Determination of Multi-performance Characteristics in Electric Discharge Machining of DIN 1.2767 Steel Using Grey Relational Analysis

Abubaker Y. Fatatit[1] and Ali Kalyon[2]

[1]Department of Manufacturing Engineering, Natural and Applied Sciences, Karabük University,
Karabük 078050, Turkey

[2]Department of Mechanical Engineering, Faculty of Engineering, Yalova University,
Yalova 077200, Turkey

***Abstract*—Electric discharge machining (EDM) is one of the most important unconventional machining processes, which can cut hard materials and complex shapes that are difficult to machine by conventional machining processes easily and with high accuracy. In this study, L18 orthogonal array combined with gray relational analysis (GRA) is implemented to investigate the multiple performances characteristics in EDM of DIN 1.2767 Tool Steel. Machining process parameters selected were discharge current (Ip), pulse-on time (T_{on}), pulse-off time (T_{off}), and electrode material (copper alloys [NSS and B2]). The investigated performances characteristics were tool wear rate (TWR) and material removal rate (MRR). Analysis of variance (ANOVA) and Taguchi's signal-to-noise ratio with the help of Minitab-17 software were used to analysis the effect of the process parameters on TWR and MRR. The experimental results and data analysis reveal that TWR and MRR are more affected by Ip and T_{on}. The minimum TWR was obtained at parametric combination Ip (6A), T_{on} (800 μs), and T_{off} (800 μs) and the maximum MRR attained at Ip (25A), T_{on} (800 μs), T_{off} (200 μs), and NSS electrode. After applying GRA, the optimal parametric combination for MRR and TWR was determined as Ip (25A), T_{on} (800 μs), T_{off} (200 μs), and NSS electrode. The study also exhibited the occurrence of an interaction between the variables on the responses. In addition, scanning electron microscopy images showed that the metal surface was affected with the increase in T_{on} and T_{off}.**

***Index Terms*—Electrical discharge machining, Gray relation, Optimization, Taguchi, DIN 1.2767 Tool steel.**

I. INTRODUCTION

The greatly improved properties of new engineering materials made it difficult to machine using the conventional machining processes. Non-conventional machining processes can easily machine hard and brittle materials, complex geometries, and delicate components with tight tolerance, extreme surface finish, and free of burrs. Electric discharge machining (EDM) is one of the non-conventional machining processes that based on the conversion of electric energy into extremely high temperature (plasma channel) in localized region impinge on the work material surface caused melting or evaporating (Amorim and Weingaertner, 2007; Ho and Newman, 2003; Muthuramalingam and Mohan, 2015). The width and intensity of the plasma channel depend on many parameters which have complex relationships between each other in addition to other factors that affect the process's mechanism, making it difficult to achieve optimal performance for the EDM process. High temperature causes melt and wear of the electrode. The most used electrodes, with high conductivity of electricity and a high melting point such as copper, are tungsten, copper tungsten, silver tungsten aluminum, graphite and other, and metals and alloys. The selection of electrode material relies on the type of the EDM machine power supply circuit, the surface quality, and the type of workpiece material that is to be machined (Daniel, 2019; Shyha and Rudd, 2016).

Several experimental tests, which have been conducted to increase efficiency and improve EDM process performance, were related to EDM and mentioned that substantial researches have been conducted for improving EDM performance measures such as material removal rate (MRR), tool wear rate (TWR), surface roughness (Ra), and wear ratio. The most widely used material are steel materials, EN series, Ti-6AL-4V, SiC, B_4C, WC-Co, Al_2O_3+Ti S45C, and Inconel 718. The main electric input parameters have been used are T_{on}, T_{off}, Ip, and V and non-electric parameters including dielectric medium, flashing pressure, and electrode rotation. There are many optimization techniques and result analysis tools used such as Taguchi, response surface methodology, gray relationships analysis, ANOVA, and multiple regression analysis (Ramabalan and S, 2015; Patil and Jadhav, 2016).

