

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

Ipsita Nayak^{*}, Jaydev Rana

(Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Burla 768018, India)

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. The aim of present experimental investigation is 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 L_9 Orthogonal Array (OA) design approach of Taguchi concept has been used for the experimental purpose to enhance the process economy. Similarly, a simple and popular multiresponse optimization approach, namely Grey Relational Analysis (GRA), is used to simultaneously optimize these five performance characteristics. The optimum process variables obtained are: T_{ON} of 110 μ s, T_{OFF} of 40 μ s, 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 Analysis of Variance (ANOVA) technique. Finally, correlations between individual output with different input parameters are established. This work will be helpful for industry personnel to use this machining process in a techno-economical way.

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

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WEDM 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 – 0.3 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 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 of this problem, researchers are trying to manipulate the process variables for optimal use of this process.

The machining efficiency of 6061 Al alloy have been analyzed by Guo et al.^[2] during the WEDM using orthogonal design. They also observed frequent wire breakage at the lowest pulse duration (5 μ s) and machining voltage (60 V) values. Puri et al.^[3] have used Taguchi's orthogonal array design in the WEDM process to investigate the average cutting speed (V_C), surface roughness and geometrical inaccuracy hardened and annealed die steel of M2 grade. The results showed that cutting rate and geometrical inaccuracy were mostly affected by T_{ON} , T_{OFF} and I_P . Similarly, Tosun et al.^[4] used 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 Taguchi and GRA technique. Through this combined analysis, the performance characteristics in the WEDM process were greatly improved. Sarkar et al.^[6] have made an attempt to predict the optimal machining conditions for better surface finish and dimensional accuracy during the cutting of γ -TiAl work material in the 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] have 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] have 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 than the RC mode. Manjaiah et al.^[9] combined the utility method with 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] have made an attempt to investigate the effect of T_{ON} , T_{OFF} , I_p and servo voltage on cutting rate of Al 6063/ZrSiO₄ (p) Metal Matrix Composite (MMC) using WEDM. Experiments were conducted as per Box-Behnken design followed in the Response Surface Methodology (RSM) technique. From the study, it was observed that the cutting rate increased with increase in T_{ON} and I_p . Saedon et al.^[11] merged the Taguchi technique with GRA and performed multi response optimization for obtaining ideal parameters which will improve MRR and cutting rate with lower R_a value. The proposed methodology greatly improved the process performance. Yukui et al.^[12] have studied the effect of open voltage and revolving speed on MRR and R_a while producing high speed rotating spindle. Soundararajan et al.^[13] have 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] have 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] have 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] have experimentally compared the machining efficiency of three different aerospace materials viz. Monel, Inconel and Incoloy by using Taguchi's technique of process optimization and it was observed that productivity is more while machining Inconel as compared to Monel and Incoloy material in terms of higher rate of material removal along with better surface finish. Sharma et al.^[17] have 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 has been discovered to be both simple and efficient. The impact of T_{ON} , I_p , and wire speed on the WEDM process machining of alumina composites loaded with Multi Walled Carbon Nanotubes (MWCNT) has been examined by Singh et al.^[18]. It was discovered that MRR and R_a increased with 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 GRA technique for optimizing above mentioned responses simultaneously, and also obtained the optimal parameter setting (such as T_{ON} of 125 μ s, 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 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 minimization of surface roughness. The optimum cutting parameters suitable for maximum MRR and minimum surface roughness were observed at T_{ON} of 25 μ s, T_{OFF} of 13.39 μ s, I_p of 2A, and V of 48.59 Vo. Sharma et al.^[22] analyzed the role of multiple process factors on the MRR, gap current (I_g) and machining time (MT) using Taguchi L_9 OA and ANOVA analysis while machining D2 die steel in WEDM. T_{OFF} was found to be the most influencing factor towards all the three responses with 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 μ s, T_{OFF} of 56 μ s, WF of 4mm/min, I_p of 3 knob position, WT of 4kg, and dielectric pressure of 13kg/m². 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 Taguchi-Grey approach. Better GRG was obtained at a combination of high pulse on time (30 μ s), low pulse off time (5 μ s) 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 the machining purpose. 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 L_{27} 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 was being done on the improvement of machining performance of D2 steel even though it is frequently utilized in the mold and die making industries where study of WEDM machining performance is of great importance. Moreover, very few works have been reported in the study of wire breakage. That means optimum use of this process without wire breakage.

