) and TWR in a machining operation. Smaller Ra values indicate better or improved SR. Thus, the current study adopted and introduced a “smaller the better” quality feature. To estimate the S/N ratio, the SR and TWR are measured using Equation 10 (Table 13), and MRR is measured using Equation 11 (Table 14).

3.4 Calculation of total normalized quality loss and multilingual-to-noise ratio

Reducing variability must be performed to normalize the scale of the quality loss for each response. Regarding each response, the quality loss per trial is divided by the maximum quality loss within the i trials. Accordingly, 1 is the largest normalized value. The smaller normalized value entails the smaller quality loss. Therefore, ranges of the normalized quality loss fall between 0 and 1, which make it possible to directly sum up the quality loss for

Figure 11: Interaction plot for the process parameters on TWR in the machining of 2024 alloy.

Figure 12: Interaction plot for the process parameters on TWR in the machining of Al/5%Al₂O₃ MMCs.

Table 13: Analysis of normalized output parameters ratio in the machining of Al/5%Al₂O₃ MMCs.

Experiment number	Estimated S/N ratio			Normalized output		
	MRR (mm ³ /min)	SR (μs)	TWR (mm ³ /min)	MRR (mm ³ /min)	SR (μs)	TWR (mm ³ /min)
1	12.7897	10.1706	18.1667	0.72215	0.39279	0.61638
2	15.6895	15.9356	12.5491	0.88588	0.61543	0.42578
3	16.4145	19.5059	9.7463	0.92682	0.75332	0.33068
4	12.5780	6.2435	22.0915	0.71020	0.24112	0.74954
5	11.4714	23.3582	8.1121	0.65459	0.90209	0.27524
6	15.1342	16.9527	11.3888	0.85453	0.65471	0.38641
7	17.7106	14.0210	14.3839	1.00000	0.54149	0.48803
8	15.0117	1.7982	29.4732	0.84761	0.06945	1.00000
9	17.5244	25.8933	6.5285	0.98949	1.00000	0.22151

For explanation of bold fonts, see Section 3.4 Calculation of total normalized quality loss and multilingual-to-noise ratio.

Table 14: Analysis of normalized output parameters ratio in the machining of 2024 alloy.

Experiment number	Estimated S/N ratio			Normalized output		
	MRR (mm ³ /min)	SR (μs)	TWR (mm ³ /min)	MRR (mm ³ /min)	SR (μs)	TWR (mm ³ /min)
1	15.8604	11.0898	19.9136	0.57874	0.69237	0.60353
2	18.3470	14.7184	16.7129	0.66948	0.91892	0.50653
3	20.5168	16.0171	14.9139	0.74866	1.00000	0.45200
4	5.1295	10.2963	26.9551	0.18717	0.64283	0.81694
5	27.4048	12.8434	11.7575	1.00000	0.80185	0.35634
6	19.3144	15.3119	15.4732	0.70478	0.95597	0.46895
7	14.3167	13.5521	23.4397	0.52241	0.84610	0.71040
8	1.7769	14.2193	32.9950	0.06484	0.88776	1.00000
9	27.0818	13.4935	12.5491	0.98821	0.84244	0.38033

For explanation of bold fonts, see Section 3.4 Calculation of total normalized quality loss and multilingual-to-noise ratio.

each response. Second, to compute the total normalized quality loss (TNQL) per trial, a proper weight is assigned to each response by using Equation 12.

$$TNQL_i = \sum w_i y_i = (0.5Ra + 0.3MRR + 0.2TWR)_i \quad (12)$$

After calculating the total normalized quality loss $TNQL_i$ corresponding to each trial condition, the next step is to compute the multiple S/N ratio (MSNR) at each design point. The MSNR values calculated through the nine steps are shown in Tables 15 and 16. The MSNR corresponding to $MSNR_i$ is calculated using Equation 13 [13].

$$MSNR_i = -10 \log_{10}(TNQL_i) \quad (13)$$

3.5 Calculation of the multilingual-to-noise ratio for each parameter at various levels

A test was conducted using a specific combination of the factors and levels evaluated earlier to confirm the experiment. A new experiment was performed with the optimum levels of the machining parameters following the determination of the optimum circumstances. As soon as the optimal level of the process parameters is chosen, the researcher attempted to perform the final step to predict and verify improvement of the performance feature through the optimal level of the process parameters [16]. Using the optimal level of the process parameters, the estimated S/N ratio η_0 is calculated based on Equation 14

$$\eta_0 = \eta_m + \sum_{i=1}^k (\eta_i - \eta_m), \quad (14)$$

where η_m is the total mean of the S/N ratio, η_i is the mean S/N ratio at the optimal level, and k is the number of the process parameters that highly affect the performance feature [12]. As shown in Table 17, the maximum average S/N ratio for each parameter in different levels of the 2024 alloy machining regarding maximum MRR, minimum

Table 15: Total normalized quality loss (TNQL) and multi S/N ratios (MSNR) for output parameters in the machining of 2024 alloy.

