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Optimization of machining parameters in sinking electrical discharge machine of caldie plastic mold tool steel

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Abstract. The aim of this study was to investigate the machinability of caldie cold work tool steel using the electro erosion technique. In the experimental study, graphite and copper were used as the electrode materials. Three levels for discharge current (6, 12 and 25 A) and three levels for pulse duration (50, 100 and 200 μs) were used as machining parameters. The experimental model was designed according to the Taguchi L_{18} orthogonal array. Signal/noise ratios, graphs and regression analysis were used to evaluate the results of the experiments. Using the Taguchi technique, the optimum machining parameters were determined with process outputs for surface roughness, material removal rate and electrode wear rate. The optimum levels were found to be $A_1B_1C_1$ for surface roughness and electrode wear rate and $A_2B_3C_3$ for material removal rate. The effect of control factors on experimental outputs was calculated by performing ANOVA. According to the ANOVA results, discharge current was the most effective parameter on machinability. When the experimental data were compared statistically with the Taguchi optimization and regression model data, the results of the designed models were shown to be successful.

Keywords. EDM; graphite; copper; caldie; Taguchi; ANOVA.

1. Introduction

Despite long years of development, it remains difficult to achieve today's desired precision using traditional manufacturing methods. The search to eliminate the boundaries and weaknesses of traditional machining methods has led to the emergence and development of unconventional manufacturing methods. Unconventional manufacturing methods, which generally involve the production of complex parts using different processing approaches, are in great demand due to the advantages they bring to design engineering [1]. One of the non-traditional manufacturing methods used in the machining industry is the electrical erosion processing method, also known as electric discharge machining (EDM). This widely used non-traditional production technique is based on the principle of material removal via a series of rapid and repeated electrical discharges between the workpiece and an electrode immersed in a dielectric fluid [2–6]. With a temperature of 8000–20,000°C, plasma is generated between the anode and the cathode [7]. The process helps in giving the accurate shape by using the electrode which is the replica of the cavity in the electrode governing the zone in which the spark erosion is occurring [8].

High conductivity heat resistance and high melting point are the main desired properties for EDM tool. The most common materials used in EDM tooling are copper, graphite, tungsten and tungsten carbide [9]. A suitable dielectric for EDM should be able to provide suitable conditions for initiation and maintain of good effective electric discharges, cool the electrodes and to carry away the debris from the spark gap. The most common dielectric mediums used are hydrocarbon oils such as Kerosene [10]. Surface integrity is one of the most important issues with EDM. Discharge current is one of the important factors that affect surface integrity. The surface roughness of the material increases with the increase in current and voltage. The crater size varies with pulse energy though it also depends on material properties [11].

In the EDM technique, the processing parameters and electrode selection significantly affect the machinability of the workpiece. Selection of the appropriate machining parameters and electrode usage directly affects the workpiece surface roughness (Ra), material removal rate (MRR) and tool wear rate (TWR). Payal *et al* processed EN-31 tool steel using the EDM technique with copper, brass and graphite electrodes. The highest MRR value in their study was obtained with the copper electrode, whereas the lowest Ra values were obtained with the brass electrode. Volcanic spills and cracks were observed on the surfaces treated with the graphite electrode because of the uneven distribution of heat [12]. Lee and Li processed tungsten carbide materials using graphite, copper and copper–tungsten electrodes. They stated that MRR increased with increasing discharge current and that the highest MRR value was obtained with the graphite electrode; however, the Ra value increased with the increase of the discharge current [13]. Son *et al* investigated the influence of the electrical pulse on machining characteristics in the EDM process and found that the pulse duration considerably affected MRR, TWR and surface accuracy [14]. A study was conducted by Gostimirovic *et al* on the effects of electrical processing parameters on die sinking EDM performance. In the machining of a manganese–vanadium tool steel workpiece using a graphite electrode, they found that the discharge current and pulse duration had highly influenced the MRR of the EDM process [15]. In the Khan study, aluminum material and mild steel were processed with copper and brass electrodes. Increased abrasion was seen on the electrodes when the discharge current was increased, with the brass electrode exhibiting more erosion than the copper electrode. This occurred because the thermal conductivity and melting point of the copper electrode were higher than those of the brass. The MRR increased in parallel with the discharge current, and the highest MRR was obtained in the processing of the aluminum material with the brass electrode [16]. In the study of Amorim and Weingaertner, AISI P20 tool steel was processed with copper and graphite electrodes in a sinker EDM machine. The highest MRR value was obtained using the graphite electrode with a negative polarity, while the graphite and copper electrodes exhibit similar performances in positive polarization. The researchers obtained the best Ra values under the test condition in which the copper electrode had a negative polarity [17]. Dewangan *et al* investigated the effect of electrodes on surface integrity using the EDM method. They used copper, brass and graphite electrodes in their experimental studies and obtained the best surface finish with the copper electrode. They stated that the discharge current was the most effective parameter on surface roughness [18]. Torres *et al* studied the influence of EDM parameters using a graphite electrode on an INCONEL 600 alloy. They evaluated the machining performances in terms of MRR, electrode wear, and surface roughness, and reported that better results were achieved with the graphite electrode having a negative polarity [19].

Previous studies show that, the use of mathematical modeling such as optimization and artificial neural networks is beneficial in terms of cost and time. Jung and Kwon used the Taguchi technique in experimental studies to investigate the effect of processing parameters on the experimental results. They stated in the conclusion of their study that the most effective processing parameter was the discharge current [20]. In another studies using the Taguchi method, Lin *et al* supported their work with analysis of variance (ANOVA) and noted that the discharge current and pulse duration increased the MRR, but had a negative effect on the Ra value [21]. Nikalje *et al* in their study, processed MDN 300 steel using EDM and found the most effective processing parameters to be the discharge current, pulse-on time, and pulse-off time. They stated that increasing the discharge current and pulse duration negatively affect the workpiece surface roughness [22]. The experimental investigation of Mohanty *et al* examined the machinability of Inconel 718 super alloy via the EDM process to identify the multiple performance characteristics of MRR, TWR, surface roughness, and radial overcut. Nonlinear regression analysis was conducted to develop a valid empirical model relating to the process parameters. They reported that the optimal levels of cutting parameters obtained for both the algorithms were validated through confirmation testing [23].

