

Process Parameter Optimization in EDM Using Copper Electrode for MRR and TWR Using Taguchi - Grey Relational Analysis for Nak80 Steel

Duc Nguyen Van

Vietnam- Japan center, Hanoi University of Industry, Hanoi, Vietnam,
* Corresponding Author

ABSTRACT:

Electrical Discharge Machining (EDM) is a widely used machining method in the plastic injection molding industry. This technology can machine difficult-to-reach areas that traditional methods cannot. However, it has low machining productivity and electrode wear during the machining process. While the goal is to achieve the highest possible productivity and minimize electrode wear, these two factors are often contradictory in practice; higher productivity leads to greater electrode wear. NAK80 steel is widely used in plastic injection molding, capable of achieving good surface quality. It is commonly used in the plastic injection molding industry to produce optical components such as eyeglass lenses and camera lenses. This paper presents the optimization of two targets: material removal rate (MRR) and tool wear rate (TWR) using gray relational analysis (GRA). Using the Taguchi method, an experimental design combined with GRA was employed for multi-objective optimization. Input technological parameters were U, I, and Ton (I: current; U: voltage; Ton: discharge time). Output parameters were material removal rate and electrode wear rate. The Taguchi method was used in the analysis and experimental design, and the orthogonal matrix L9 was selected. The results showed that the optimal machining parameters for EDM of NAK80 steel, requiring high material removal rate and reasonable electrode wear rate, were $I = 8\text{ A}$, $U = 60\text{ V}$, and $Ton = 150\text{ }\mu\text{s}$, resulting in cost and time savings for the experiment.

Keywords: EDM, NAK80 steel, material removal rate, tool wear rate

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I. INTRODUCTION

Electrical Discharge Machining (EDM) is a machining method using shaped electrodes, which is particularly effective in manufacturing complex plastic mold cavities that cannot be machined by traditional methods. This machining process requires both the electrode and the workpiece material to be electrically conductive. During machining, the material removal rate is very important and affects the product cost. Conversely, the higher the material removal rate, the greater the electrode wear rate [1, 2, 5, 6, 7]. Domestic and foreign studies have mentioned many optimization methods in the field of electrical discharge machining such as Taguchi, RSM surface feedback method, ANN artificial networks; PSO swarm optimization; The GA genetic algorithm... with workpiece materials such as SKD11, SKD61, 45 steel, NAK80... [6, 7, 8, 9], but there has been no research on electrical discharge machining with copper electrodes with NAK80 plastic mold steel material with the output criteria to be optimized for multiple objectives, namely material removal rate and electrode wear rate. This research is the basis for application when machining NAK80 steel with material removal rate as the top priority. In this paper, two output criteria are used: material removal rate and electrode wear rate. Input parameters including U, I, and Ton are included for optimization. The experimental design uses the Taguchi method and the GRA method for optimization. The workpiece material is NAK80 steel, and copper electrodes are used.

II. EXPERIMENTAL EQUIPMENT

Experiments were conducted on a CM 323C EDM machine, workshop on the first floor of building A10, campus 1, HaUI (Figure 1). The steel used was NAK80, with test sample dimensions of 20 x 20 x 20 mm (Figure 2). The electrode was made of copper with a clamping diameter of $\text{Ø}18\text{ mm}$, and the workpiece diameter was $\text{Ø}14\text{ mm}$ and a length of 28 mm (Figure 2). The EDM was performed in D323 oil as the dielectric medium. Material removal rate was measured by weighing the workpiece before and after machining (MRR). Electrode wear rate was measured by weighing the electrode before and after machining (TWR). The AJ 203

electronic balance (manufactured by Shinko Denshi Co. LTD - made in Japan) (Figure 3) has a maximum weighing capacity of 200g and an accuracy of 0.001g were used.