Yerui et al., 2016, conducted experiments on TiC/Ni using EDM. The experimental results revealed that as the Ip

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Corresponding author's e-mail: ali.kalyon@yalova.edu.tr

increased, the discharge energy increased, which results in an increase in the MRR. MRR increases with the increase of T_{on}, but when T_{on} was longer than 30 µs MRR decreased slowly. This was as a result of the expansion of the plasma channel and the effect of debris on it. Dastagiri and Kumar, 2014, reported that the higher the Ip, the more discharging energy. Then, the metal temperature rises in a very localized region, thus more MRR can be achieved. T_{on} increases, MRR increases and then decreases. Kalyon, 2020, applied Taguchi method and gray relational analysis (GRA) for optimization of EDM of Caldie cold work tool steel, considering process parameters such as Ip, T_{on}, and electrode materials (graphite and copper). The results revealed that with increasing Ip and T_{on}, the MRR and Ra increased. The optimal parameter setting for maximum MRR and minimum Ra obtained by GRA is graphite electrode, 6 A and 50 µs. Habib, 2009, performed experiments using copper as a tool electrode on an EDM with selected input parameters on conductive metal matrix composite Al/SiC. Results of the study showed that the higher Ip offered higher MRR. An increase of Ton caused an increase in MRR until it reached 200 µs and then MRR began to decrease. TWR was found to be directly proportional to Ip and Ton. Gopalakannan et al., 2013, investigated EDM performance and optimizing the process parameters of AL7075-B_4C MMC using response surface methodology. The process parameters were Ip, T_{on}, T_{off}, and gap voltage. It was concluded that the two main significant process parameters that affect the MRR were Ip and T_{on}. The MRR increased with the increase in T_{on} and then decreased with longer T_{on}. Furthermore, TWR decreased with the increase of T_{on}. Ip and T_{on} have statistically significant effect on TWR. Venkatesh et al., 2015, studied the EDM performance of EN 31, EN 8, and HCHCr, and they used three electrodes, copper, brass, and chromium copper. They mentioned that the optimal MRR and TWR were at chromium copper electrode followed by copper then brass. The brass electrode achieved minimal surface roughness, but TWR was high and MRR was low. Besides, performance measures were influenced by workpiece material. Kumar, 2012, conducted EDM experiments on OHNS Die Steel using three different electrodes (copper-chromium, brass, and copper). Their results showed that the copper-chromium electrode produced higher MRR, better surface finish, and lower TWR compared to other electrodes. Lin and Lin, 2002, adopted the orthogonal array (OA) with GRA for multiperformance characteristics optimization of KD11 alloy steel. It was concluded that the performance characteristics such as MRR, TWR, and surface roughness were improved. Doniavi et al., 2008; Singh et al., 2004, concluded that OA and GRA can be successfully applied to obtain optimal level of EDM process parameters for multiperformance characteristics.

The electrode performance used in EDM is an important problem affecting machinability. TWR and MRR are important performance measures when evaluating the electrode performance. The low rate of wear of the electrode will ensure the dimensional integrity of the workpiece. High MRR will result in shorter machining times and reduced machining costs. This study aims to determine the optimal parametric setting for minimizing TWR and maximizing MRR on DIN 1.2767 steels by applying GRA. In addition to determine the effect of the process parameters on TWR and MRR Taguchi optimization method was used. As a result, machinability of DIN 2767 Tool Steel was improved by using application of EDM method.

II. Experimental Setup

The experiments were designed according to L_{18} Taguchi OA and performed on the FURKAN M25A sinker EDM machine. The experimental setup of EDM machine is shown in Fig. 1. Two electrodes, B2 and NSS, with a diameter of 16 mm were used. The physical properties and chemical compositions of electrodes are presented in Tables I-III. Before conducting each experiment, the electrode was polished on silicon carbide paper with grit sizes in this sequence, 150, 240, 320, 400, 600, and 800. The work material was DIN 1.2767 tool steel. This type of steel has crucial application in industry such as cutting and bending tools, drawing jaws, plastic molds, gears requiring shock resistance, heavy-duty shafts, and axles. Its chemical composition is listed in Table IV.