In the EDM technique, the determination of the machining parameters for the workpiece and electrode pair significantly affects the processing outputs. Determination of the appropriate levels of the processing parameters used is another important point in EDM. The Taguchi technique is often used to optimize processing parameters. The significance levels of the processing parameters on the process outputs can be determined using variance analysis ANOVA. The present study aimed to overcome the deficiency in the literature on the machinability of caldie cold work tool steel, widely used in mold production, using EDM. Thus, the study investigated its machinability using EDM with copper and graphite electrodes.

In this study, the investigation into the erosion process of caldie cold work tool steel using the EDM technique was carried out both experimentally and via mathematical modeling. In the experimental design, three levels of discharge current and three levels of pulse duration were used as the major process control parameters, with graphite and copper electrodes as the tools. The MRR and TWR were calculated using the results obtained from the experiments. Surface roughness, MRR and TWR were studied in depth using regression analysis. The most favorable machining parameters were determined for specified combinations of yield parameters via the Taguchi method. The role of the major process control parameters on the yield parameters was determined by ANOVA. The theoretical data were compared with the experimental data to validate the efficacy of the optimization. The data obtained in the experimental study were interpreted by scanning electron microscopy (SEM) images and supported by graphs.

2. Materials and methods

The experimental study was carried out on a FURKAN EDM M25A sinker electro erosion machining center. Caldie plastic mold tool steel was used as the workpiece. Caldie plastic mold steel is a non-standard cold work tool steel patented by Uddeholm Tooling, a Swedish tool steel manufacturer [24]. The chemical composition of caldie

Table 1. Chemical composition of caldie plastic mold tool steel.

Elements	C%	Si%	Mn%	Cr%	Mo%	V%	Fe%
wt.%	0.7	0.2	0.5	5.0	2.3	0.5	Balance

Table 2. Physical properties of graphite and copper electrodes.

Properties	Unit	Graphite	Copper
Density	g/cm^3	1.85	8.92
Melting point	°C	3350	1083
Electrical resistivity	µΩcm	1100	9
Thermal conductivity	W/mK	116	391
Hardness	HB	10	100

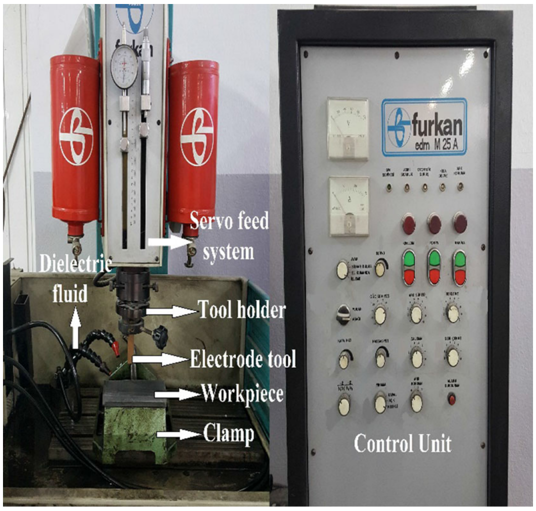


Figure 1. Experimental set-up.

plastic mold tool steel is shown in table 1. The electrodes used were of graphite and copper, in dimensions of 15 × 15 × 100 mm. Table 2 shows the physical properties of the graphite and copper electrodes.

The electrodes were prepared individually for each test condition. The surfaces of the electrodes were polished progressively using 200–1200 grid sandpaper. In the experiments, the processing time was kept constant at 1 h. The kerosene used as the dielectric medium fluid in the machinability tests was applied using lateral spraying. The surface roughness measurements were taken after the machining using the Mitutoyo SJ 410 device. The mean surface roughness (Ra) value was taken as the average of the values measured on three different areas of the treated surfaces. The Precisa XB200h precision scale with an accuracy of 1/10000 was used for weight measurements. Equations (1) and (2) were used to calculate MRR and TWR values. The experimental set-up is shown in figure 1.

$$MRR\left(\mathrm{mm}^3/\mathrm{min}\right) = \frac{\left(W_i - W_f\right)}{\rho x t} \tag{1}$$

$$TWR\left(\mathrm{mm}^3/\mathrm{min}\right) = \frac{\left(T_i - T_f\right)}{\rho x t} \tag{2}$$

In these equations, W_i is the initial weight of the workpiece and W_f is the final weight, T_i is the initial weight of the electrode and T_f is the final weight, ρ is the density and t is the processing time.

3. Experimental design and optimization

In the studies conducted in the field of machinability, different statistical analysis methods have been used to optimize the cutting parameters and to determine their effect on the results. The most commonly applied of these are the Taguchi and ANOVA analyses [25–27]. Experimental set was prepared using the Taguchi method. Thus, the effect of the parameters on the test results can be calculated. The optimum test condition can also be determined using the Taguchi method. The ANOVA method is used to determine the relationship between inputs and outputs and the magnitude of the relationship. In experimental studies especially, it is very important in the interpretation of the test results to determine whether there is a relationship between the test parameters used and the experimental results. Regression analysis is one of the most frequently used subject areas of statistics. In case of multiple factors affecting an event, it is possible to investigate the cause–effect relationship via regression analysis.

Certain characteristics are used in the evaluation of test results obtained using the Taguchi method. One of these, “Smallest is better”, was selected for Ra and TWR in this study because Ra and TWR are required to be low during the electro erosion process. The “Smallest is better” approach of the Taguchi method is given in Eq. (3). The “Larger is better” approach, as shown in Eq. (4), was used for MRR. In Eqs. (3) and (4), *yi* is the performance response, *i* is the observation value and *n* is the number of tests in an experiment [28, 29].

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{3}$$

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right] \tag{4}$$

The signal/noise (S/N) ratio is based on both the mean values and the variability. The signal (S) factor refers to the real value obtained from the system, while the noise (N) factor refers to the factors which are not taken into consideration in the experimental design but have an effect

Table 3. Control factors and levels.

Factor	Unit	Level 1	Level 2	Level 3
Tool material	–	Graphite	Copper	
Discharge current	A	6	12	25
Pulse duration	µs	50	100	200

Table 4. Taguchi L_{18} orthogonal experimental design.

