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Parametric Optimization of Wire-Electrical Discharge Machining Process on AISI D2 Tool Steel

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Abstract: Wire-Electrical Discharge Machining (WEDM) process can create any complex contour in any conducting material, regardless of its strength or hardness, with higher accuracy. Present experimental investigation aims to determine suitable input process/machining parameters, e.g. pulse on time (T_{ON}), peak current (I_P), wire feed rate (WF), and pulse off time (T_{OFF}), for optimizing the process performances, namely, cutting rate, kerf width, average roughness value of the machined surface, micro hardness, and surface crack density. Since four input parameters are considered in the present investigation, and each parameter is assumed to vary at three different levels (i.e. low, medium, high), the Taguchi L9 Orthogonal Array (OA) design approach has been used for the experimental purpose to enhance the process effiency. Similarly, a simple and popular multiresponse optimization approach, namely Grey Relational Analysis (GRA), is used to optimize five performance characteristics (output responses) simultaneously. The optimum process variables obtained are: T_{ON} of 110 μs, T_{OFF} of 40 μs, I_P of 10 A, and WF of 6 mm/min. These optimum process variables are validated with confirmatory experiment. The relative impact of input variables is determined using the Analysis of Variance (ANOVA) technique. Finally, correlations between individual outputs with different input parameters are established. This work will be helpful for industry personnel to use this machining process in a techno-economic way.

Keywords: WEDM; surface roughness; surface crack density; GRA; ANOVA; orthogonal array

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0 Introduction

WEDM (Wire-Electrical Discharge Machining) process uses spark erosion technique to precisely machine and produce complex shapes (both 2D and 3D) in difficult-to-machine electrically conductive work piece materials with the help of a thin wire electrode. This unconventional machining technique has become increasingly significant in the mould-making, aerospace, and automotive industries in recent years. During the machining process, work material is eroded/removed by a continuously moving wire of diameter 0.05 – 0.30 mm. The metal on the surface melts and evaporates through a continuous segment of sparks occurring between the wire and the work piece. The wire and the work piece are separated by a stream of liquid dielectric (i.e. deionized water) which helps in flushing the eroded material away. Regardless of how strong or hard a material is, WEDM can easily machine any conductive material since there is no physical connection between the work material and the wire electrode[1]. The critical phenomenon that occurs during machining is the breakage of electrode wire. If the process parameters are not properly controlled, there will be frequent breakdowns of the wire, resulting in the reduction of productivity. Keeping in view this problem, researchers are trying to manipulate the process variables for optimal use of this process.

The machining efficiency of 6061 Al alloy was analyzed by Guo et al.[2] during the WEDM using orthogonal design. They also observed frequent wire breakage at the lowest pulse duration (5 μs) and machining voltage (60 V) values. Puri et al.[3] used Taguchi's orthogonal array design in the WEDM process to investigate the average cutting speed (V_C), surface roughness, and geometrical inaccuracy of hardened and annealed M2 grade die steel. The results showed that cutting rate and geometrical inaccuracy

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were mostly affected by T_{ON}, T_{OFF} and I_P. Similarly, Tosun et al.[4] used the Taguchi method to evaluate the effect of machining parameters on kerf width and Material Removal Rate (MRR) in WEDM operation. Regression analysis was used to develop the relationship between the machining parameters and the kerf width and MRR. From the analysis, open circuit voltage (78.67%) and T_{ON} (12.76%) were found to be the most effective machining parameters.