The size of each workpiece is 50 mm × 25 mm × 12 mm. The work materials' surface was machined by milling and grinding machines before conducting the EDM experiments. The electrode materials, Ip, T_{on}, and T_{off}, were selected as process parameters. Table V illustrates the process parameters and their levels. The polarity of the workpieces was positive and the electrode was negative. The kerosene was chosen as a dielectric fluid with lateral flushing pressure of 0.25 bar. The EDM time of each experiment was 1 h. The workpieces and the electrode were weighed before and after conducting the experiments. MRR and TWR can be calculated as below:

$$MRR\,(mm^3\,/\,min) = \frac{W_i - W_f}{t * \rho} \tag{1}$$

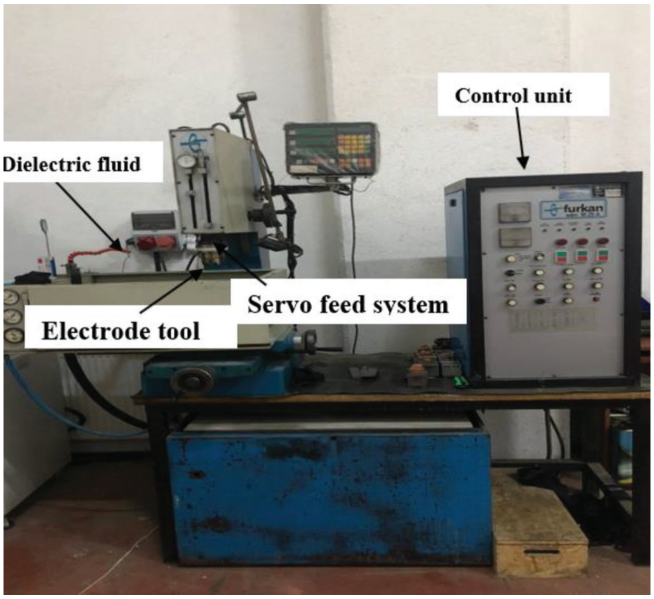

Fig. 1. Electric discharge machining (FURKAN M25A).

TABLE I
Physical properties of the electrodes

Material	Density (g/cm³)	Electrical conductivity (MS/m)	Thermal conductivity (W/m K)	Melting temperature range (°C)
B2	8,3	≥16	120–170	870–980
NSS	8,81	≥23	190–240	1020–1040

TABLE II
Chemical composition of Nss (CuNi2SiCr)

Element	Si	Mn	Cr	Ni	Fe	Pb	Cu
Weight (%)	0,65	0,10	0,35	2,5	0,15	0,02	Balance

TABLE III
Chemical composition of B2 (CuBe2)

Element	Ni	Be	Co	Fe	Cu
Weight (%)	0,30	1,95	0,30	0,20	Balance

TABLE IV
Chemical composition of DIN 1.2767

Element	C	Si	Mn	Cr	Mo	Ni	Fe
Weight (%)	0,45	0,25	0,35	1,35	0,25	4,05	Balance

TABLE V
Control factors and levels

Factor notation	Factor	Unit	Level 1	Level 2	Level 3
E	Tool material		NSS	B2	
A	Ip	A	6	12	25
B	Ton	µs	50	200	800
C	Toff	µs	50	200	800

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

Where, W_i is the initial weight of the workpiece, W_f is the final weight, T_i is the initial weight of the electrode, T_f is the final weight of the electrode, ρ is the density, and t is the machining time in minutes.

Table VI shows the values of TWR and MRR after performing experiments according to L_{18} Taguchi OA and performing the calculations of MRR and TWR by applying Equations 1 and 2.

III. Taguchi’s signal-to-noise ratio (S/N)

Taguchi’s S/N is a statistic that combines the mean and variance. The goal of robust experimentation is to determine an optimal combination of process parameters (control factor) settings that achieve robustness against factors that cause variability in the performance (noise factors). Selecting type of S/N depending on the goal of the experiments. In the case of the “smaller the better,” S/N is calculated according to Equation 3, which is used when calculating TWR. When calculating MRR, larger the better, and the S/N ratio is given by Equation 4. Higher values of the S/N indicate process parameter settings that optimize the performance characteristics (Krishnaiah and Shahabudeen, 2012).

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

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

Where, y_i is the performance response, i is the observation value, and n is the number of tests in an experiment.