Figure 1. CM 323C electrical discharge machine

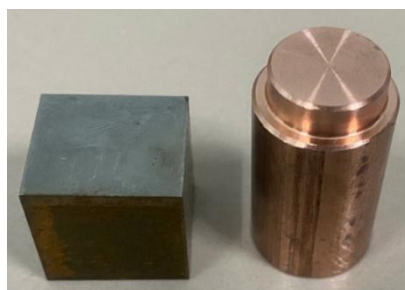


Figure 2. Workpiece and electrode

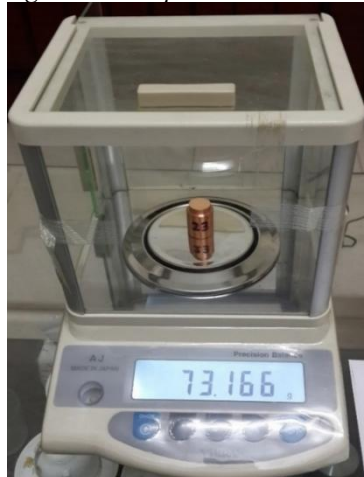


Figure 3. AJ 203 Electronic Scale

III. DEVELOPING AN EXPERIMENTAL PLAN

In the Taguchi method[3]matrix selection depends on the number of input technological parameters and levels. In this paper, the technological parameters (U, I, Ton) affecting surface roughness are selected with 3 levels of a parameter (Table 1). The number of degrees of freedom of the experiment is 8. The appropriate Taguchi experimental design for this case is L9. The matrix is as in Table 2; the matrix parameters are as in Table 3; the results are as in Table 4.

Table 1. Input parameters and levels

Levels	A	B	C
	I (A)	U (V)	T _{on} (μ s)
1	2	40	50
2	5	60	100
3	8	80	150

Table 2. Matrix

Exp	A	B	C
	I (A)	U (V)	T _{on} (μ s)
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3. Specifications

Exp	A	B	C
	I (A)	U (V)	T _{on} (μ s)
1	2	40	50
2	2	60	100
3	2	80	150
4	5	40	100
5	5	60	150
6	5	80	50
7	8	40	150
8	8	60	50
9	8	80	100

IV. EXPERIMENT ON EDM

The workpiece was mounted on the EDM machine table (Figure 1), clamped securely by electromagnetic force on the table, the electrode was mounted on the EDM head, the EDM machining motion was in the Z direction (perpendicular to the table), each workpiece was EDMed sequentially, each workpiece

was EDMed with a specific EDM mode according to the matrix in Table 3, EDM time per workpiece 30 minutes. Each workpiece used one electrode, and the electrodes were fine milled using a 4-blade solid high-speed steel end mill, $\phi 18$ diameter, from Nachi (Japan), machined on a 3-axis CNC milling machine (Moriseiki, Japan) with the same surface roughness ($R_a = 0.2 \mu\text{m}$). The dielectric fluid was D323 oil, with 2 nozzles at a 30-degree spray angle, and a constant pressure of 0.2 kg/cm². Nine experiments were conducted, each experiment was repeated 3 times, and the average value was taken, on the EDM machine.

Table 4. Experimental results

Exp	I (A)	U (V)	T _{on} (μs)	MRR (mg/p)	TWR (mg/p)
1	2	40	50	6.0000	0.3333
2	2	60	100	4.9666	0.3000
3	2	80	150	3.8000	0.2666
4	5	40	100	23.6333	0.3666
5	5	60	150	26.7333	0.2666
6	5	80	50	41.0333	0.4333
7	8	40	150	58.7333	1.0666
8	8	60	50	93.2666	1.2000
9	8	80	100	84.4666	0.8333

V. CHECKING THE RELIABILITY OF EXPERIMENTAL DATA

Experimental data must be checked for bias and fit: (Use Minitab 22 software)[4]

- The Normal Probability figure, compared to the normal distribution, shows that the data points are distributed along a straight line, with outliers but not significant. This demonstrates that the data are normally distributed and there is no bias.
- The Versus Fit figure shows the random distribution of residuals on both sides of the zero line; the points are randomly distributed, not following any pattern, indicating that the received y data is not affected by any other regular control factors besides x.
- The Histogram shows the frequency of occurrence of residuals. The protrusion of the distribution columns in the figure indicates the bias of the results. The spacing between the distribution columns indicates the outliers of the results appearing in the experimental values, and the data histogram does not show any normal distribution trend. Therefore, the values of the data surveyed according to Taguchi's experimental design model are appropriate.
- The Versus Order diagram is a diagram of the residuals of the experiments, examining the order of the experiments to find non-random errors. The random distribution of points does not follow a pattern, demonstrating that the input data y is not affected by time factors.