Considering the aforementioned details, GRA technique is chosen for simultaneous optimization of five machining performances due to its simplicity and 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 wire electrode. The experiments have been economically planned to reduce the cost of experimentation. Further, maximum possible performance characteristics have been studied in the present investigation which was not done earlier.

1 Methodology

1.1 Design of Experiment (DOE)

Taguchi's Orthogonal Arrays (OA) technique is employed to arrange the cutting factors along with the levels which 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 that shows 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],

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

(b) For larger, the better category,

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

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

2 Experimentation

The experiments have been conducted on D2 tool steel also known as high carbon-high chromium steel. The chemical composition of D2 steel is 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 set up. For the machining purpose, brass wire of 0.25mm ϕ coated with Zn was utilized as cutting tool. From the literatures it was observed that coated wire produces better surface quality and improves the machining efficiency compared to un-coated wire [31-32]. When compared to ordinary plain brass wires i. e. uncoated wires, this coating of Zn offers a noticeable raise in the V_C value. Deionized water was used as dielectric medium.



Fig.1 The WEDM machine

In view of the literature analysis, four process parameters shown in Table 1 have been selected to investigate their effect on V_C (cutting rate), K_w (kerf width), R_a (surface roughness average), micro hardness and surface crack density of D2 steel specimen. In order to plan the experimental trials, Taguchi's L_9 OA design has been used, which is produced with MINITAB software as illustrated in Table 2. OA design approach helps in reducing the experimental runs [33].

Table 1 Input parameters

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

Note: A, B

Table 2 L_9 orthogonal array design

Expt. No.	$T_{ON}(\mu\text{s})$	$T_{OFF}(\mu\text{s})$	$I_P(A)$	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 Grey Relational Analysis (GRA) Technique

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

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

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

$$\eta_{xy} = -10 \log_{10} L_{xy} \quad (3)$$

where, L_{xy} is the loss function value of x^{th} 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 stated below:

(a) For larger-the-better,

$$Y_{xy} = \frac{\eta_{xy} - \eta_y^{\min}}{\eta_y^{\max} - \eta_y^{\min}} \quad (4)$$

(b) For smaller-the-better,

$$Y_{xy} = \frac{\eta_y^{\max} - \eta_{xy}}{\eta_y^{\max} - \eta_y^{\min}} \quad (5)$$

where, Y_{xy} is the normalized S/N ratio value of x^{th} output factor at j^{th} experiment, η_y^{\min} is the least S/N ratio value of the corresponding response parameter i. e. $\eta_y^{\min} = \min \{ \eta_{1y}, \eta_{2y}, \dots, \eta_{my} \}$ and η_y^{\max} is the largest S/N ratio value of the corresponding response parameter i.e. $\eta_y^{\max} = \max \{ \eta_{1y}, \eta_{2y}, \dots, \eta_{my} \}$. Using the previously described equations, all of the responses are proportionally standardized within the

band of zero to one.

Step 3: Computation of the Grey Relational Coefficients (GRC), γ_{xy} .

The GRC value for each response characteristic is calculated as described below:

$$\gamma_{xy} = \frac{\Delta_y^{\min} + \xi \Delta_y^{\max}}{\Delta_{xy} + \xi \Delta_y^{\max}} \quad (6)$$

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

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

The GRG value for i^{th} experimental run is calculated following the below formulae:

$$\text{GRG} = \sum_{y=1}^n w_y \gamma_{xy} \quad (7)$$

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

Using ANOVA, an attempt has been made in this work to ascertain the significant impact of various machining factors, namely $T_{\text{ON}}, T_{\text{OFF}}, I_p$, and WF, on the several performance measures. Finally, a confirmatory experiment using the best parametric setting has been carried out to validate the optimized results.

2.2 Measurement of Response Characteristics

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

Using Eq. (8), the V_c for each experimental run was determined as follows:

$$V_c = \frac{L}{t} \text{mm/min} \quad (8)$$

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 every machined specimen was measured using Talysurf Surtronic profilometer having a 0.8mm cut off value. And, the micro hardness of the machined specimen

was measured using a Rockwell hardness tester with diamond tip. Table 3 presents the experimental outcomes.