IV. GRA

In many experiments and studies, process parameters cannot be set only for one response. Because of many reasons, one of them is that the objective is to maximize some responses and to minimize some responses together. GRA is among methods that can be employed to solve/optimize multiresponse problems. In GRA, the multiresponses are converted into a single response and then attain the levels of the optimal factors (Kalyon et al., 2018; Singh, 2018). Optimization in GRA is performed as the following steps:

1. Data pre-processing: Translation of responses values Y_{ij} into normalized values Z_{ij} ($0 \leq Z_{ij} \leq 1$). In case of normalized data processing for the response larger the better, Equation (5) is used, if the response smaller the better, the Equation (6) is applied and if the response is nominal the best, then the normalized values can be expressed by Equation (7).

$$Z_{ij} = \frac{Y_{ij} - \min(Y_{ij},\ i = 1,2\ldots,n)}{\max(Y_{ij},\ i = 1,2\ldots,n) - \min(Y_{ij},\ i = 1,2\ldots,n)} \tag{5}$$

$$Z_{ij} = \frac{\max(Y_{ij},\ i = 1,2\ldots,n) - Y_{ij}}{\max(Y_{ij},\ i = 1,2\ldots,n) - \min(Y_{ij},\ i = 1,2\ldots,n)} \tag{6}$$

$$Z_{ij} = \frac{(|Y_{ij} - T|) - \min(|Y_{ij} - T|,\ i = 1,2\ldots,n)}{\max(|Y_{ij} - T|,\ i = 1,2\ldots,n) - \min(|Y_{ij} - T|,\ i = 1,2\ldots,n)} \tag{7}$$

where: i=1,2…., n experiments. Y_{ij}= the i^th normalized value of the j^th response variable.

2. Gray relational coefficient: Gray relational coefficient is implemented for obtaining how close ideal and normalized response Zij are. The gray relational coefficient can be expressed by Equation (8).

$$GC_{ij} = \frac{\Delta_{min} + \lambda\Delta_{max}}{\Delta_{ij} + \lambda\Delta_{max}} \tag{8}$$

where: $\Delta = |Y_{oj} - Y_{ij}|$,$\Delta_{min}$ = minimum value of Δ, Δ_{max} = maximum value of Δ, Y_{oj} = the ideal normalized value of th response, λ = distinguish coefficient in between zero and one. It dominates the range of the gray relational coefficient.

3. Gray relational grade (G_j): The G_j computes the average sum of the GC_{ij}, and it is calculated as in Equation (9). The highest value of G_j is referred to optimal multiple response. Where m is number of responses.

TABLE VI
Experimental results

Exp. No.	Control factors	Tool	Ip (A)	Ton (µs)	Toff (µs)	Tool wear rate (mm^3/min)	Material removal rate (mm^3/min)
1	$E_1A_1B_1C_1$	NSS	6	50	50	0,25	3,59
2	$E_1A_1B_2C_2$	NSS	6	200	200	0,19	2,16
3	$E_1A_1B_3C_3$	NSS	6	800	800	0,02	0,06
4	$E_1A_2B_1C_2$	NSS	12	50	200	1,63	4,65
5	$E_1A_2B_2C_3$	NSS	12	200	800	0,19	7,2
6	$E_1A_2B_3C_1$	NSS	12	800	50	0,02	4,01
7	$E_1A_3B_1C_3$	NSS	25	50	800	1,68	2,86
8	$E_1A_3B_2C_1$	NSS	25	200	50	2,19	22,72
9	$E_1A_3B_3C_2$	NSS	25	800	200	0,15	25,24
10	$E_2A_1B_1C_1$	B2	6	50	50	0,63	2,01
11	$E_2A_1B_2C_2$	B2	6	200	200	0,02	1,97
12	$E_2A_1B_3C_3$	B2	6	800	800	0,02	0,65
13	$E_2A_2B_1C_2$	B2	12	50	200	0,66	0,8
14	$E_2A_2B_2C_3$	B2	12	200	800	0,4	4,08
15	$E_2A_2B_3C_1$	B2	12	800	50	0,04	4,35
16	$E_2A_3B_1C_3$	B2	25	50	800	1,14	0,65
17	$E_2A_3B_2C_1$	B2	25	200	50	2,42	18,14
18	$E_2A_3B_3C_2$	B2	25	800	200	0,36	20,5

$$G_j = \frac{1}{m}\sum GC_{ij} \tag{9}$$

Where: m is number of responses.

