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Parameter optimization of electrical discharge machining process by using Taguchi approach

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Electrical discharge machining (EDM) is one of the most extensively used non-traditional material removal processes for difficult-to-cut materials. The full potential of the EDM process has not yet been exploited due to its complicated discharge mechanism. Though a lot of research has been done to improve the process performance, optimal selection of process parameters for the best performance measures still remains a challenge. Parameter optimization is one of the techniques used in manufacturing processes to achieve best manufacturing conditions, which is an essential need for industries towards manufacturing of higher quality products at lower cost. In this paper, the cutting of hot work tool steel 2714 using electro discharge machining process with copper and graphite electrodes has been investigated. In this work L_{27} (3*4) orthogonal array based on the Taguchi experimental design is utilized to plan the experiments. Raw data is assessed by the Analysis of Variance (ANOVA) to find optimal conditions for response parameters. The main machining parameters such as pulse-on time, pulse-off time, discharge current, average machining voltage are chosen to determine the EDM response parameters such as material removal rate, surface roughness and gap size. Response tables and graphs are used to find the optimal parameter levels in the EDM process.

Key words: Electrical discharge machining (EDM), tool steel 2714, Taguchi approach, material removal rate, surface roughness and gap size.

INTRODUCTION

Electrical discharge machining (EDM) is an extremely prominent machining process among newly developed non-traditional machining techniques for difficult-to-cut materials. EDM is a thermo-electric process in which material is removed from work piece by the erosion effect of a series of electric discharges (sparks) between two electrodes (tool and workpiece) immersed in a dielectric liquid. The location of the discharge is determined by the narrowest gap between the two electrodes (McGeough, 1998). The workpiece and the tool should be made of electrically conductive material. EDM is especially well-suited for cutting intricate contours or delicate cavities that would be difficult to produce with a grinder, an end mill or other cutting tools. Physical and metallurgical properties do not create any limitation for the materials to be machined on EDM as there is no physical contact between tool and work piece (Yan et al., 2000). The EDM process has a very strong stochastic nature due to the

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complicated discharge mechanisms (Pandit and Mueller, 1987) making it difficult to optimize the sparking process. The optimization of the process often involves relating the various process variables with the performance measures maximizing material removal rate, while minimizing gap size and yielding desired surface roughness. Though a lot of researches have been done to improve the EDM process performance, optimal selection of the process parameters for the best performance measures still remains a challenge. Although studying of these parameters has been performed by many researchers, most of the studies do not much consider the optimization of the EDM process using both engineering philosophy design of experiments (DOE) and S/N ratio together with the analysis of variance (ANOVA) techniques which are used to measure the amount of deviation from the desired performance measures and identify the crucial process variables affecting the process responses (Ranjit, 1996, 2001).

Traditionally, the selection of the most favorable process parameters was based on experience or handbook values, which produced inconsistent machining performance. However, the optimization of parameters now relies on process analysis to identify the effect of operating variables on achieving the desired machining characteristics. Other works have applied the Taguchi approach to analyze and design the ideal EDM process. Taguchi design is a powerful tool for parametric design of performance characteristics; it recognizes that not all factors that cause variability can be controlled in practice. Using Taguchi's parameter design, significant machining parameters affecting the performance measures are identified. The Taguchi design has been employed to obtain the optimum factor/level combination of process parameters (Ranjit, 1996, 2001; Peace, 1993).

Taguchi modeling is helpful in the study of interaction of the different processing parameters, which would give a more precise image of the experimental results (Lorelei et al., 2012). Renjie et al. (2010, 2012) adopted the L_{25} orthogonal array based on Taguchi method, and evaluated the experimental data statistically by analysis of variance and stepwise regression. Renjie et al. (2010) optimized the machining parameters of silicon carbide ceramics with ED milling and mechanical grinding combined process. Mahapatra and Patnaik (2006) studied the optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method. They demonstrated that the WEDM process parameters can be adjusted to achieve better metal removal rate, surface finish and cutting width simultaneously. Marafona and Wykes (2000) used the Taguchi method to improve the TWR by introducing high carbon content to the electrode prior to the normal sparking process. Optimization of the operating parameters for EDM process of AISI D3 steel material has been studied using Taguchi method (Nipanikar, 2012). Lin et al. (2000) employed Taguchi approach with a set of fuzzy logic to optimize the process parameters taking the various performance measures into consideration. The implementation of Taguchi method on the EDM process of Tungsten Carbide has been reported (Mohd et al., 2009). Also, the effects of the EDM process variables on the material removal rate have been investigated using Taguchi parameter design approach (Amit and Pradeep, 2012). Tzeng and Chen (2003) optimized the high-speed EDM process by making use of dynamic signal-to-noise (S/N) ratio to classify the process variables into input signal, control and noise factors generating a dynamic range of output responses. Yan-Cherng et al. (2009) investigated EDM machining performance and optimizing machining parameters of Al_2O_3–TiC ceramics using Taguchi method. Utilizing L18 orthogonal array based on the Taguchi experimental design is used to plan the experiments and raw data assessed by the Analysis of Variance (ANOVA) to find optimal conditions for material removal rate (Singh et al., 2011).