To improve MRR and R_a at the same time, Chiang et al.[5] combined the Taguchi and the GRA (Grey Relational Analysis) techniques. Through this combined analysis, the performance characteristics in the WEDM process were greatly improved. Sarkar et al.[6] attempted to predict the optimal machining conditions for improved surface finish and dimensional accuracy during the cutting of γ-TiAl work material in WEDM process. It was found that when cutting speed increases, surface quality diminishes, and the Pareto optimization technique produced superior results than the desirability function approach. Alias et al.[7] studied the effect of machine feed rate on kerf width, MRR, R_a and surface topography in WEDM of Ti-6Al-4V. A feed rate of 4 mm/min was found to be the ideal machining condition. Li et al.[8] evaluated surface integrity and WEDM process performance while machining Inconel 718 in three Trim Cuts (TC) after a single Rough Cut (RC). They observed that nearly invisible recast layers with zero cracks were produced during TC3 mode more than during RC mode. Manjaiah et al.[9] combined the utility method with the Taguchi concept for optimizing MRR and R_a simultaneously while cutting TiNi shape memory alloys in the WEDM operation. At large pulse duration, craters, micro cracks and recast layer were observed on the machined work surface. Sharma et al.[10] investigated the effect of T_{ON}, T_{OFF}, I_P and servo voltage on cutting rate of Al 6063/$ZrSiO_4$(p) Metal Matrix Composite (MMC) using WEDM. Experiments were conducted as per the Box-Behnken design, followed by the Response Surface Methodology (RSM) technique. From the study, it was observed that the cutting rate increased with an increase in T_{ON} and I_P. Saedon et al.[11] merged the Taguchi technique with GRA and performed multi response optimization for obtaining optimal parameters that will improve MRR and cutting rate with a lower R_a value. The proposed methodology greatly improved the process performance. Yukui et al.[12] studied the effect of open voltage and revolving speed on MRR and R_a while producing a high-speed rotating spindle. Soundararajan et al.[13] examined the impact of various WEDM process parameters on MRR and R_a by employing the RSM technique's Central Composite Rotatable Design (CCRD) method. It was observed that R_a was greatly influenced by T_{ON} (43.79%), whereas, MRR was affected by peak current (30.47%). Saha et al.[14] combined the grey relational analysis technique with Principal Component Analysis (PCA) to identify the optimal cutting conditions in WEDM for machining nanostructured hardfacing materials. Zn-coated wire was found to be more appropriate for cutting such substances. Mouralova et al.[15] examined how the machining factors affected the material's mechanical and physical properties as well as how it was heat treated. Ajay et al.[16] experimentally compared the machining efficiency of three different aerospace materials, viz. Monel, Inconel and Incoloy by using Taguchi's technique of process optimization, it was observed that productivity is more higher while machining Inconel as compared to Monel and Incoloy material in terms of a higher rate of material removal along with better surface finish. Sharma et al.[17] proposed a hybrid method of optimization, i.e., Taguchi-GRA, along with PCA to optimize the controlling factors of the WEDM operation during the machining of Inconel 706. The suggested method for determining the objective weights of responses was discovered to be both simple and efficient. The impact of T_{ON}, I_P, and wire speed on the WEDM machining of alumina composites reinforced with Multi Walled Carbon Nanotubes (MWCNTs) was examined by Singh et al.[18]. It was discovered that MRR and R_a increased with increasing T_{ON}. Padhi et al.[19] simultaneously optimized cutting rate, surface roughness, and dimensional deviation by adopting grey relational analysis methodology while machining EN-31 material using WEDM. ANOVA analysis proved that T_{ON} was the major influencing factor with 55.45% contribution towards the performance of the process. Gupta et al.[20] experimentally analyzed the effects of T_{ON}, T_{OFF}, and SV (Servo Voltage) on cutting rate and surface roughness. They utilized the GRA technique for optimizing above-mentioned responses simultaneously, and also obtained the optimal parameter setting (such as T_{ON} of 125 μs, T_{OFF} of 48 s, and SV of 55V), which will improve the