V. Results and Discussion

A. Effect of the Process Parameters on TWR and MRR

Taguchi's S/N is used in the analysis of experiments results to indicate the effect of the process parameters and the process parameter settings that optimize the performance characteristics. Fig. 2 shows the main effects plot for S/N of MRR and TWR, where smaller is better is used in the case of TWR and larger is better in the case of MRR. It is clear that the optimum value of MRR gained by NSS electrode, Ip (25A), T_{on} 200 µs, and T_{off} 50 µs and optimum value of TWR gained at parameters Ip 6 A, T_{on} 800 µs, and T_{off} 800 µs while the effect of both electrodes on TWR response is close. MRR is directly proportional to Ip and inversely proportional to T_{off}. Similar observation has been reported by Lee and Li, 2001. As Ip increases, discharge energy increases, the highest temperature reached on the workpiece is also increases, hence, more MRR achieved (Dastagiri and Kumar, 2014). Furthermore, as it shown, MRR is directly proportional to Ip and inversely proportional to T_{off}. The increase of the T_{on}, TWR decreases gradually while MRR increases. However, a long T_{on}, MRR decreased. This decrease is due to the expansion of the electric plasma channel (Dastagiri and Kumar, 2014; Kalyon, 2020; Kumar, 2012). On the other hand, Lee and Li (2001) explained that a long Ton causes the arcing and decreases MRR. Furthermore, as it is shown, the NSS electrode achieves the best MRR while the effect of both electrodes on TWR response is close.

Interaction exists when the influence of one process parameters depends on the level of the other process parameter (Antony, 2003). Fig. 3-5 represent the combined effect (interaction) of process parameters on TWR. It is clear that the change in TWR from level to level of any process parameter depends on the level of the other parameter. While, the fluctuating effect of these parameters on the TWR was observed, but a lower TWR could be achieved when treated with the parameters Ip (6A), Ton (800 µs), and Toff (800 µs). Hence, minimum TWR can be achieved at low Ip and high values of Ton and Toff.

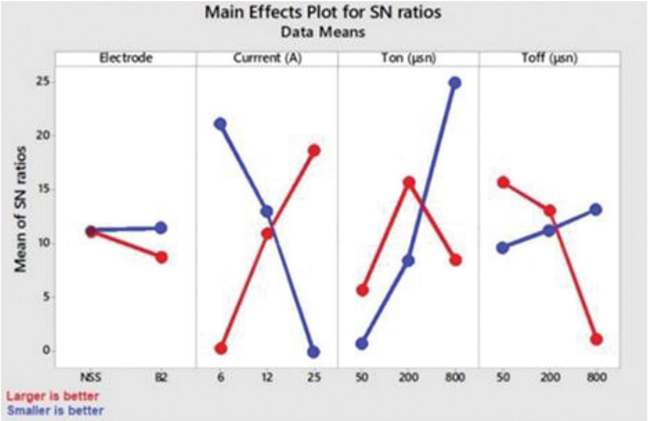

Fig. 2. Signal-to-noise ratio for tool wear rate and material removal rate.

The interaction effects of parameters for MRR are illustrated in Fig. 6-8. It is seen the strong combined effect of process parameters on MRR. As can be seen from figure, MRR is positively affected by increase of Ip. For achieving maximum MRR, the optimum process parameter settings are Ip = 25A, T_{on} = 800 µs and T_{off} = 200 µs or Ip =25A, T_{on} = 200 µs and T_{off} = 50 µs.

It is important to study the contribution of the process parameters because not all parameters affect the performance in the same manner. Fig. 9 shows the results of the ANOVA analysis in determining the contribution of process parameters to TWR and MRR. Ip has the most significant effect on the

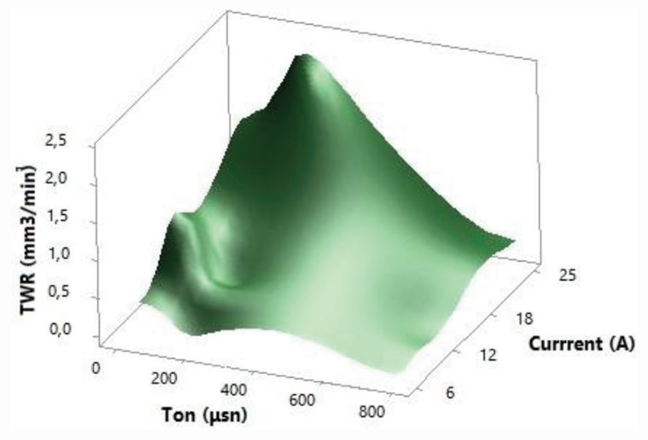

Fig. 3. Effect of T_{on} and current on tool wear rate.