Test no.	Variables	Tool material	Discharge current (A)	Pulse duration (µs)
1	$A_1B_1C_1$	Graphite	6	50
2	$A_1B_1C_2$	Graphite	6	100
3	$A_1B_1C_3$	Graphite	6	200
4	$A_1B_2C_1$	Graphite	12	50
5	$A_1B_2C_2$	Graphite	12	100
6	$A_1B_2C_3$	Graphite	12	200
7	$A_1B_3C_1$	Graphite	25	50
8	$A_1B_3C_2$	Graphite	25	100
9	$A_1B_3C_3$	Graphite	25	200
10	$A_2B_1C_1$	Copper	6	50
11	$A_2B_1C_2$	Copper	6	100
12	$A_2B_1C_3$	Copper	6	200
13	$A_2B_2C_1$	Copper	12	50
14	$A_2B_2C_2$	Copper	12	100
15	$A_2B_2C_3$	Copper	12	200
16	$A_2B_3C_1$	Copper	25	50
17	$A_2B_3C_2$	Copper	25	100
18	$A_2B_3C_3$	Copper	25	200

on the test result. The sources that cause noise are all variables that result in a deviation from the intended value. Table 3 shows the test variables and their levels.

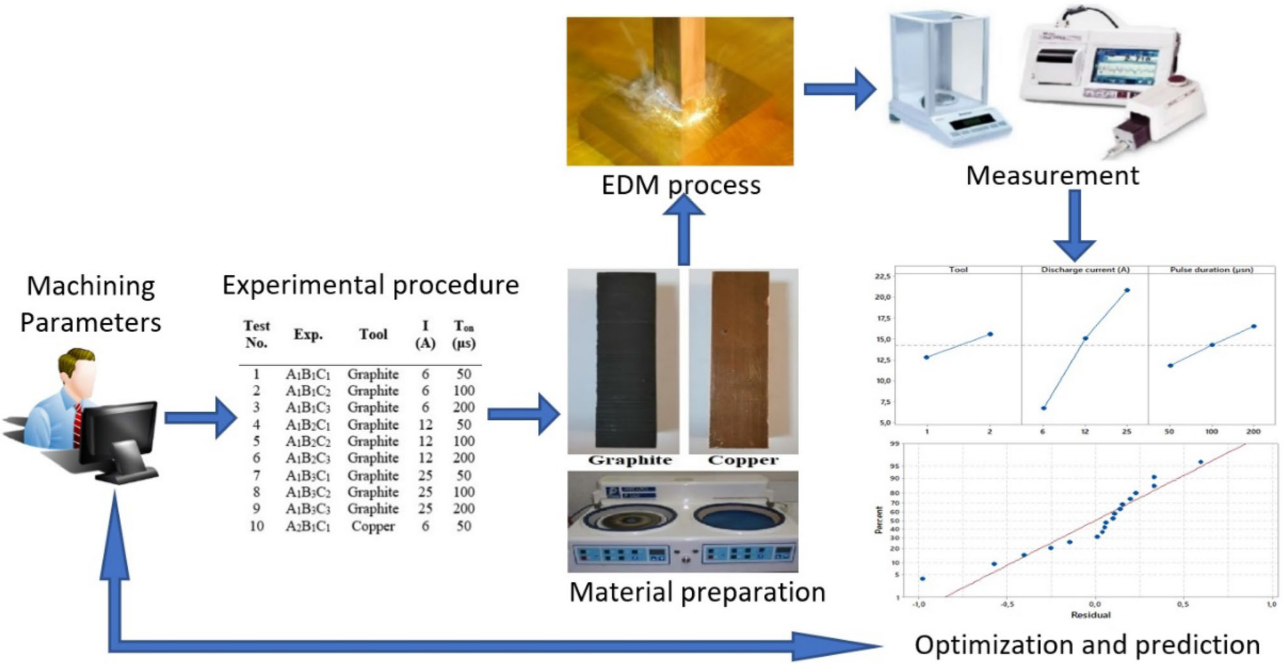
In this study, two different electrodes, three different discharge current and three pulse duration current values were taken as control factors. The Taguchi L_{18} experimental design was used with Minitab software. Table 4 shows the design of the experiment determined by the Minitab package program and the test variables assigned in accordance with the matrix. Figure 2 shows the experimental procedure as a schematic diagram.

4. Results and discussion

4.1 *Analysis of experimental results*

Table 5 shows the Ra values of the surfaces processed using graphite and copper electrodes and the MRR, TWR values calculated using Eqs. (1) and (2). In table 5, the highest Ra value (10.36 µm) was obtained with the copper electrode during the test conditions using processing parameters of 25 A discharge current at 200 µs pulse duration. The highest Ra value with the graphite electrode was 9.38 µm.

Figure 3 shows the effect of discharge current and pulse duration on the Ra. The graph shows that the increases in discharge current caused higher Ra values with both electrodes. In the graph, it can be seen that the Ra value was more adversely affected by the discharge current under processing with the copper electrode. Figure 3 shows that



Test No.	Exp.	Tool	I (A)	T_{on} (µs)
1	$A_1B_1C_1$	Graphite	6	50
2	$A_1B_1C_2$	Graphite	6	100
3	$A_1B_1C_3$	Graphite	6	200
4	$A_1B_2C_1$	Graphite	12	50
5	$A_1B_2C_2$	Graphite	12	100
6	$A_1B_2C_3$	Graphite	12	200
7	$A_1B_3C_1$	Graphite	25	50
8	$A_1B_3C_2$	Graphite	25	100
9	$A_1B_3C_3$	Graphite	25	200
10	$A_2B_1C_1$	Copper	6	50

Figure 2. Experimental procedure.

under equivalent experimental conditions, better Ra results were obtained in the trials with the graphite electrode.

Increase in discharge current results impulsive force acting on the workpiece high. This enhances formation of large and deep craters and consequently high material removal efficiency. Also increase in discharge current causes high material removal rate which deteriorates surface of workpiece. Hence an approximate increasing trend of Ra is observed with increase in discharge current. Figure 4 shows SEM images of surfaces processed using copper and graphite electrodes at 12 A discharge current and 200 µs pulse duration. Bubbles adversely affecting the Ra were formed due to rapid cooling and can be seen in the processing zone. The craters and micro-cracks on the surface likewise negatively affected the Ra [30, 31]. The topography of the graphite electrode treated surface in figure 4b is better than that seen in figure 4a.

Table 5. Experimental results.