process efficiency. Yunus et al.[21] studied the impact of WEDM process variables on multiple responses like MRR and surface roughness using particle swarm optimization technique during the machining of Nitinol alloy. ANOVA analysis was performed to establish a relationship between input variables and output attributes which was later optimized using composite desirability method of RSM. Experimental analysis showed that T_{ON} and I_P mostly influenced the maximization of MRR and the minimization of surface roughness. The optimal cutting parameters suitable for maximum MRR and minimum surface roughness were observed at T_{ON} of 25 μs, T_{OFF} of 13.39 μs, I_P of 2 A, and V of 48.59 V. Sharma et al.[22] analyzed the role of multiple process factors on the MRR, gap current (I_g) and machining time (MT) using the Taguchi L_9 OA and ANOVA analysis while machining D2 die steel in WEDM. T_{OFF} was found to be the most influential factor towards all three responses with an overall 60% contribution. Phate et al.[23] used PCA technique in conjunction with ANN (Artificial Neural Network) to optimize the WEDM process in Al/SiC MMC. Utilizing ANN made the optimization and assessment of whole process more effective. Through the experimental analysis, the optimum process parameters setting was found to be at SiC (wt.%) of 15%, T_{ON} of 112 μs, T_{OFF} of 56 μs, WF of 4 mm/min, I_P of 3 knob position, WT of 4 kg, and dielectric pressure of 13 kg/m^2. Based on the ANOVA results, the most significant parameter was found to be percentage composition of SiC (contributing 49.58%). Bose et al.[24] developed Titanium matrix composite and carried out experimental investigation to optimize MRR, SR (Surface Roughness), kerf width (K_w) and over cut using RSM methodology. Manikandan et al.[25] investigated the effect of pulse on time, pulse off time, and peak current on the machining performance of Monel-400 by using the Taguchi-Grey approach. Better GRG was obtained at a combination of high pulse on time (30 μs), low pulse off time (5 μs) and high peak current (3 A) values. From the investigation, T_{ON} was identified to be the most influential factor affecting the surface finish with MRR during WEDM of Monel-400 material. Muttamara et al.[26] studied the effect of wire electrode material on various machining aspects of tungsten carbide work piece material. They used Zn-coated brass wire for machining purposes. It was observed that use of ultrasonic vibration and coated wire had impacted the overall machining process in a better way, resulting in improved stability and surface finish. Khan et al.[27] employed Taguchi L27 OA design approach for developing prediction models for GRG while machining Ti-6Al-4V in WEDM. ANOVA analysis revealed that current had the greatest influence on MRR (95.21%), SR (81.63%), dimensional deviation (89.99%), form error (80.73%), and orientation error (90.90%). Also, they observed 97.53% accuracy between the developed prediction model and actual experimental values.

According to an assessment of earlier research studies, relatively little work has been done to improve the machining performance of D2 steel, even though it is frequently utilized in mold and die making industrie, where study of WEDM machining performance is of great importance. Moreover, very few studies have been conducted on wire breakage, which indicates that achieving the optimum use of this process without wire breakage is still a challenge.

Considering the aforementioned details, the GRA technique is chosen for the simultaneous optimization of five machining performances due to its simplicity, without the help of any software. The D2 steel is chosen as the work piece material for the present investigation so that research gap can be eliminated. The most important novelty of the present work is to obtain maximum productivity without the breakage of the wire electrode. The experiments have been economically designed to lower the cost of experimentation. Further, maximum possible performance characteristics have been studied in this investigation.

1 Methodology

Taguchi's OA technique is employed to arrange the cutting factors along with the levels that have an impact on the machining process. Three categories are utilized to group the response variables[28]: nominal-the-best, larger-the-better, and smaller-the-better. Signal-to-Noise (S/N) ratio, which indicates how far the response variables deviate from the intended value, is employed in the Taguchi technique. The following formulas are used to find the S/N ratio value for various response variable categories, i.e.

(a) The smaller, the better category[29],

$$\text{Lossfunction } (L_{xy}) = \frac{1}{m}\sum_{i=1}^{n} y_{xyk}^2 \tag{1}$$

(b) For larger, the better category,

$$\text{Lossfunction}\ (L_{xy}) = \frac{1}{m}\sum_{i=1}^{n}\frac{1}{y_{xyk}^{2}} \tag{2}$$

where, m represents number of recurrent trials and y_{xyk} means experimental result of the yth response characteristics in x^{th} run at k^{th} repetition.

2 Experimentation

The experiments were conducted on D2 tool steel, also known as high carbon-high chromium steel. The chemical composition of D2 steel is the same as mentioned by Nayak et al.[30]. This material exhibits greater corrosion resistance compared to other steel materials. An Elektra CNC wire cut EDM machine with specifications as mentioned in Ref.[30] was used for conducting the experimental runs. Fig.1 demonstrates the WEDM setup. For the machining purpose, a brass wire with a diameter of 0.25 mm coated with Zn was utilized as the cutting tool. From Refs.[31-32], it was observed that coated wire produced better surface quality and improved the machining efficiency compared to un-coated wire. When compared to ordinary plain brass wires, i.e., uncoated wires, this coating of Zn offers a noticeable rise in the V_C value. Deionized water was used as a dielectric medium.