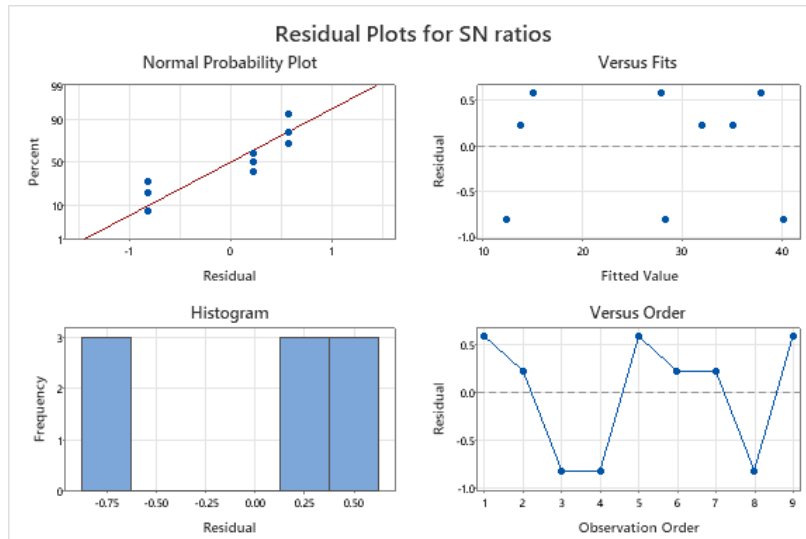


Figure 4. Statistical graph of residuals plot for SN ratio of MRR

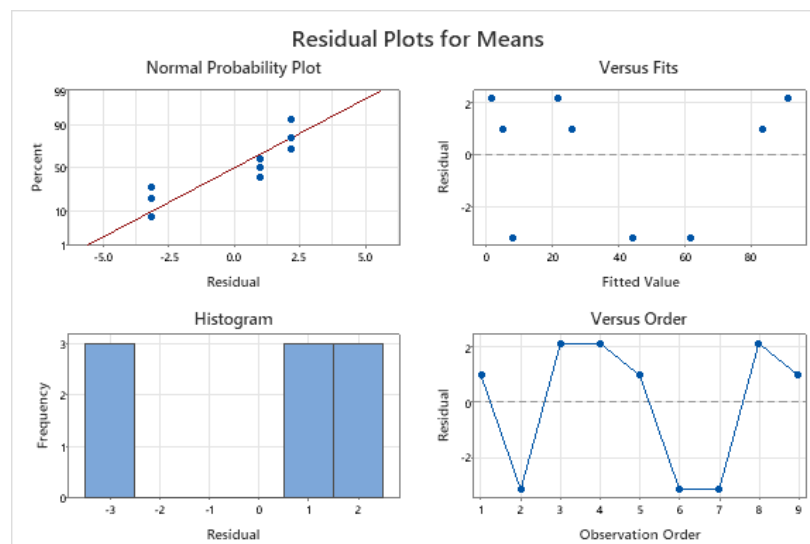


Figure 5. Statistical graph of residuals for means of MRR

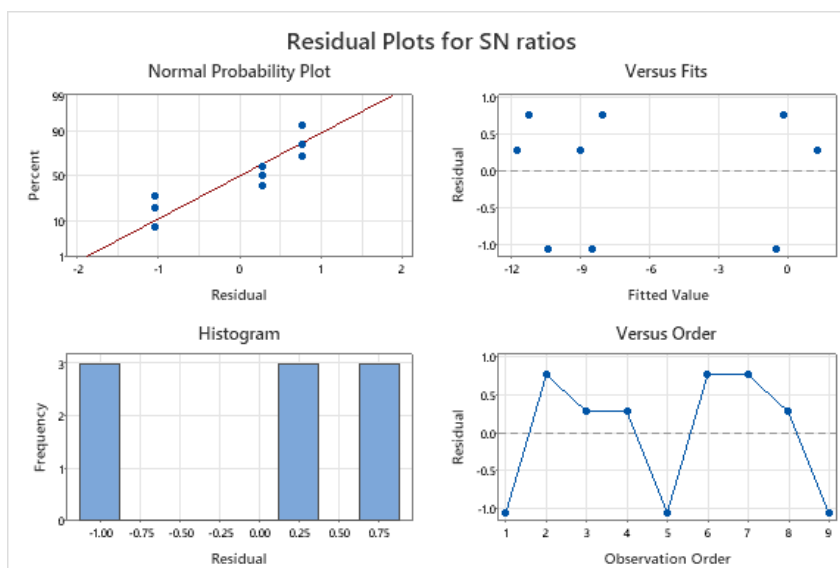


Figure 6. Statistical graph of residuals for SN ratio of TWR

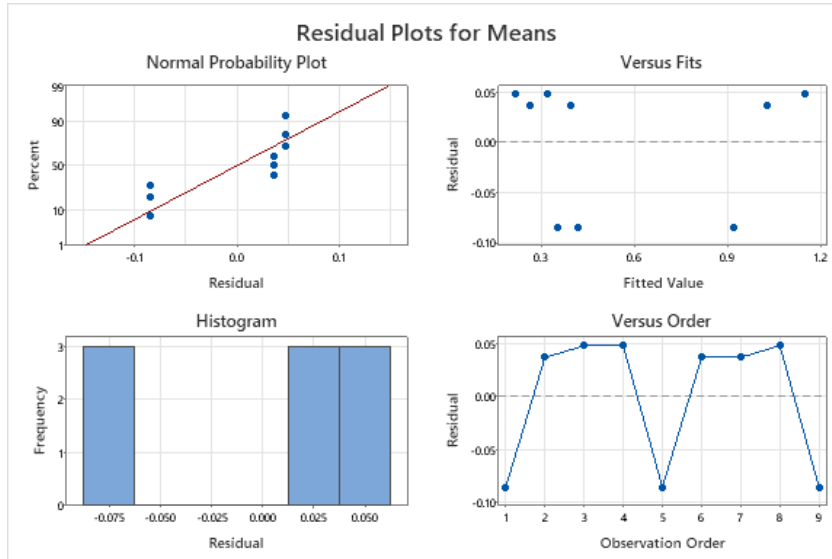


Figure 7. Statistical graph of residuals plot for means of TWR

VI. The influence of parameters on MRR

ANOVA analysis of MRR stripping efficiency with 95% confidence is shown in tables 5 and 6. Parameters with large F values have a strong influence on the output results. Table 5 shows that current intensity (F = 180.00) has the strongest influence on MRR, followed by discharge time Ton (F = 9.26) and the weakest influence on MRR is U (F = 7.18). The influence of the parameters on MRR as follows: I = 91.17%; Ton = 4.69%; U = 3.64%.

Table 5. Analysis of Variance of MRR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
I (A)	2	8451.98	91.17%	8451.98	4225.99	180.00	0.006
U (V)	2	337.10	3.64%	337.10	168.55	7.18	0.122
Ton (µs)	2	434.72	4.69%	434.72	217.36	9.26	0.097
Error	2	46.96	0.51%	46.96	23.48		
Total	8	9270.75	100.00%				

Table 6. Response Table for Signal to Noise Ratios of MRR (Larger is better)

Level	I (A)	U (V)	Ton (µs)
1	13.69	26.14	29.07
2	29.42	27.29	26.64
3	37.77	27.46	25.17
Delta	24.08	1.33	3.90
Rank	1	3	2

Table 7. Response Table for means of MRR (Larger is better)

Level	I (A)	U (V)	Ton (µs)
1	4.922	29.456	46.767
2	30.467	41.655	37.689
3	78.822	43.100	29.756
Delta	73.900	13.644	17.011
Rank	1	3	2