Test no.	Variables	Ra (µm)	MRR (mm^3/min)	TWR (mm^3/min)
1	$A_1B_1C_1$	3.11	0.82	0.144
2	$A_1B_1C_2$	3.72	1.76	0.241
3	$A_1B_1C_3$	4.14	2.94	0.372
4	$A_1B_2C_1$	5.16	4.16	0.405
5	$A_1B_2C_2$	5.38	5.12	0.471
6	$A_1B_2C_3$	6.05	6.35	0.650
7	$A_1B_3C_1$	6.76	8.98	0.946
8	$A_1B_3C_2$	8.28	10.04	1.032
9	$A_1B_3C_3$	9.38	11.65	1.196
10	$A_2B_1C_1$	4.15	2.15	0.242
11	$A_2B_1C_2$	4.64	2.91	0.325
12	$A_2B_1C_3$	4.92	3.87	0.478
13	$A_2B_2C_1$	5.37	5.13	0.515
14	$A_2B_2C_2$	5.74	6.3	0.592
15	$A_2B_2C_3$	7.29	7.92	0.725
16	$A_2B_3C_1$	8.74	10.56	1.065
17	$A_2B_3C_2$	9.32	11.83	1.145
18	$A_2B_3C_3$	10.36	13.55	1.320

Figure 5 shows the effect of the discharge current and pulse duration on MRR. It can be seen that an increase of discharge current increased the MRR under processing with both the graphite and the copper electrodes. The increase in the discharge current caused more material melting and evaporation of the workpiece surface in the unit time [32]. This led directly to the increase of the MRR.

Figure 6 shows the SEM image of a surface processed at 25 A discharge current and 200 µs pulse duration using the copper electrode. The highest MRR (13.55 mm^3/min) was obtained under the current test condition. With the electro erosion process, the arcs coming from the electrode to the surface make pulses on the workpiece in an irratic manner. Therefore, the topography of the surface displays a varied form. Increased discharge current increased the intensity of the arc applied to the surface and caused deeper craters and pits. With the use of the dielectric liquid, larger particles were removed from the surface from these craters and pits and the processing was achieved. This situation enabled the MRR to reach high values. A longer duration of discharges applied to the workpiece surface also increased the amount of melted and vaporized material.

Figure 7 shows the effect of the discharge current and pulse duration on the amount of electrode wear formed after processing using the copper and graphite electrodes. Increase in discharge current results in higher degree of

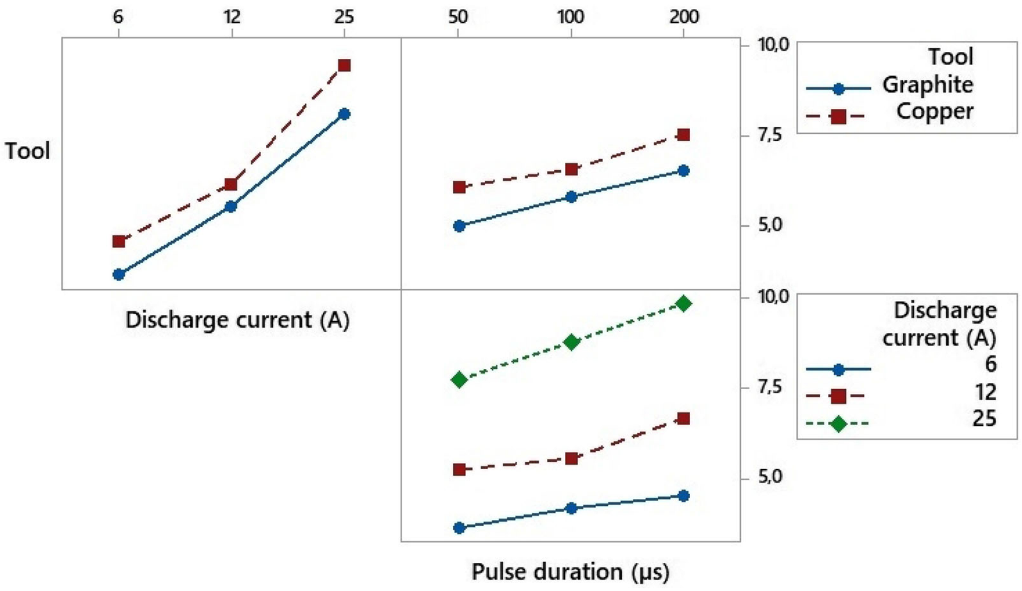


Figure 3. Effect of tool material, discharge current and pulse duration on Ra.

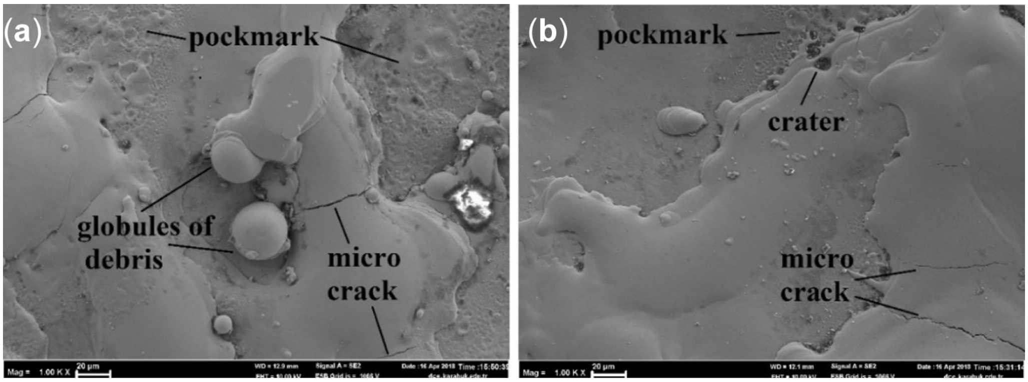


Figure 4. SEM surface images after machining at 12 A discharge current and 200 µs pulse duration: (**a**) copper electrode; (**b**) graphite electrode.