Fig.1 The WEDM machine

In view of the literature analysis, four process parameters shown in Table 1 were selected to investigate their effects on five performance of output responses, which are V_C (cutting rate), K_w (kerf width), R_a (surface roughness average), microhardness and surface crack density of D2 steel specimen. We assume that A, B, C, D are the symbols for T_{ON}, T_{OFF}, I_P and WF, respectively, and that A_i, B_i, C_i, D_i are the corresponding values at the ith level (i = 1,2,3). In order to plan the experimental trials, Taguchi's L9 OA design was used, which is produced with MINITAB software as illustrated in Table 2. OA design approach helps reduce the experimental runs[33].

Table 1 Input parameters

Levels	T_{ON}(μs)	T_{OFF}(μs)	I_P(A)	WF (mm/min)
1	105	30	10	4
2	110	40	11	6
3	115	50	12	8

Table 2 L9 orthogonal array design

Expt. No.	T_{ON}(μs)	T_{OFF}(μs)	I_P(A)	WF(mm/min)
1	105	30	10	4
2	105	40	11	6
3	105	50	12	8
4	110	30	11	8
5	110	40	12	4
6	110	50	10	6
7	115	30	12	6
8	115	40	10	8
9	115	50	11	4

2.1 GRA Technique

The steps of the GRA method below have been followed for analyzing different performance measures simultaneously[30,34-35]:

Step 1: Determination of S/N ratio (η_{xy}).

The S/N ratio value for each output factor is evaluated as follows:

$$\eta_{xy} = -10\log_{10} L_{xy} \tag{3}$$

where, L_{xy} is the loss function value of xth output factor at y^{th} experiment.

Step 2: Computation of normalized S/N ratio (Y_{xy}).

The normalized S/N ratio value for each output factor is computed as follows:

(a) For larger-the-better,

$$Y_{xy} = \frac{\eta_{xy} - \eta_y^{min}}{\eta_y^{max} - \eta_y^{min}} \tag{4}$$

(b) For smaller-the-better,

$$Y_{xy} = \frac{\eta_y^{max} - \eta_{xy}}{\eta_y^{max} - \eta_y^{min}} \tag{5}$$

where, Y_{xy} is the normalized S/N ratio value of xth output facror at y^{th} experiment, η_y^{min} is the smallest S/N ratio value of the corresponding response parameter,

i.e., $\eta_y^{\min} = \min\{\eta_{1y}, \eta_{2y}, \ldots\ldots \eta_{my}\}$, and $\eta_y^{\max}$ is the largest S/N ratio value of the corresponding response parameter i.e. $\eta_y^{\max} = \max\{\eta_{1y}, \eta_{2y}, \ldots\ldots \eta_{my}\}$. Using the previously described equations, all responses are proportionally standardized within the range of zero to one.

Step 3: Computation of the GRC, γ_{xy}.

The GRC value for each response characteristic is calculated as follows:

$$\gamma_{xy} = \frac{\Delta\min_y + \xi\,\Delta\max_y}{\Delta_{xy} + \xi\,\Delta\max_y} \tag{6}$$

where, $\Delta_{xy} = |1 - Y_{xy}|$, $\Delta_y^{\min} = \min\{\Delta_{1y}, \Delta_{2y}\cdots, \Delta_{my}\}$, $\Delta\max_y = \max\{\Delta_{1y}, \Delta_{2y}, \cdots, \Delta_{my}\}$. ξ represents the relational coefficient or distinguishing coefficient, and its value lies between 0 and 1.

Step 4: Computation of Grey Relational Grades (GRGs).

The GRG value for i^{th} experimental run is calculated as follows:

$$\text{GRG} = \sum_{y=1}^{n} w_y\,\gamma_{xy} \tag{7}$$

where w_y respresents weightage given to y^{th} response characteristic, n means number of performance characteristics, and $\sum_{y=1}^{n} w_y = 1$.

Using ANOVA, this sudy aims to ascertain the significant effect of various machining factors, namely T_{ON}, T_{OFF}, I_{P}, and WF, on the several performance measures. Finally, a confirmatory experiment using the best parameter settings has been carried out to validate the optimized results.