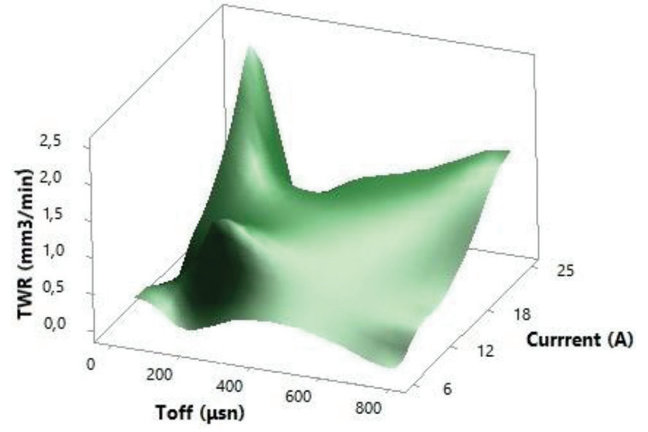

Fig. 4. Effect of T_{off} and current on tool wear rate.

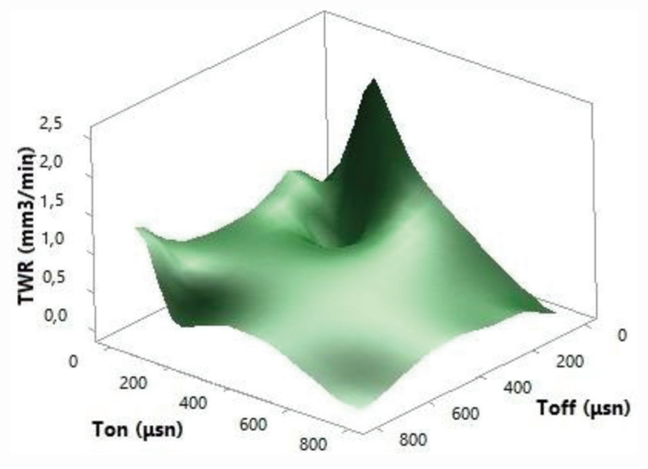

Fig. 5. Effect of T_{on} and T_{off} on tool wear rate.

MRR and EWR followed by T_{on} and T_{off} while electrode material has the least effect on MRR and TWR. By focusing on the most influencing factors, a higher performance improvement ratio can be obtained. It is also clear that Ip and T_{off} have higher impact ratios in the case of MRR compared to the TWR. In the case of T_{on}, the rate of impact on the TWR is higher. In Ton, the TWR effect is higher. Electrode material has a negligible effect for both responses.

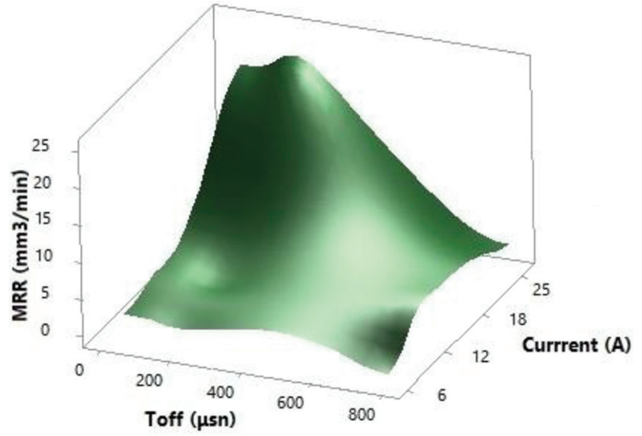

Fig. 6. Effect of T_{off} and current on material removal rate.

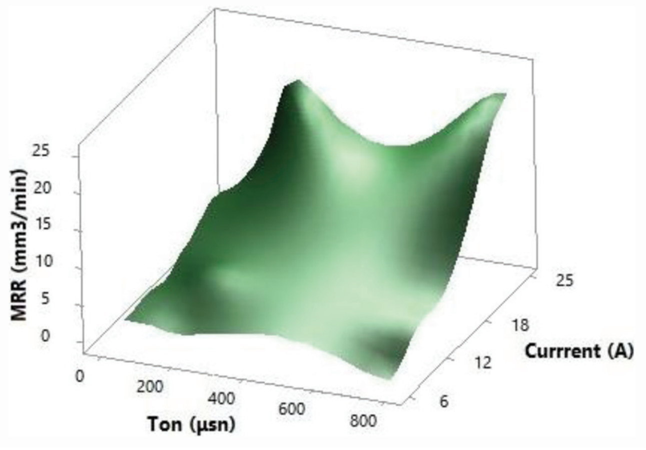

Fig. 7. Effect of T_{on} and current on material removal rate.