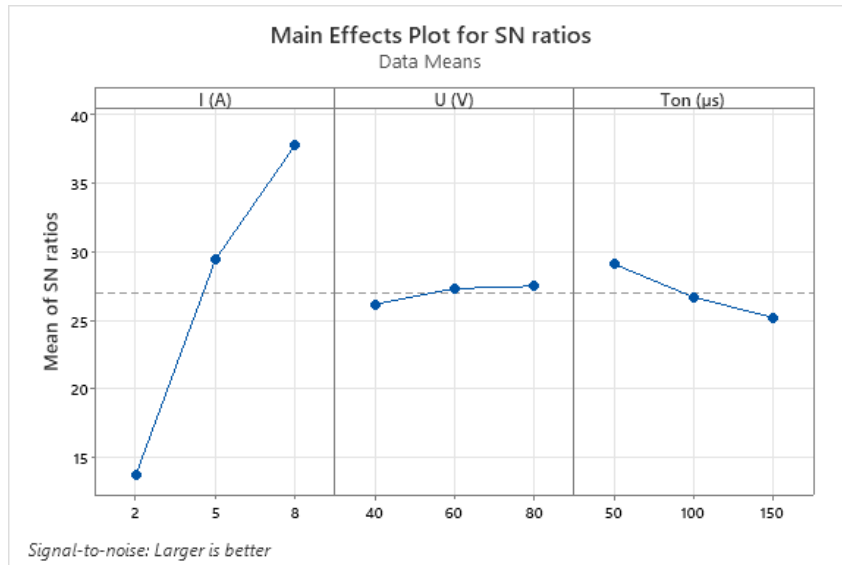


Figure 8. Influence of input parameters on the S/N ratio of MRR

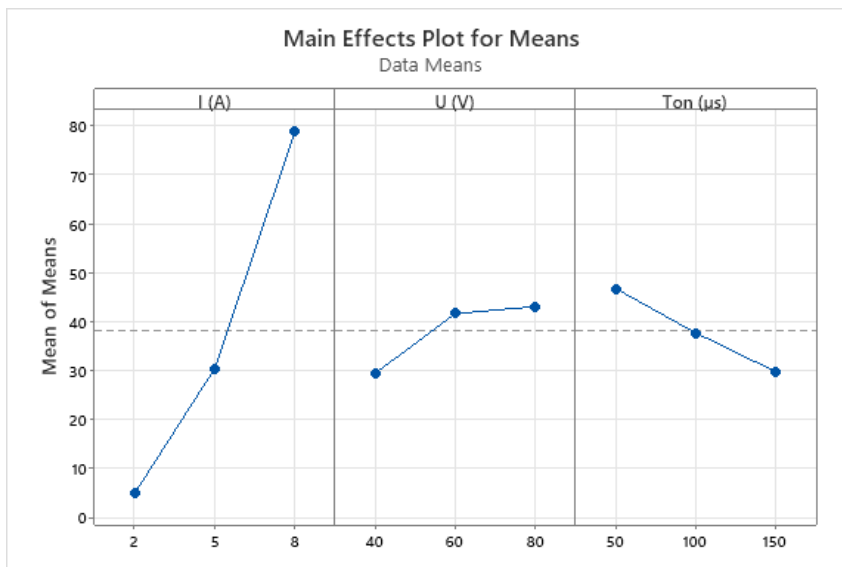


Figure 9. Influence of input parameters on plot for means of MRR

VII. The influence of parameters on TWR

ANOVA analysis of TWR stripping efficiency with 95% confidence is shown in tables 4.17 and 4.18. Parameters with large F values have a strong influence on the output results. Table 4.17 shows that current intensity ($F = 30.46$) has the strongest influence on TWR, followed by discharge time Ton ($F = 1.23$) and the weakest influence on MRR is U ($F = 0.37$). Table 4.18 shows the influence of the parameters on TWR as follows: $I = 92.15\%$; $Ton = 3.71\%$; $U = 1.11\%$

Table 8. Analysis of Variance of TWR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
I (A)	2	1.00027	92.15%	1.00027	0.500137	30.46	0.032
U (V)	2	0.01210	1.11%	0.01210	0.006050	0.37	0.731
Ton (µs)	2	0.04026	3.71%	0.04026	0.020130	1.23	0.449
Error	2	0.03284	3.03%	0.03284	0.016421		
Total	8	1.08548	100.00%				

Table 9. Response Table for Signal to Noise Ratios of TWR (Smaller is better)

Level	I (A)	U (V)	Ton (μ s)
1	10.4946	5.8998	5.0746
2	9.1544	6.7856	6.9192
3	-0.1866	6.7770	7.4685
Delta	10.6811	0.8858	2.3939
Rank	1	3	2

Table 10. Response Table for means of TWR (Smaller is better)

Level	I (A)	U (V)	Ton (μ s)
1	0.3000	0.5888	0.6555
2	0.3555	0.5889	0.5000
3	1.0333	0.5111	0.5333
Delta	0.7333	0.0778	0.1556
Rank	1	3	2