2.2 Measurement of Response Characteristics

Nine experiments were carried out using various combinations of the cutting parameters as indicated in Table 2. The time taken to cut a 5 mm wide piece of work material was recorded by using a stopwatch for each experiment. Fig.2 represents the sample specimen after machining.

V_{C} for each experimental run was determined as follows:

$$V_{\text{C}} = \frac{L}{t}\ \text{mm/min} \tag{8}$$

where L represents the machined length, and t represents the duration of cutting. The Scanning Electron Microscope (SEM) was used to measure the kerf width (K_{w}). The surface roughness (R_{a}) of each machined specimen was measured using a Talysurf Surtronic profilometer with a 0.8 mm cutoff value. The microhardness of the machined specimen was measured using a Rockwell hardness tester with a diamond tip. Table 3 presents the experimental outcomes.

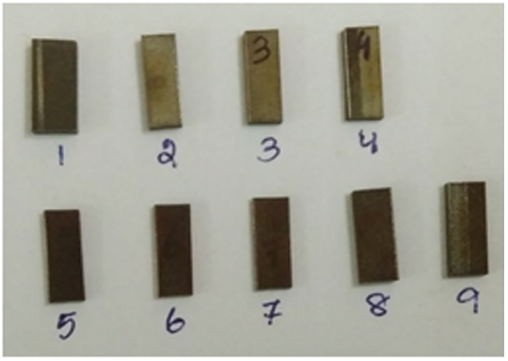

Fig.2 Machined specimen

Table 3 Experimental results

Expt. No.	V_{C} (mm/min)	K_{w} (mm)	R_{a} (μm)			Microhardness	Crack density (mm/mm^3)
			R_{a1}	R_{a2}	R_{a3}		
1	0.261	0.35	0.98	1.12	1.38	18.70	0.001390
2	0.193	0.51	1.12	1.18	1.10	17.95	0.001190
3	0.759	0.42	0.70	1.12	0.76	17.65	0.000531
4	0.217	0.47	1.06	1.08	1.34	11.85	0.000649
5	1.961	0.37	1.07	1.11	1.18	16.45	0.001430
6	0.125	0.50	1.48	1.36	1.14	11.75	0.001980
7	0.259	0.55	0.78	0.74	0.70	5.90	0.002230
8	0.202	0.48	0.79	0.80	0.82	17.75	0.002360
9	0.133	0.44	1.10	0.60	0.66	13.35	0.002260

The density of surface cracks was determined by analyzing the top surface morphology of the WEDMed specimen under 1500 times magnification using Scanning Electron Microscopy (SEM). The length of the cracks that are occurring in the designated area was measured using the same software. The average length of a crack (SCD) for each machined surface can be calculed as follows:

$$\mathrm{SCD} = \frac{l_1 + l_2 + l_3 + \cdots + l_n}{A} \tag{9}$$

where, l_1, l_2, $\cdots$, l_n are length of cracks occurring on the machined surface in μm, A represents area of the region measured under SEM in μm^2, $A = 45720\ \mu m^2$. Fig.3 represents SEM micrographs of the machined surface of D_2 steel at different experimental runs.

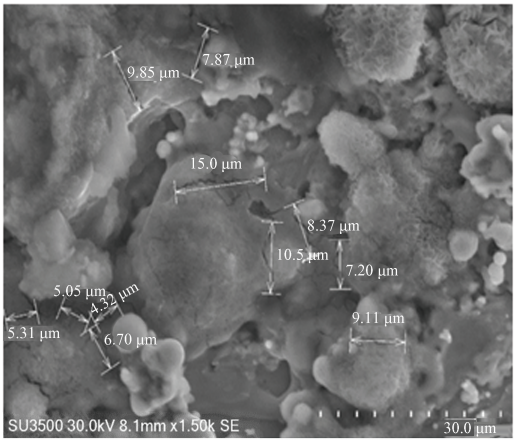

Fig. 3 SEM micrograph of sample specimen showing the measured surface cracks

3 Analysis on Experimental Results

The experimental findings listed in Table 3 are analyzed by using the GRA methodology in this section. In this study, smaller values of R_a, K_w, microhardness, and crack density indicate better performance and are classified as "smaller-the-better". In contrast, larger values of V_C are classified as "larger-the-better".