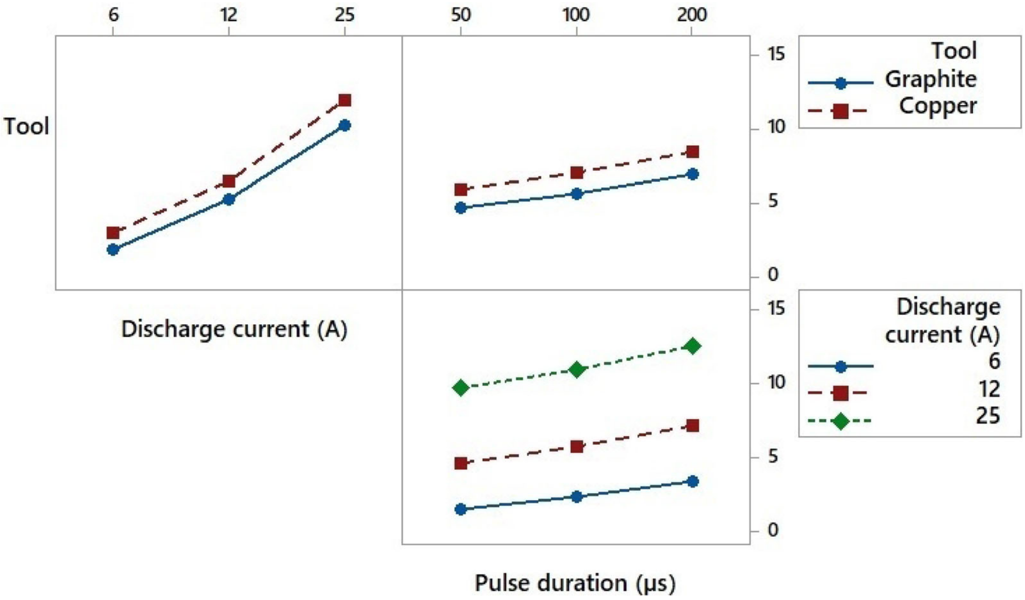


Figure 5. Effect of tool material, discharge current and pulse duration on MRR.

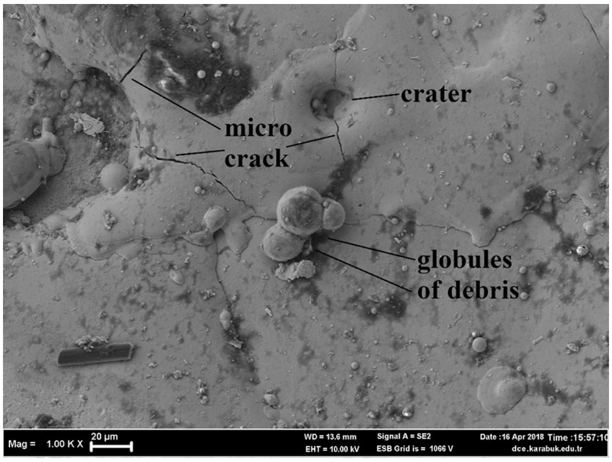


Figure 6. SEM surface image after machining with copper electrode at 25 A and 200 µs.

material erosion form the tool electrode. Therefore, with increase in discharge current, gradual increase in tool wear rate is observed. Figure 7 shows that the copper electrode was more eroded with the increasing discharge current. In the studies where the discharge current was increased to 25 A, the electrode was reported to have been more eroded. In the study in which the pulse duration and discharge current were high (24 A, 200 µs), the highest TWR value obtained was 1.32 mm^3/min. As seen in figure 7, in the experiment using the graphite electrode, when the discharge current was increased, the amount of wear on the electrode also increased. Figure 7 shows that the copper electrode was more worn than the graphite electrode. The highest TWR with the graphite electrode was calculated as 1.196 mm^3/min under the test conditions of 25 A discharge current and 200 µs pulse duration. The reason for this was that electrode materials with low melting temperatures are

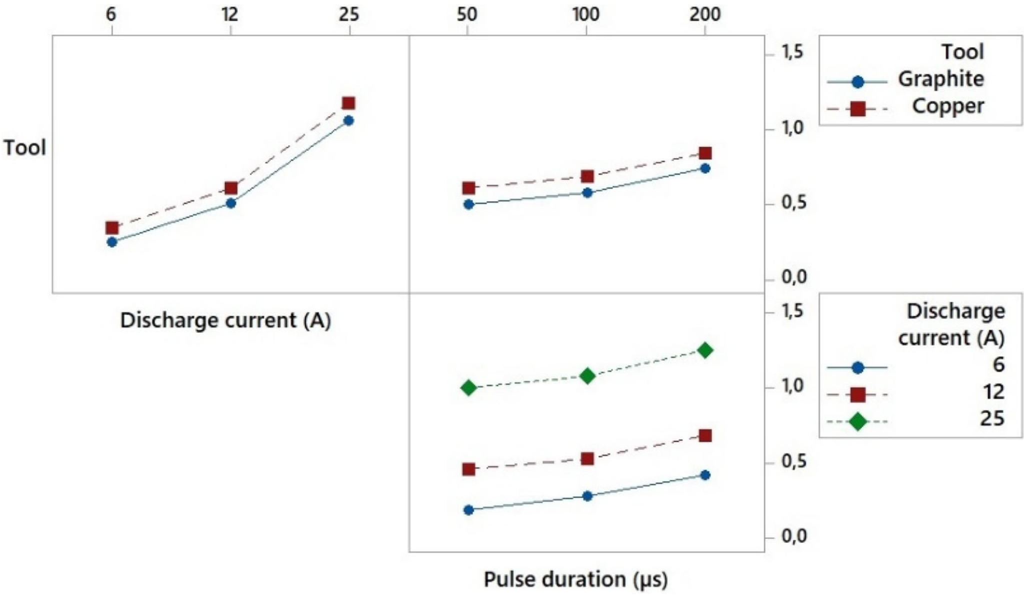


Figure 7. Effect of tool material, discharge current and pulse duration on TWR.

more subject to wear than electrode materials with high melting temperatures. The low melting temperature of the copper electrode compared to the graphite caused the TWR to be higher. The lower the TWR, the lower the electrode consumption and hence, the electrode production cost [33, 34].

4.2 *Signal-to-noise (S/N) analysis*

Using the Taguchi optimization technique, signal/noise (S/N) ratios were obtained for each combination of parameters in the orthogonal test sequence for Ra, MRR and TWR. The results obtained in the Taguchi experiments were converted to S/N ratios. In the S/N ratio results, the larger value is separated into the nominal value and the minimum value and analyzed by calculating it in that way. The highest S/N ratio according to the results shows the best performance. The calculated S/N ratios for Ra, MRR and TWR are shown in figure 8. The S/N ratios given in figure 8 show that the most effective factors on MRR and TWR were the discharge current, pulse duration and tool material, respectively.

The S/N ratios shown in figure 8 are given in a chart form in table 6 for a better understanding of the effects of the machinability factors and levels on Ra, MRR and TWR. These values in table 6 show the effect of each factor level on changes of Ra, MRR and TWR. The most effective factors and levels on the parameters are given in bold in table 6. In the Taguchi method results the most effective factors and levels found for Ra were the tool material (1), discharge current (1) and pulse duration (1). The most effective factors and levels for MRR were the tool material (2), discharge current (3) and pulse duration (3) and for TWR they were the tool material (1), discharge current (1) and pulse duration (1).