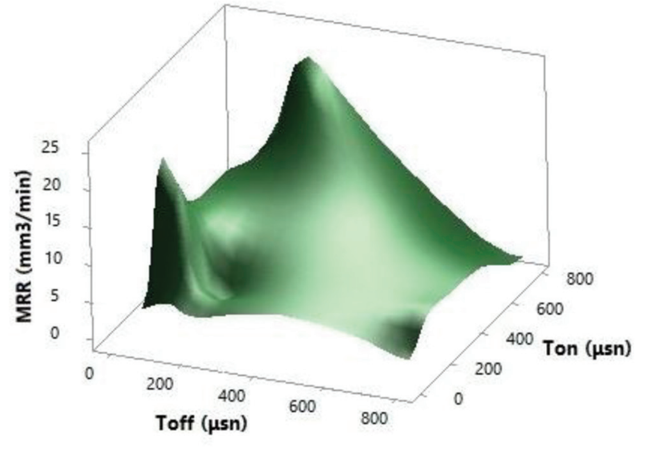

Fig. 8. Effect of T_{off} and T_{on} on material removal rate.

B. Multiresponse Optimization with GRA

From Fig. 2, we note that the values of the process parameters that achieve optimal MRR differ from the values of the process parameters that achieve optimal TWR. While, the study aims to obtain the optimal set of process parameters to achieve the minimum TWR and maximum MRR. To achieve this, GRA provides statistical and mathematical equations which enables it to optimize multiobjective problems (Harpreet and Amandeep, 2012; Krishnaiah and Shahabudeen, 2012; Singh, 2018). After implementing the GRA steps as in Equations 5–9 which were previously mentioned, the results are shown in Table VII. It is clear from the last column in the table that Experiment 9 was ranked 1 and this means that it achieved the best parametric combination ($E_1A_3B_3C_2$), that is, NSS electrode, Ip (25 A), T_{on} (800 µs), and T_{off} (200 µs) for optimal TWR and MRR of DIN 2767 Tool Steel.

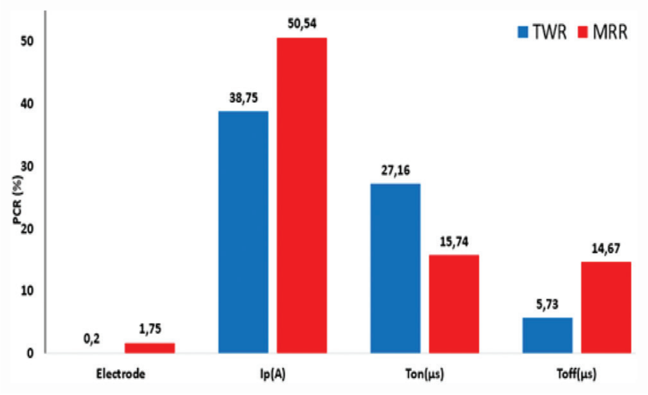

Fig. 9. Effect of parameters on tool wear rate and material removal rate as a result of ANOVA.

C. Effect of Process Parameters on Surface Quality

In EDM, the workpiece surface is subjected to very high temperature and rapid cooling, which causes cracks and changes in surface properties. Fig. 6 exhibits scanning electron microscopy (SEM) images of EDMed surfaces. In Fig. 10a, when the process parameters Ip (6 A), T_{on} (50 µs), and T_{off} (50 µs), SEM image is examined, it is seen that there are globules of debris, pockmarks, microcracks, and crater formations on the surface. Fig. 10b shows surface EDMed with Ip (6A), T_{on} (200 µs), and T_{off} (200 µs). It is seen that microcracks are more on the surfaces processed with 6 A, T_{on} (200 µs), and T_{off} (200 µs). The surface crack density (SCD), microholes, and pits on the workpiece surface are intensively dependent on pulse energy (Ip and T_{on}) variations (Jabbaripour et al., 2012). When Ton excessive (i.e., 23 µs), the severity of the crack width increases (Lee and Li, 2001).