3.1 Performance Optimization

The first stage in the optimization is to use Eq.(1) and Eq.(2) as necessary to determine the quality losses of each response variable. Next, Eq.(3) is used to convert loss function values into S/N ratios. Eq.(4) is then utilized for normalizing the associated S/N ratio values of V_C, and Eq.(5) is used for K_w, R_a, microhardness, and crack density. Afterwards, Eq.(6) is used to calculate the gray relational coefficients. All four machining factors are assumed to have an equal impact on V_C, K_w, R_a, microhardness, and surface crack density in this study. Therefore, in Eq.(6), ξ is assumed to be 0.5, as this value was commonly used by earlier researchers in their studies[36-38]. Then, the GRG value is calculated by using Eq.(7). The GRG and GRC values for each experimental run are displayed in Table 4. The Taguchi method and GRA were combined to simplify the multi-performance optimization analysis to a single Process Performance Index (PPI).

Table 4 GRC and GRG values

Expt. No.	GRC					GRG
	V_C(mm/min)	K_w(mm)	R_a(μm)	Microhardness	Crack density(mm/mm^3)	
1	0.4057	0.3333	0.6940	1.0000	0.5849	0.6036
2	0.3725	0.7496	0.6440	0.9337	0.5214	0.6442
3	0.5919	0.4559	0.4140	0.9089	0.3333	0.5408
4	0.3847	0.5898	0.6873	0.5584	0.3662	0.5173
5	1.0000	0.3631	0.6282	0.8182	0.5982	0.6815
6	0.3333	0.7034	1.0000	0.5538	0.8095	0.6800
7	0.4047	1.0000	0.3333	0.3333	0.9294	0.6002
8	0.3772	0.6241	0.3671	0.9171	1.0000	0.6571
9	0.3384	0.5032	0.3753	0.6312	0.9451	0.5587

The orthogonal experimental design allows for the separation of the impact of individual machining parameters at various factor levels. Table 5 displays the computed mean GRG values for each process parameter, and the main effects plot for GRG analyzed by MINITAB software is shown in Fig.4. Basically, greater performance characteristics are indicated by a larger GRG number. $A_2B_2C_1D_2$ in Table 1, which corresponds to T_{ON} of 110 μs, T_{OFF} of 40 μs, I_P of 10 A, and WF of 6 mm/min, could be suggested as the ideal cutting parameters in the present machining process. Optimality of this setting was validated through a confirmatory experiment.

Table 5 Response for GRG

Level average values	T_{ON}(μs)	T_{OFF}(μs)	I_P(A)	WF (mm/min)
Level 1	0.5962	0.5737	**0.6469**	0.6146
Level 2	**0.6263**	**0.6610**	0.5734	**0.6415**
Level 3	0.6053	0.5932	0.6075	0.5717
Total mean GRG = 0.6093				

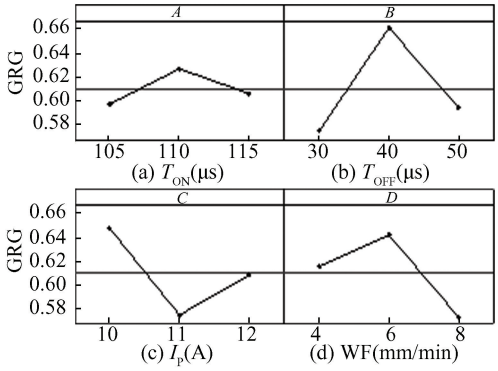

Fig.4 Variation of input parameters with GRG value

It is evident that with a rise in T_{ON}, T_{OFF}, and WF, the mean GRG value first rises and then decreases. With a rise in T_{ON} value, V_C increases due to the increased discharge energy, but it also affects the surface quality of the machined specimen in terms of roughness and a larger number of surface cracks. Similarly, with an increase in T_{OFF}, cutting rate decreases due to fewer discharges occurring in a given period of time, however the surface quality is improved with increasing T_{OFF}. Since we are simultaneously optimizing all the responses, a moderate value of T_{ON} and T_{OFF} shows better performance. Increasing the wire feed rate raises the cutting rate along with the surface cracks and roughness, because with faster moving wire, machining becomes unstable, and due to improper flushing of debris, the surface becomes rough. Whereas, for I_P, the mean GRG value first decreases and then increases. At moderate values of T_{ON}, T_{OFF}, and WF, better performance is observed in terms of surface integrity and cutting rate. However, the low level of I_P provides maximum GRG, because at a lower current value, the cutting will be slow, hence the surface becomes smooth with a lesser number of cracks.