4.3 *ANOVA analysis*

The ANOVA is used to determine the relationship between inputs and outputs and the magnitude of each relationship. In experimental studies especially, it is very important to determine the existence of a relationship between the test parameters used and the experimental results. The ANOVA was used in the statistical analysis of the experimental results using the Taguchi design. The difference of the group variables compared to the average performance was examined. This mathematical technique divides the total variability into its components by calculating values including the sum of squares, degree of freedom, variance, F-ratio and *p*-values [25]. Table 7 shows the ANOVA results at 95% confidence level for Ra, MRR and TWR.

According to the ANOVA results obtained in table 7, the effects of the factors on Ra, MRR and TWR are given in graphic form in figure 9. Figure 9 shows that the factors effective on Ra were the discharge current at 84.28%, pulse duration at 8.19% and tool material at 5.06%. Factors influencing the MRR were the discharge current at 89.48%, pulse duration at 6.84% and tool material at 3.32%. The ANOVA analysis of TWR results showed that the factors affecting TWR were the discharge current at 90.23%, pulse duration at 7.53% and tool material at 2.16%.

The *p*-value determines the significance of the model and individual parameters. In general, a parameter having a *p*-value of less than 0.05 was considered to have a significant effect. Although the significance of each parameter was justified by its contribution factor, the F-test and probability

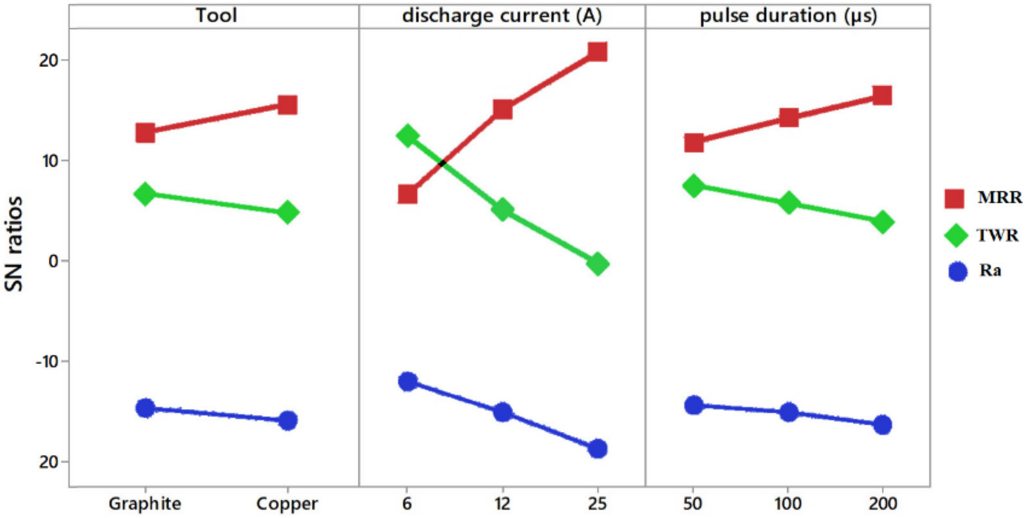


Figure 8. S/N ratios for machinability parameters.

Table 6. S/N ratios for Ra, MRR and TWR.

Output	Levels	Tool material	Discharge current (A)	Pulse duration (µs)
Ra	1	**−14.72**	**−12.19**	**−14.42**
	2	−16.12	−15.26	−15.38
	3	–	−18.82	−16.47
	Delta	1.40	6.63	2.05
MRR	1	12.845	6.706	11.841
	2	**15.602**	15.131	14.309
	3	–	**20.833**	**16.519**
	Delta	2.757	14.127	4.678
TWR	1	**6.0631**	**11.0465**	**7.1177**
	2	4.1637	5.2071	5.2942
	3	–	−0.9134	2.9282
	Delta	1.8994	11.9599	4.1895

values reconfirmed the significance of the process parameter. Table 7 shows higher discharge current F-values for Ra, MRR and TWR (i.e., 204.47; 1490.88 and 7169.39 respectively) and lower *p*-values (below 0.05), proving that the model was significant and could be used to optimize the machining parameters in the sinker electrical discharge machining of caldie plastic mold tool steel.

4.4 *Regression analysis*

Regression analysis is one of the most frequently used subject areas of statistics. In the case of multiple factors affecting an event, investigation of the cause–effect relationship is made possible by multiple regression analysis. A regression model consists of dependent and independent variables. The independent variable is the non-random variable used to describe the dependent variable. In general, multiple regression analysis is used to find the mean output values for the dependent variable [35–37].

The coefficient of determination, expressed as R^2, indicates the reliability of the predicted model. In regression analysis results, the closer the R^2 is to "1", the better the independent variable explains the change in the dependent variable [35]. The regression analysis used the tool material, discharge current and pulse duration as the machining parameter variables to estimate the Ra, MRR and TWR.

For this, regression equations were formed for Ra, MRR and TWR by using statistical data obtained using the experimental data in table 5. The functional form of the simple linear regression model can be written in the form of Eq. (5) for a set. In this equation, y denotes the output, v_1, v_2 and v_3 the variables and β represents the regression coefficient.

$$y = \beta_0 + \beta_1.v_1 + \beta_2.v_2 + \beta_3.v_3 \tag{5}$$

Table 7. ANOVA results for Ra, MRR and TWR.

	Factors	Degree of freedom	Sum of squares	Mean of squares	F ratio, α=0.05	P
Ra	Tool material	1	4.061	4.0613	24.55	0
	Discharge current	2	67.661	33.8307	204.47	0
	Pulse duration	2	6.572	3.2858	19.86	0
	Error	12	1.985	0.1655		
	Total	17	80.28			
MRR	Tool material	1	8.542	8.542	110.67	0
	Discharge current	2	230.145	115.072	1490.88	0
	Pulse duration	2	17.602	8.801	114.03	0
	Error	12	0.926	0.077		
	Total	17	257.215			
TWR	Tool material	1	0.05014	0.05014	343.74	0
	Discharge current	2	2.09147	1.04573	7169.39	0
	Pulse duration	2	0.17451	0.08725	598.2	0
	Error	12	0.00175	0.00015		
	Total	17	2.31787			