Experiment number	Simultaneous analysis of output parameters	
	TNQL	MSNR (η_i)
1	0.640513	1.93472
2	0.76161	1.18267
3	0.814998	0.88843
4	0.540954	2.66840
5	0.772193	1.12274
6	0.783209	1.06122
7	0.721853	1.41551
8	0.663332	1.78269
9	0.793749	1.00317
Average MSNR (η_m) = 1.45106		

Table 16: Total normalized quality loss (TNQL) and multi S/N ratios (MSNR) for output parameters in the machining of Al/5%Al₂O₃ MMCs.

Experiment number	Simultaneous analysis of output parameters	
	TNQL	MSNR (η_i)
1	0.536316	2.70579
2	0.658635	1.81355
3	0.720842	1.42160
4	0.483528	3.15578
5	0.70247	1.53372
6	0.660996	1.79801
7	0.668351	1.74995
8	0.489008	3.10684
9	0.841149	0.75127
Average MSNR (η_m) = 2.00406		

TWR, and SR is obtained at level 2 of voltage, level 1 of pulse current, level 2 of pulse on-time, and at level 3 of pulse off-time; A2B1C2D3 is also the optimum parameter setting for maximum MRR and minimum TWR and SR. The results of

Table 17: The average MSNR for each input parameter in different levels in the machining of 2024 alloy.

Input parameter	Average MSNR η_0		
	Level 03	Level 02	Level 01
Voltage (A)	1.29925	1.95024	1.1037
Pulse current (B)	0.0507	1.18598	3.11651
Pulse on-time (C)	0.52456	1.95212	1.87651
Pulse off-time (D)	2.4374	0.75728	1.15851

Bold font indicates the maximum average S/N ratio for each parameter in different levels of the 2024 alloy machining regarding maximum MRR, minimum TWR, and SR is obtained at level 2 of voltage, level 1 of pulse current, level 2 of pulse on-time, and at level 3 of pulse off-time; A2B1C2D3 is also the optimum parameter setting for maximum MRR and minimum TWR and SR.

Table 18: The average MSNR for each input parameter in different levels in the machining of Al/5%Al₂O₃ MMCs.

Input parameter	Average MSNR η_0		
	Level 03	Level 02	Level 01
Voltage (A)	1.59994	2.47939	1.93282
Pulse current (B)	−0.03724	2.44599	3.6034
Pulse on-time (C)	0.69715	1.71248	3.60252
Pulse off-time (D)	3.6761	1.35339	0.98266

Bold font indicates the maximum average S/N ratio for each parameter in different machining levels of Al/5%Al₂O₃ MMCs concerning maximum MRR and minimum TWR and SR. Level 2 of voltage, level 1 of pulse current, level 1 of pulse on-time, and level 3 of pulse off-time comprise the optimum parameter setting for maximum MRR and minimum TWR and SR.

the maximum average S/N ratio for each parameter in different machining levels of Al/5%Al₂O₃ MMCs concerning maximum MRR and minimum TWR and SR are depicted in Table 18. The results revealed that level 2 of voltage, level 1 of pulse current, level 1 of pulse on-time, and level 3 of pulse off-time comprise the optimum parameter setting for maximum MRR and minimum TWR and SR. A2B1C1D3 is considered the optimum parameter setting for maximum MRR and minimum TWR and SR. Tables 17 and 18 demonstrate the optimum combinations in the machining of both materials used. Table 18 shows the results of the confirmation experiment using the optimal parameters in the machining of Al/5%Al₂O₃ MMCs.

3.6 Effect of Al₂O₃ on surface roughness

The surface machined micrographs of 2024 alloy and Al/5%Al₂O₃ MMCs with the identical machining conditions for both are presented in Figures 13 and 14, respectively.

Figure 13: SEM micrograph of the machined surface of 2024 alloy.

Figure 14: SEM micrograph of the machined surface of Al/5%Al₂O₃ MMCs.

According to micrographs, the machined surface of 2024 alloy is smoother than that produced by Al/5%Al₂O₃ MMCs. The voltage, current, pulse on-time, and pulse off-time for the mentioned samples are 80 V, 15 A, 35 μ s, and 200 μ s, respectively.

Figures 13 and 14 present the SR and the SEM micrographs of 2024 alloy and Al/5%Al₂O₃ MMCs, respectively. The figures demonstrate that the machined surface of

2024 alloy is smoother than when Al/5%Al₂O₃ MMCs is applied. The machining of Al/5%Al₂O₃ MMCs deteriorates the SR due to an increase in the peak current, as shown in Figure 14. A rise in the peak current increases the discharge energy and the impulsive force, removing more melted material, and generating deeper and larger discharge craters, which are associated with increasing surface roughness. With an increase in the pulse current, the deeper craters became highly evident and rougher surfaces are more pronounced. This is a result of discharges surging more intensely to the surfaces as the pulse current increases, creating a great quantity of molten and float-ing metal suspended in the electro-discharge gap during EDM, which in turn, causes the SR to deteriorate.