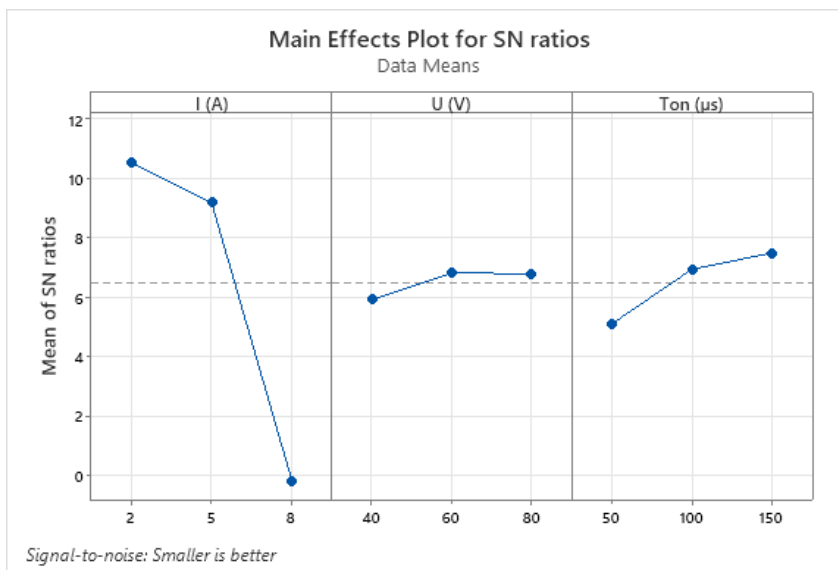


Figure 10. Influence of input parameters on the S/N ratio of TWR

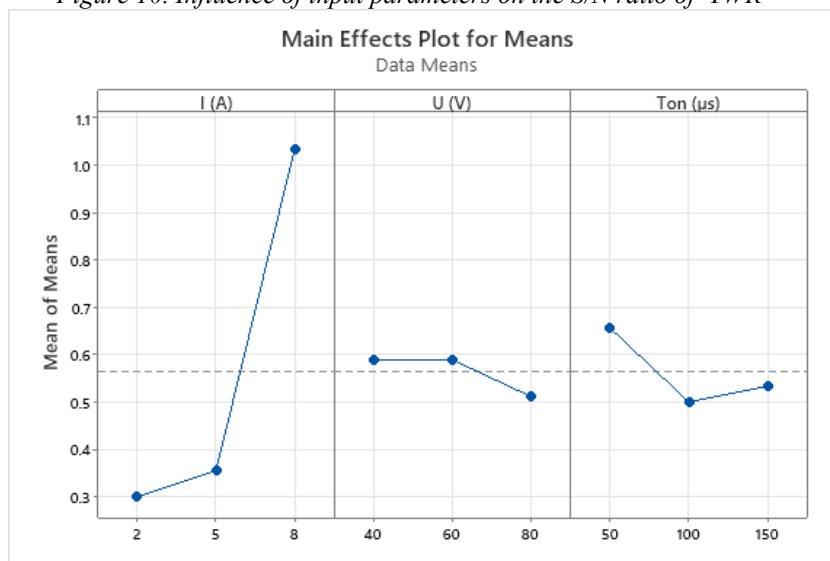


Figure 11. Influence of input parameters on plot for means of TWR

VIII. GREY RELATIONAL ANALYSIS

Since the machining performance involves multiple responses with conflicting objectives, Grey Relational Analysis (GRA) was applied to convert the multi-response optimization problem into a single equivalent Grey Relational Grade (GRG).

In this study:

- MRR was treated as a “Larger-the-better” characteristic.
- TWR was treated as a “Smaller-the-better” characteristic.

8.1 Data Normalization

For MRR, the larger-the-better normalization criterion was used:

$$x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{1}$$

For TWR, the smaller-the-better normalization criterion was adopted:

$$x_i^*(k) = \frac{\max x_i(k) - x_i(k)}{\max x_i(k) - \min x_i(k)} \tag{2}$$

The normalized experimental results are presented in Table 3.

Table 11. Normalized response values

Exp	Normalized MRR	Normalized TWR
1	0.025	0.959
2	0.013	0.980
3	0.000	1.000
4	0.222	0.938
5	0.256	1.000
6	0.416	0.898
7	0.614	0.510
8	1.000	0.000
9	0.902	0.653

8.2 Grey Relational Coefficient (GRC)

The Grey Relational Coefficient was calculated using:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta \Delta_{max}}{\Delta_{0i}(k) + \zeta \Delta_{max}} \tag{3}$$

where:

- ζ is the distinguishing coefficient,
- $\zeta = 0.5$ was selected in this study.

The calculated Grey Relational Coefficients are summarized in Table 4.

Table 12. Grey relational coefficients and grades

Exp	GRC (MRR)	GRC (TWR)	GRG
1	0.339	0.925	0.632
2	0.336	0.962	0.649
3	0.333	1.000	0.667
4	0.391	0.891	0.641
5	0.402	1.000	0.701
6	0.461	0.831	0.646
7	0.564	0.505	0.535
8	1.000	0.333	0.667
9	0.836	0.590	0.713

8.3 Grey Relational Grade Analysis

The Grey Relational Grade (GRG) was obtained by averaging the Grey Relational Coefficients:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \tag{4}$$

A higher GRG value indicates superior overall machining performance.