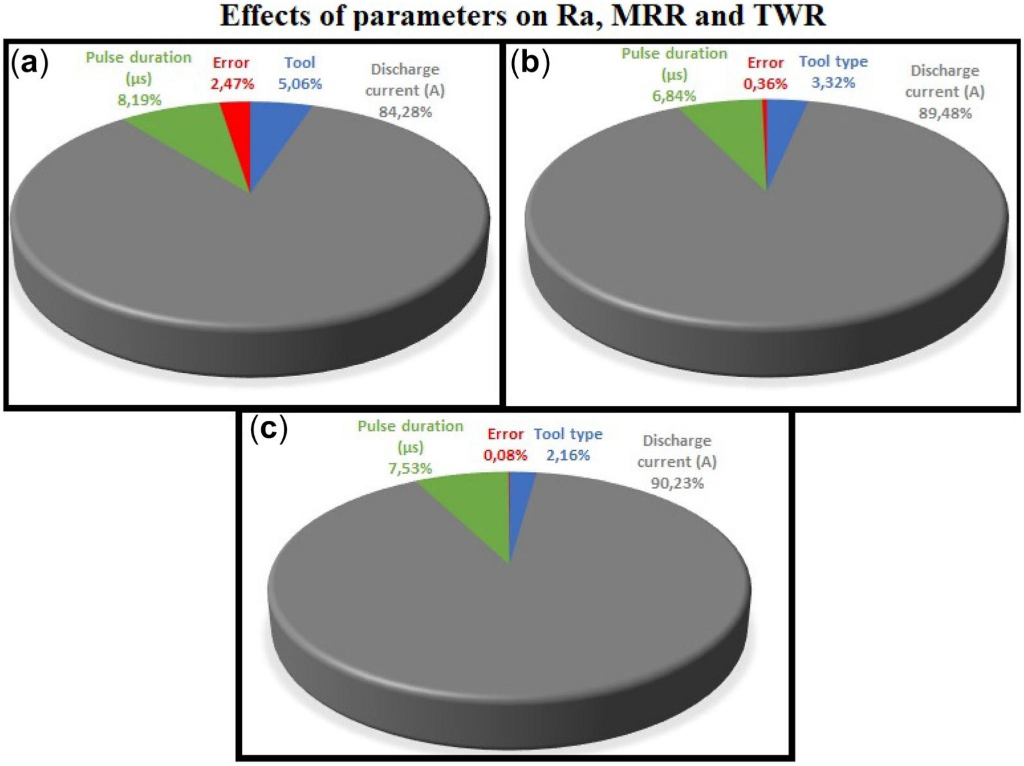


Figure 9. Graphical representation of the ANOVA results: (**a**) Ra; (**b**) MRR; (**c**) TWR.

The regression equations show the relationship between the input parameters and the outputs. Using data obtained experimentally under the machining conditions given in table 5, the regression equations of the system for Ra, MRR and TWR were generated as Eq. (6), (7) and (8) respectively.

$$Ra(\mu m) = 0.203 + 0.95 * Tool\,material + 0.2441 * discharge\,current + 0.00963 * pulse\,duration \quad (6)$$

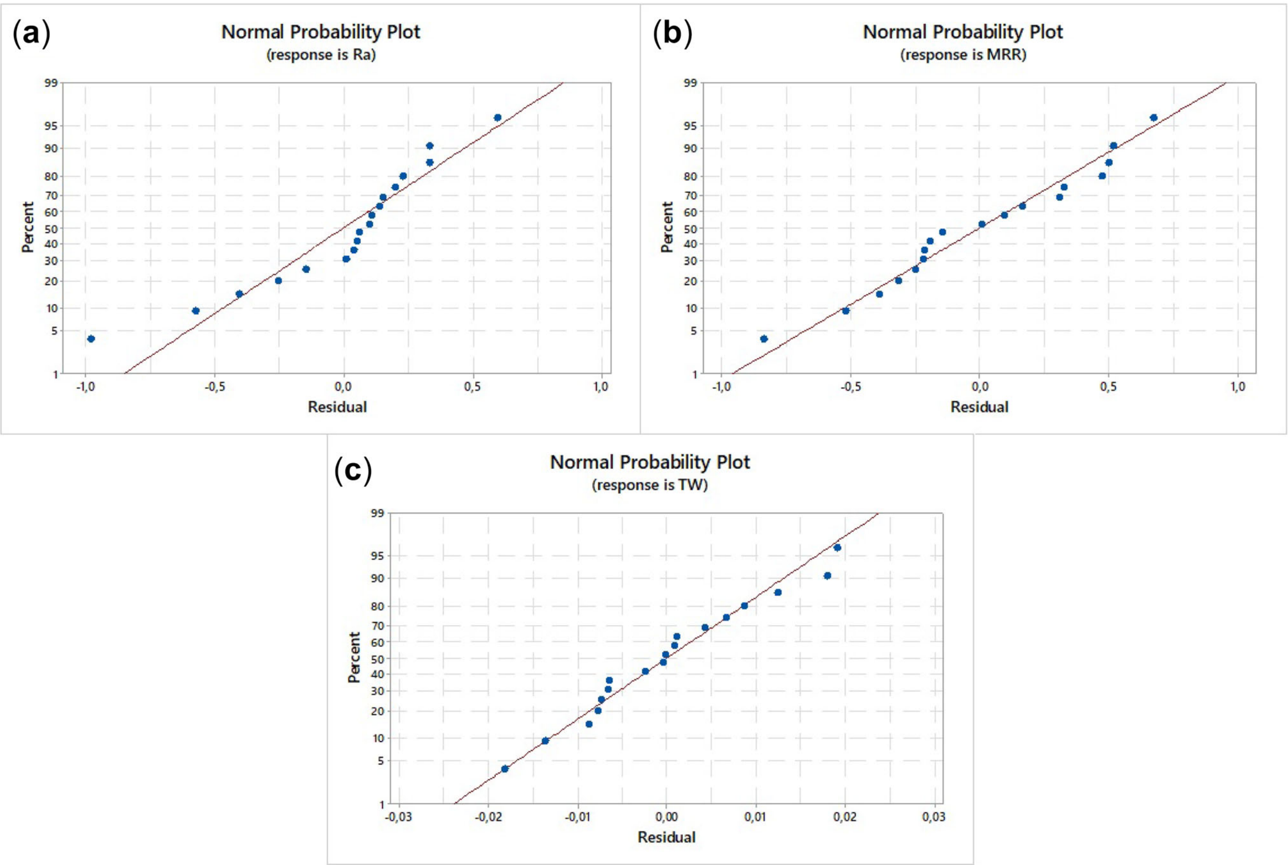


Figure 10. Normal probability plot of the residuals: (**a**) Ra; (**b**) MRR; (**c**) TWR.

$$MMR\left(\mathrm{mm}^3/\mathrm{min}\right) = -3.898 + 1.378\, Tool\, material + 0.4492 * discharge\, current + 0.01577 * pulse\, duration \quad (7)$$

$$TWR\left(\mathrm{mm}^3/\mathrm{min}\right) = -0.2995 + 0.10556 * Tool\, material + 0.042984 * discharge\, current + 0.001579 * pulse\, duration \quad (8)$$

In this study, the value of R^2 was found to be 97.17% for Ra, 98.89% for MRR and 99.92% for TWR. A strong relationship (evaluated as close to "1") was noted among the variables. The resulting R^2 value indicated that the regression model was successful. Figure 10a–c shows that the correlation coefficient of the plots was greater than the critical value, indicating that the normal distribution of residuals was satisfied.