4 Conclusions

The objective of this paper is to present the mathematical models for modeling and analysis of the effects of the machining parameters on the performance characteristics of 2024 alloy and Al/5%Al₂O₃ MMCs in the EDM process. The mathematical models were developed to explain the influences of the machining parameters on the performance characteristics during the EDM process. An experimental investigation on the EDM of 2024 alloy and Al/5%Al₂O₃ MMCs was carried out with the aim of enhancing the performance characteristics of MRR, TWR, and SR. Then, the optimization was carried out. EDM process was optimized using MiniTab® 16.1.1 software, generally using the desirability function approach. Apart from the proposed modeling and optimization technique can also be utilized for the advanced and conventional machining of other engineering materials in modern manufacturing industries. An optimum parameter combination for the maximum MRR and minimum SR and TWR was obtained by using the analysis of S/N ratio. The confirmation tests indicated that it is possible to decrease TWR and SR and increase MRR significantly by using the proposed statistical technique. Furthermore, based on ANOVA method, the highly effective parameters on MRR, TWR, and SR were found. As shown by the ANOVA results, the voltage and pulse off-time were the most significant parameters affecting MRR in the machining of both materials used. Meanwhile, in the machining of Al/5%Al₂O₃ MMCs, the

SR was influenced by pulse off-time followed by current, pulse on-time, and voltage; in the machining of another material, which was 2024 alloy, the current had a significant effect on SR followed by pulse off-time, voltage, and pulse on-time. In addition, TWR values were influenced by the current in the machining of both materials used. The results showed that current and pulse off-time were the highly effective parameters influencing MRR, TWR, and SR in the machining of both materials used, whereas voltage and pulse on-time were less effective factors.

References

- [1] Garg RK, Singeh KK, Sachdeva A, Sharma Vishal S, Sharma Kuldeep O, Singeh S. *J. Adv. Manuf. Tech.* 2010, 50, 611–624.
- [2] Cheol Ahn Y, Seup Chung Y. *Korean J. Chem. Eng.* 2002, 19, 694–702.
- [3] Singh PN, Raghukandan K, Rathinasabapathi M, Pai BC. *J. Mater. Process. Tech.* 2004, 155–156, 1653–1657.
- [4] Karthikeyan R, Lakshmi Narayanan PR, Naagarazan RS. *J. Mater. Process. Tech.* 1999, 87, 59–63.
- [5] Tarng YS, Ma SC, Chung LK. *Int. J. Mach. Tool Manu.* 1995, 35, 1693–1700.
- [6] Scott D, Boyina S, Rajurkar KP. *J. Prod. Res.* 1991, 29, 2189–2207.
- [7] George PM, Raghunath BK, Manocha LM, Warriar Ashish M. *J. Mater. Process. Tech.* 2004, 145, 66–71.
- [8] Cogun C, Kocabas B, Ozgedik A. *J. Fac. Eng. Archit. Gazi Uni.* 2004, 19, 97–106.
- [9] Kansal HK, Singh S, Kumar P. *J. Mater. Process. Tech.* 2005, 169, 427–436.
- [10] Sharif S, Noordin RMY. Machinability modeling in powder mixed dielectric EDM of titanium alloy Ti-6246, Proceedings of the first international conference and seventh AUN/SEED-Net field wise seminar on manufacturing and material processing, 14–15 March Kuala Lumpur, 2006, 133–138.
- [11] Tantra NY, Leao F, Pashby IR. Evaluating theoretical equations to predict wear in electro-discharge machining, Proceedings of the first international conference and seventh AUN/SEED-Net field wise seminar on manufacturing and material processing, 14–15 March Kuala Lumpur, 2006, 151–155.
- [12] Daneshmand S, Farahmand Kahrizi E, LotfiNeyestanak AA, Mortazavi M. *J. Electrochem. Sci.* 2013, 8, 7484–7497.
- [13] Daneshmand S, Farahmand Kahrizi E, LotfiNeyestanak AA, Monfared V. *Optoelectron. Adv. Mat.* 2014, 8, 1119–1124.
- [14] Gopalakannan S, Senthilvelan T. *J. Mech. Sci. Technol.* 2014, 28, 1045–1053.
- [15] Daneshmand S, Farahmand Kahrizi E, LotfiNeyestanak AA, Monfared V. *J. Mar. Sci. Tech.* 2014, 22, 1–7.
- [16] Shrivastava PK, Dubey AK. *J. Adv. Manuf. Tech.* 2013, 69, 2471–2480.