From Table 4, Experiment 9 exhibited the highest GRG value of 0.713, indicating the best multi-response performance among the conducted experiments.

The optimal machining parameter combination identified through GRA was:

- Current (I) = 8 A
- Voltage (U) = 80 V
- Pulse-on time (Ton) = 100 μs

IX. RESPONSE TABLE ANALYSIS

The average GRG values for each factor level were computed to determine the influence of machining parameters on overall process performance.

Table 13. Response table for GRG

Factor	Level 1	Level 2	Level 3	Max-Min	Rank
Current (I)	0.649	0.663	0.638	0.025	3
Voltage (U)	0.603	0.672	0.675	0.072	1
Ton	0.648	0.668	0.634	0.034	2

The results indicate that pulse-on time and discharge current were the most influential parameters affecting the combined machining performance.

The optimal parameter levels based on the highest GRG values were:

- I3 = 8 A
- U2 = 60 V
- Ton3 = 150 μs

Thus, the predicted optimal combination was:

$$I_3 - U_2 - Ton_3$$

X. DISCUSSION

The experimental findings reveal that the discharge current significantly influenced the material removal rate. Increasing current intensity enhanced spark energy, thereby increasing erosion efficiency and improving MRR. However, excessive discharge energy also accelerated tool wear.

Similarly, pulse-on time strongly affected both MRR and TWR. Longer pulse durations increased thermal energy transfer into the machining zone, promoting material removal but also contributing to electrode degradation.

The Grey Relational Analysis successfully transformed the multi-objective optimization problem into a single performance index, enabling simultaneous optimization of MRR and TWR. The obtained results demonstrate that the Taguchi-GRA approach is highly effective for determining optimal machining conditions with a limited number of experiments.

XI. CONCLUSIONS

A hybrid optimization method based on the Taguchi method and Grey Relational Analysis (GRG) was successfully implemented to simultaneously optimize material removal rate (MRR) and workpiece cutting speed (TWR) when machining NAK80 mold steel using copper electrodes on an EDM machine.

The main conclusions are summarized as follows:

1. The Taguchi-GRA method effectively converted the multi-response optimization problem into a single grey relational score.
2. Experiment 9 yielded the highest GRG value (0.713), indicating the best overall machining performance.
3. The optimal machining conditions predicted by response table analysis are:
 - Current = 8 A
 - Voltage = 60 V
 - Pulse duration = 150 μs
4. Discharge current and pulse duration are identified as the most important machining parameters affecting the combined performance characteristics.
5. The proposed method can be effectively applied to multi-objective optimization in EDM machining and related advanced machining processes.

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REFERENCES

- [1] Elman C. Jameson, *Electrical Discharge Machining*, International Standard Book Number: 0-87263-521-X . Printed in the United States of America, 2001
- [2] Xiaodong Zhang, Wentong Zhang, Peng Yu* and Yiquan Li, *Research on Machining Parameter Optimization and an Electrode Wear Compensation Method of Microgroove Micro-EDM*, *Micromachines* 2025, 16(4), 481; <https://doi.org/10.3390/mi16040481>
- [3] Ranjit Roy, *A-Primer-on-the-Taguchi-Method*, Library of Congress Catalog Card Number 89-14736 ISBN 0-442-23729-4, Printed in the United States of America, 1990.
- [4] *Minitab22*. Internet:<https://www.minitab.com/en-us/>, 10/3/2026.
- [5] Debasis Nayak, Shiba Narayan Sahu, Suhrith Mula, Metallurgical Approach Towards Explaining Optimized EDM Process Parameters for Better Surface Integrity of AISI D2 Tool Steel, Internet 2016.
- [6] Dušan, P., Miloš, M., Miroslav, R., Valentina, G., (2017). *Application of the performance selection index method for solving machining mcdm problems*. *Mechanical Engineering*, 15, 97-106.
- [7] Gurminder Singh, Pulak Mohan Pandey & Narinder Singh, *Surface roughness study in cryogenic EDM of tool steel using novel copper electrode with channels fabricated by additive manufacturing*, *Materials and Manufacturing Processes*, Pages 639-652, Accepted 20 Jan 2025, Published online: 11 Feb 2025.