4.5 *Determination of optimum Ra, MRR and TWR*

In order to test the accuracy of the optimum processing parameters obtained using the Taguchi technique, verification tests needed to be carried out. The optimum levels calculated for Ra, MRR and TWR in the verification experiments are shown in table 8. The optimum test conditions for Ra and TWR were $A_1B_1C_1$. The optimum processing conditions for MRR were $A_2B_3C_3$. Equations (9), (10) and (11) were used to calculate the optimum test conditions for Ra, MRR and TWR respectively.

$$R_{a_{opt}} = (A_1 - T_{R_a}) + (B_1 - T_{R_a}) + (C_1 - T_{R_a}) + T_{R_a} \quad (9)$$

$$MRR_{opt} = (A_2 - T_{MRR}) + (B_3 - T_{MRR}) + (C_3 - T_{MRR}) + T_{MRR} \quad (10)$$

$$TWR_{opt} = (A_1 - T_{TWR}) + (B_1 - T_{TWR}) + (C_1 - T_{TWR}) + T_{TWR} \quad (11)$$

The values used in these equations ($A_1B_1C_1$), ($A_2B_3C_3$) and ($A_1B_1C_1$) are the mean values of the S/N ratios shown in table 8, while the T_{R_a}, T_{MRR} and T_{TWR} values are the mean values of the experimental test results.

The results of the validation test and the optimum variable levels were evaluated by taking into account the

Table 8. Mean S/N ratios.

	Level	Tool material	Discharge current (A)	Pulse duration (µs)
Ra	1	5.776	4.113	5.548
	2	6.726	5.832	6.180
	3		8.807	7.023
MRR	1	5.758	2.408	5.3
	2	7.136	5.830	6.327
	3		11.102	7.713
TWR	1	0.6063	0.3003	0.5528
	2	0.7119	0.5597	0.6343
	3		1.1173	0.7902

Table 9. Experimental and prediction results.

Output	Level	Experimental result	Taguchi prediction	Error%	Regression prediction	Error%
Ra	$A_1B_1C_1$	3.11	2.93	5.78	3.09	0.64
MRR	$A_2B_3C_3$	13.55	13.07	3.67	13.24	2.28
TWR	$A_1B_1C_1$	0.144	0.141	2.08	0.143	0.69

confidence interval *CI* value and calculated, respectively, using Eq. (12) and (13) [35].

$$CI = \sqrt{F_{0.05}(1, v_e)V_e\left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \qquad (12)$$

$$n_{eff} = \frac{N}{1 + v_T} \qquad (13)$$

The values $F_{0.05}$ (1, v_e) in the equations took into account the *F* (error degrees of freedom) in the table. Here, V_e refers to the error degrees of freedom, n_{eff} the number of experimental repetitions, *r* the number of validation experiments, *N* the total number of experiments and v_T the sum of the degrees of freedom of the variables. The *CI* values calculated at a 95% reliability estimate using Eqs. (12) and (13) were found to be 0.723 for Ra, 0.493 for MRR and 0.021 for TWR are calculated as follows.

$$\left(Ra_{opt} - CI\right) < R_{a_{exp.}} < \left(Ra_{opt} + CI\right) = 2.1 < 3.11 < 3.55$$

$$\left(MRR_{opt} - CI\right) < MRR_{exp.} < \left(MRR_{opt} + CI\right) = 12.57 < 13.55 < 13.56$$

$$\left(TW - CI\right) < TW_{exp.} < \left(TW_{opt} + CI\right) = 0.119 < 0.157 < 0.162$$

As the results of Ra, MRR and TWR were measured within the confidence interval, the optimization study performed using the Taguchi method at a significance level of 0.05 was considered to be successful.

4.6 *Experimental validation*

Verification experiments were performed on the machining parameters to find optimum values for the best results and prediction model. Table 9 shows the results obtained by the Taguchi optimization and the regression equation. The regression model estimation values were closer to the experimental results than the Taguchi estimation results (table 9). Accordingly, these results demonstrate that the optimization study was successful.

5. Conclusions

This study investigated the machinability of caldie plastic mold steel using different processing parameters with graphite and copper electrodes in a sinker EDM center. An optimization and estimation model was developed using experimental results. The results were examined experimentally and statistically and the findings are given below.

- An increase in the discharge current negatively affected Ra and TWR, while the MRR was positively affected.
- Under equivalent test conditions, lower Ra values were obtained with the graphite electrode compared to the copper electrode.
- Using the same experimental parameters, higher MRR and TWR values were calculated with the copper electrode compared to the graphite electrode.
- As a result of the Taguchi optimization, the optimum processing parameter levels for Ra and TWR were

determined as $A_1B_1C_1$, while levels for MRR were found to be $A_2B_3C_3$.

- As a result of the ANOVA, the tool material was effective by 84.28%, followed by the discharge current by 8.19%, and the pulse duration by 5.06%.
- The effect rates of the parameters on MRR were 89.48% for the discharge current, 6.84% for the pulse duration and 3.32% for the tool material.
- According to ANOVA results, the factors affecting TWR were calculated and ranked as discharge current (90.23%), pulse duration (7.53%) and electrode material (2.16%).
- The values calculated for the experimental results and the estimated results were close, thus demonstrating the success of the optimization study.

Nomenclature

EDM	Electric discharge machining
MRR	Material removal rate, mm^3/min
TWR	Tool wear rate, mm^3/min
W_i	Initial weight of the workpiece, g
W_f	Final weight of the workpiece, g
T_i	Initial weight of the electrode, g
T_f	Final weight of the electrode, g
ρ	Density, g/cm^3
t	Time, min
R^2	Coefficient of determination
V_e	Error degrees of freedom
n_{eff}	Number of experimental repetitions
r	Number of validation experiments
N	Total number of experiments
v_T	Sum of the degrees of freedom
CI	Confidence interval

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