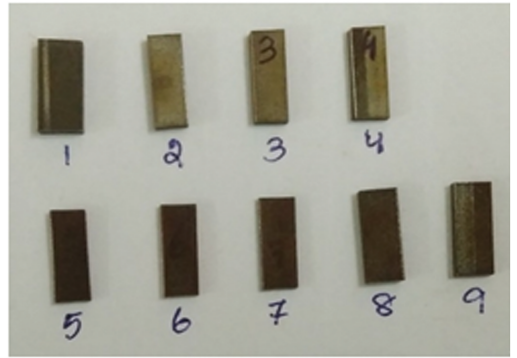


Fig.2 Machined specimen

The density of surface cracks has been determined by analyzing the top surface morphology of the WEDMed specimen under 1.5 K times magnification using Scanning Electron Microscopy (SEM). The length of the cracks that are occurring on the designated region has been measured using the same software. The average length of a crack for every machined surface can be found using the following formula.

$$\text{Surfacecrackdensity (SCD)} = \frac{l_1 + l_2 + l_3 + \dots + l_n}{S} \quad (9)$$

where, l_1, l_2, \dots, l_n are length of cracks occurring on the machined surface in μm and, A represents area of the region focused under SEM in μm^2 , $S = 45720 \mu\text{m}^2$. Fig.3 represents SEM micrographs of machined surface of D2 steel at different experimental runs.

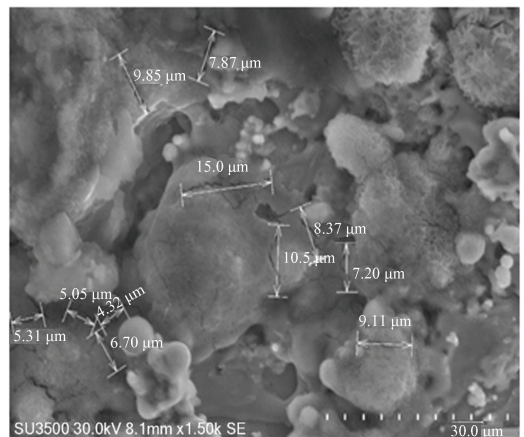


Fig. 3 SEM micrograph of sample specimen illustrating the measured surface cracks

Table 3 Experimental Results

Expt. No.	V_C (mm/min)	K_w (mm)	R_a (μm)			Micro hardness	Crack density (mm/mm^3)
			R_{a1}	R_{a2}	R_{a3}		
1	0.261	0.35	0.98	1.12	1.38	18.7	0.00139
2	0.193	0.51	1.12	1.18	1.10	17.95	0.00119
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	0.00143
6	0.125	0.50	1.48	1.36	1.14	11.75	0.00198
7	0.259	0.55	0.78	0.74	0.70	5.90	0.00223
8	0.202	0.48	0.79	0.80	0.82	17.75	0.00236
9	0.133	0.44	1.10	0.60	0.66	13.35	0.00226

3 Analysis on Experimental Results

This part analyzes the experimental findings listed in Table 3 by using the GRA methodology, which was discussed in the previous section. While smaller values of R_a , K_w , micro hardness, and crack density imply desired performance and are therefore considered as the smaller, the better category aspects, bigger values of V_C are represented as the larger, the better category aspect in this study.

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) was used to convert loss function values into S/N ratios. Eq.(4) was then utilized for normalizing

the associated S/N ratio values of V_C , and Eq.(5) was applied to K_w , R_a , micro hardness, and crack density. Next, Eq.(6) was used to calculate the gray relational coefficients. All four of the machining factors are thought to have an equivalent impact on the V_C , K_w , R_a , micro hardness, and surface crack density in this study. Therefore, in Eq.(6), ξ is assumed to be 0.5, as this value has been commonly used by earlier researchers in their studies^[36-38]. Then, the GRG value is calculated by using Eq.(7). The grey relational grade and grey relational coefficient values for each experimental run are displayed in Table 4. The Taguchi method and grey relational analysis 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)	Micro hardness	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. $A_2 B_2 C_1 D_2$ in Table 1, which corresponds to a T_{ON} of 110 μs , a T_{OFF} of 40 μs , a I_p of 10A, and a WF of 6mm/min, could be suggested as

the ideal cutting parameters in the present machining process. Optimality of this setting has been validated through confirmatory experiment.