3.2 Analysis of Variance (ANOVA)

ANOVA, which is based on the sum of squared deviations from the total mean of the GRG, is used to examine the importance of each process parameter with respect to the many WEDM performance parameters. An F-test is used in ANOVA analysis, and the F-ratio value is used to show the relative influence or percentage contribution of various cutting factors. The factor that has the least F value is considered to have a negligible impact on the process performance, hence that factor is included in the error term. The ANOVA analysis's results are displayed in Table 6. From the results, it is clear that factor A which is pulse-on-time (T_{ON}) has the least F value (i.e., 1.00), so it is included in the error term. According to the findings, I_P (contributing 27.47%) and T_{OFF} (contributing 42.69%) are the most influential factors that affect the overall performance metrics. Sharma et. al.[22] analyzed D_2 steel and stated that T_{OFF} was the most influential parameter (60%). Similarly, in the present investigation, T_{OFF} is found to be the most influential parameter (i.e., 42.69%). The percentage is varied, which may be due to the variation of the total number of output parameters. Pulse on time is deemed statistically unimportant because it has the lowest F value contributing 4.75%. It is, therefore, a part of the error phrase.

Table 6 ANOVA results

Source of variance	Sum of squares due to factors (SS_f)	Degrees of freedom (DOF)	Mean sum of squares (SS_m)	F-ratio	Percentage(%)
A	0.0014	2	0.0007	1.00	4.75
B	0.0126	2	0.0063	9.00	42.69
C	0.0081	2	0.0041	5.79	27.47
D	0.0074	2	0.0037	5.29	25.09
Error	*A*	–	–	–	–
Total	0.0295	–	–	–	100

3.3 Regression Analysis

The prediction models for V_C, R_a, K_w, microhardness, and crack density have been developed by multiple regression analysis to enhance

comprehension of the connection between input and output. The MINITAB program yielded the regression equations listed below:

$$V_C = -1.260 - 0.02060T_{ON} + 0.00470T_{OFF} + 0.3990\,I_P - 0.0980WF \quad (9)$$

$$R_a = 5.24 - 0.0273\,T_{ON} - 0.00133\,T_{OFF} - 0.0950\,I_P - 0.0208WF \quad (10)$$

$$K_w = -0.359 + 0.00633\,T_{ON} - 0.00017\,T_{OFF} + 0.00170\,I_P + 0.01750WF \quad (11)$$

$$\text{Microhardness} = 89.5 - 0.577\,T_{ON} + 0.105\,T_{OFF} - 1.37\,I_P - 0.104WF \quad (12)$$

$$\text{Crackdensity} = -0.00890 + 0.000125\,T_{ON} + 0.000008\,T_{OFF} - 0.000257\,I_P - 0.000128WF \quad (13)$$

Using the above regression equations, the error percentage between the actual and predicted results of V_C, K_w, R_a, microhardness, and crack density are calculated and presented in Tables 7-11.

Table 7 Error analysis for V_C

Expt. No.	V_C(mm/min) (Experimental)	V_C(mm/min) (Predicted)	Error percentage(%)
1	0.261	0.316	-21.07
2	0.193	0.266	-37.82
3	0.759	0.816	-7.51
4	0.217	0.22	-1.38
5	1.961	1.858	5.25
6	0.125	0.111	11.20
7	0.259	0.272	-5.02
8	0.202	0.235	-16.34
9	0.133	0.203	-52.63
Average percentage error			-13.92

Table 8 Error analysis for R_a

Expt. No.	R_a(μm) (Experimental)	R_a(μm) (Predicted)	Error percentage(%)
1	1.16	1.30	-12.10
2	1.13	1.15	-1.81
3	0.86	1.00	-16.35
4	1.16	0.99	15.03
5	1.12	0.96	14.23
6	1.33	1.10	17.62
7	0.74	0.80	-7.54
8	0.80	0.93	-16.36
9	0.79	0.91	-14.66
Average percentage error			-2.44