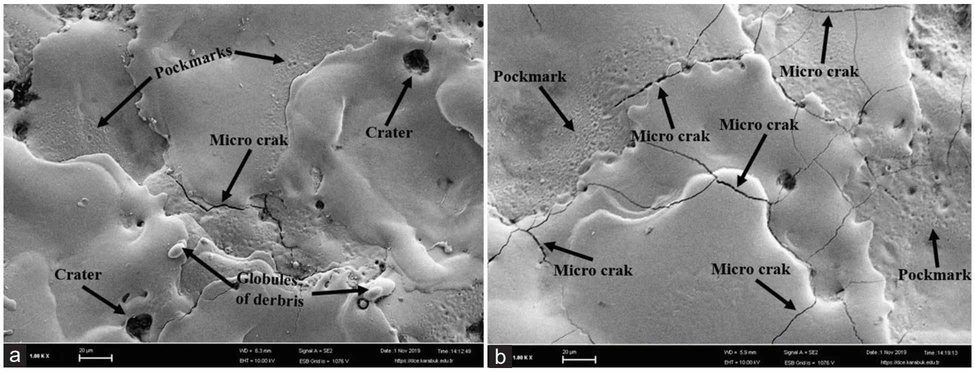

Fig. 10. Scanning electron microscopy surface images: (a) Process parameters Ip (6 A), T_{on} (50 µs), and T_{off} (50 µs), (b) process parameters Ip (6 A), T_{on} (200 µs), and T_{off} (200 µs).

TABLE VII
Normalization and coefficient matrix values

Exp. No.	Normalized tool wear rate	Normalized material removal rate	Gray relation coefficient tool wear rate	Gray relation coefficient material removal rate	Gray relation grade	Rank
1	0,904	0,140	0,839	0,368	0,603	10
2	0,929	0,083	0,876	0,353	0,614	9
3	1,000	0,000	1,000	0,333	0,667	7
4	0,329	0,182	0,427	0,379	0,403	17
5	0,929	0,284	0,876	0,411	0,643	8
6	1,000	0,157	1,000	0,372	0,686	3
7	0,308	0,111	0,420	0,360	0,390	18
8	0,096	0,900	0,356	0,833	0,595	11
9	0,946	1,000	0,902	1,000	0,951	1
10	0,746	0,077	0,663	0,351	0,507	13
11	1,000	0,076	1,000	0,351	0,676	5
12	1,000	0,023	1,000	0,339	0,669	6
13	0,733	0,029	0,652	0,340	0,496	14
14	0,842	0,160	0,759	0,373	0,566	12
15	0,992	0,170	0,984	0,376	0,680	4
16	0,533	0,023	0,517	0,339	0,428	16
17	0,000	0,718	0,333	0,639	0,486	15
18	0,858	0,812	0,779	0,726	0,753	2

The values of SCD reported by Bhattacharyya et al., 2007, were minimum at Ip and T_{on} in range 18–22 A and 20–100 µs, respectively. Guu, 2005, concluded that low discharge energy should be used to avoid surface damage.

VI. Conclusions

This paper presented the use of OA with GRA for the optimization for the EDM process with the multiple performance characteristics. Taguchi method and ANOVA were applied to determine the contribution of parameters which affecting MRR and TWR. The main conclusions of this paper are summarized as follows:

- Ip was the most significant process parameter followed by T_{on}, T_{off}, and electrode material, respectively
- When Ip increased, MRR increases gradually. With the increase of T_{on}, MRR increased first and then decreases. MRR decreases with increase of T_{off}
- TWR is inversely proportional to Ip and directly proportional to T_{on} and T_{off}
- NSS electrode has higher effect on MRR than B2, while the effect of both electrodes for TWR was close to each other
- The minimum TWR was achieved at Ip (6A), T_{on} (800 µs), and T_{off} (800 µs) and the maximum MRR achieved at Ip (25A), T_{on} (800 µs), and T_{off} (200 µs). After applying GRA, the optimal parameters combination for MRR and TWR was determined as Ip (25A), T_{on} (800 µs), T_{off} (200 µs), and NSS electrode.

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