Table 5 Response table for GRG

Symbol	Parameters	Level average values		
		Level 1	Level 2	Level 3
A	T_{ON}	0.5962	0.6263	0.6053
B	T_{OFF}	0.5737	0.6610	0.5932
C	I_p	0.6469	0.5734	0.6075
D	WF	0.6146	0.6415	0.5717
Total mean GRG = 0.6093				

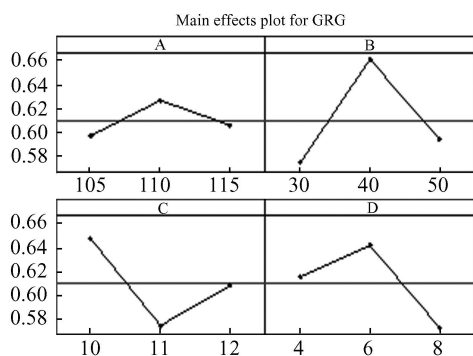


Fig.4 Variation of input parameters with GRG value

It is evident that with a raise in T_{ON} , T_{OFF} , and WF, the mean GRG value first raises and then diminishes. With a raise 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 more number of surface cracks. Similarly, with increase in T_{OFF} , cutting rate decreases due to a smaller number of 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, moderate value of T_{ON} and T_{OFF} shows better performance. Increasing 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 value 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 lower current value the cutting will be slow hence, the surface becomes smooth with 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 which has least F value is considered to have negligible impact on the process performance, hence that factor is included in error term. The ANOVA analysis’s results are displayed in Table 6. From the results, it is clear that factor A has least F value (i.e. 1.00), so it is included in error term. According to the findings, I_p (contributing 27.47%) and T_{OFF} (contributing 42.69%) are the most influential factors which affect the overall performance metrics. Sharma et. al.^[22] analyzed D₂ steel and stated that T_{OFF} was the most influencing parameter (60%). Similarly, in the present investigation T_{OFF} is found to be the most influencing parameter (i.e. 42.69%). The percentage is varied may be due to variation of total numbers of output parameters. Pulse on time is deemed statistically unimportant because it has the least 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 , micro hardness, 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:

$$V_c = -1.260 - 0.0206 T_{ON} + 0.00470 T_{OFF} + 0.3990 I_p - 0.0980 WF \quad (9)$$

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

$$K_w = -0.359 + 0.00633 T_{ON} - 0.00017 T_{OFF} + 0.0017 OI_p + 0.01750 WF \quad (11)$$

$$\text{Micro hardness} = 89.5 - 0.577 T_{ON} + 0.105 T_{OFF} - 1.37 I_p - 0.104 WF \quad (12)$$

$$\text{Crack density} = -0.00890 + 0.000125 T_{ON} + 0.000008 T_{OFF} - 0.000257 I_p - 0.000128 WF \quad (13)$$

Using the above regression equations, the error percentage between the actual result and predicted result of V_c , K_w , R_a , micro hardness, and crack density are calculated and presented in the Table 7, 8, 9, 10, and 11, respectively.

Table 7 Error analysis for V_c

Expt. No.	V_c (Experimental)	V_c (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 (Experimental)	R_a (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 (Experimental)	K_w (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 micro hardness

Expt. No.	Micro hardness (Experimental)	Micro hardness (Predicted)	Error percentage(%)
1	18.7	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 (Experimental)	V_c (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 the five responses is 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 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	K_w	R_a	Micro hardness	Crack density
Optimal cutting parameters ($A_2B_2C_1D_2$)	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

3 Conclusion

The following conclusion are obtained from the present investigation.

1) Optimum process variables namely T_{ON} , T_{OFF} , I_p and WF have been determined for simultaneous optimization of WEDM performances such as: cutting rate, kerf width, surface roughness, micro hardness 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 optimum combination of input variables is: T_{ON} of 110 μ s, T_{OFF} of 40 μ s, I_p of 10A and WF of 6mm/min and the corresponding best performances are: V_c of 0.112mm/min, K_w of 0.41mm, R_a of 1.06 μ m, micro hardness of 15.21HRC, and surface crack density of 0.00189mm/mm².

4) From the experimental results it is found that a minimum surface crack density of 0.00119 mm/mm² was obtained at low value of T_{ON} (105 μ s) and intermediate values of T_{OFF} (40 μ s), I_p (11A) and WF (6mm/min).

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

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

7) The optimum process parameters are ensured for improvement of machining performance while confirmation experiment is performed. It may be noted that although micro hardness value is reduced slightly and crack density is increased marginally which has least effect on the overall productivity.

8) This work will definitely help industry personnel due to 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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