Table 9 Error analysis for K_w

Expt. No.	K_w(mm) (Experimental)	K_w(mm) (Predicted)	Error percentage(%)
1	0.35	0.39	-11.43
2	0.51	0.42	17.65
3	0.42	0.46	-9.52
4	0.47	0.49	-4.26
5	0.37	0.42	-13.51
6	0.5	0.45	10.00
7	0.55	0.49	10.91
8	0.48	0.52	-8.33
9	0.44	0.45	-2.27
Average percentage error			-1.20

Table 10 Error analysis for microhardness

Expt. No.	Microhardness (Experimental)	Microhardness (Predicted)	Error percentage(%)
1	18.70	17.95	4.02
2	17.95	17.42	2.95
3	17.65	16.89	4.29
4	11.85	13.28	-12.05
5	16.45	13.37	18.70
6	11.75	16.96	-44.31
7	5.90	9.23	-56.46
8	17.75	12.81	27.81
9	13.35	12.91	3.30
Average percentage error			-5.75

Table 11 Error analysis for crack density

Expt. No.	V_C(mm/min) (Experimental)	V_C(mm/min) (Predicted)	Error percentage(%)
1	0.00139	0.00138	0.72
2	0.00119	0.00095	20.17
3	0.000531	0.000517	2.64
4	0.000649	0.00124	-91.06
5	0.00143	0.00157	-9.79
6	0.00198	0.00191	3.54
7	0.00223	0.00186	16.59
8	0.00236	0.0022	6.78
9	0.00226	0.00254	-12.39
Average percentage error			-6.98

From the above tables, it is found that the overall predicted values for all five responses are deviated by 6.06% from the experimental values. Finally, the

expected values of all the output characteristics have been assessed against the actual results of a confirmatory experiment done at the optimal parameter combination, i.e., $A_2B_2C_1D_2$. Table 12 represents the result of the confirmatory experiment. It is evident from the results that the developed regression equations can predict the values of the responses with good accuracy.

Table 12 Results of confirmatory experiment

Level			V_c(mm/min)	K_w(mm)	R_a(μm)	Microhardness	Crack density(mm/mm^3)
Optimal cutting parameters ($A_2B_2C_1D_2$)	GRG	Prediction	0.064	0.45	1.11	15.91	0.00183
		Experiment	0.112	0.41	1.06	15.21	0.00189
Improvement (%)			75.00	8.89	4.50	4.40	3.28

4 Conclusions

The following conclusions are obtained from the present investigation.

1) Optimal process variables, namely T_{ON}, T_{OFF}, I_P and WF were determined for simultaneous optimization of WEDM performances such as cutting rate, kerf width, surface roughness, microhardness, and crack density in case of D2 steel using hybrid Grey-Taguchi technique.

2) Attempts have been made to achieve maximum possible productivity without the breakage of electrode wire.

3) The optimal combination of input variables is: T_{ON} of 110 μs, T_{OFF} of 40 μs, I_P of 10 A and WF of 6 mm/min, and the corresponding best performances are: V_C of 0.112 mm/min, K_w of 0.41 mm, R_a of 1.06 μm, microhardness of 15.21, and surface crack density of 0.00189 mm/mm^2.

4) From the experimental results, it is found that a minimum surface crack density of 0.00119 mm/mm^2 was obtained at low value of T_{ON} (105 μs) and intermediate values of T_{OFF} (40 μs), I_P (11 A) and WF (6 mm/min).

5) Among the four input process parameters, T_{OFF} is found to be the most influential parameter contributing 42.69% and T_{ON} is found to be the least influential parameter towards the overall machining performances.

6) The developed regression models are best suited for predicting the five different process performances with different values of four input process parameters.

7) The optimal process parameters are ensured to improve machining performance, and a confirmation experiment is performed. It may be noted that although the microhardness value decreas slightly and the crack density increases marginally, these changs have a negligible effect on the overall productivity.

8) This study will definitely help industry personnel because of the simplicity of the used methodology and process. The same process and method can also be applied to other materials for obtaining maximum productivity.

Future study can examine the impact of other cutting parameters towards machining accuracy namely dimensional deviation and corner profile during contour cutting in WEDM.

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