In this work, the Taguchi method is used to determine the optimal machining parameters for maximum material removal rate, minimum surface roughness and minimum gap size in EDM operations. The level of influence of input parameters (on performance measures) has also been identified after experimental investigation with the help of ANOVA. Experimental verification of results achieved demonstrates that process performance may be improved significantly by this technique.

EXPERIMENTAL WORK

The experimental studies were performed on a NC die sinking EDM (Sodick AQ35LR) as shown in Figure 1. A kerosene type working fluid (Sodick hightech VITOL2) was used. Short cylindrical bars of both copper and graphite (Ibiden ED-3) materials of 8 mm in diameter were used as electrodes. Different settings of four controllable factors such as pulse-on time, pulse-off time, peak current and average machining voltage were used in the experiments. The electrode polarity was positive when using graphite electrodes and copper electrodes. The working EDM conditions are as listed in Table 1. A series of EDM experiments with varying discharge conditions were carried out.

Hot work tool steel 2714 is chosen as the workpiece material. Tool steel 2714 is a chromium-nickel-molybdenum alloy steel (56 Ni Cr Mo V 7) with the chemical composition listed in Table 2. The hardness of this steel as delivered ranges from 1250 to 1400 Mpa. This material can be used in forge and press dies, shear blades, extrusion rams die holders and hot deburring plates. The work piece is weighed before and after each experiment using an electric balance with a resolution of 0.01 mg to determine the value of material removal rate. For each set of values, three experiments are performed in randomized sequence in order to eliminate the influence of systematic errors, as recommended by Taguchi. Material removal rate is calculated as,

$$MRR = \frac{\left(W_i - W_f\right) \times 1000}{\left(D_w \times t\right)} \quad (1)$$

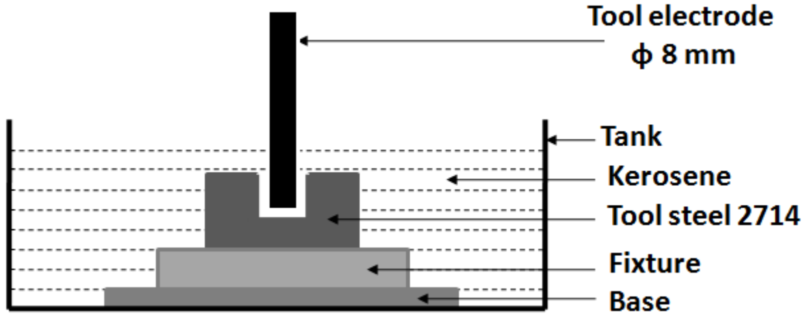

Figure 1. Principle of an EDM process.

Table 1. EDM conditions.

Condition name	Electrode type	
	Copper	Graphite
Pulse-on time (µs)	50, 100 and 150	20, 60 and 100
Pulse-off time (µs)	40, 50 and 60	10, 40 and 60
Discharge current (Amp.)	1, 4 and 6	1, 5 and 10
Average machining voltage (V)	40, 50 and 60	40, 45 and 50
Working fluid	Kerosene	
Workpiece material	Tool steel 2714	

Table 2. Chemical composition of 2714 tool steel.

C	Cr	Ni	Mo	V	St
0.56	1.10	1.70	0.50	0.10	Rem.

(Unit: mass %).

Where MRR is the material removal rate (mm^3/min), W_i is the initial average weight of the workpiece (g), W_f is the final average weight of the workpiece (g), D_w is the density of the workpiece (g/cm^3), t is the time of machining (min).

The surface roughness (SF) value Rz (µm) was measured using a 'Mitutoyo Talysurf (SJ-201) portable surface measuring unit with stylus radius of 5 µm. The cutoff length for each measurement was taken as 0.8 mm. The surface roughness values were measured for each specimen three times and the average was calculated. The resulted EDM cavities diameters were measured using an optical microscope (Keyence VH-7000 optical digital, USA). The gap size (GS) value is determined based upon the average of three results from Equation 2.

$$GS = \frac{D_H - D_{TE}}{2} \qquad (2)$$

Where D_H is the hole cavity diameter in mm and D_{TE} is the tool-electrode diameter in mm.

Design of experiments (DOE)

In the present study, four process parameters namely, pulse-on time, pulse-off time, discharge current and average machining voltage are considered, although a large number of factors could be considered for controlling the EDM process. Tables 3 and 4 show the design factors along with their levels for both copper and graphite electrodes respectively. Three levels, having equal spacing, within the operating range of the parameters are selected for each of the factors.

In this study, the Taguchi method, an effective and powerful tool for experimental design of the performance characteristics was used to determine the optimal machining parameters for maximization of MRR and minimization of SF and (GS) in EDM process. Taguchi designs use orthogonal arrays, which estimate the effects of factors on the response mean and variation. Orthogonal array is a statistical method of defining parameters that converts test areas into factors and levels. Test design using orthogonal array creates an efficient and concise test suite with fewer test cases without compromising test coverage. The control factors are used to select the best conditions for stability in design of manufacturing process, whereas the noise factors denote all factors that cause variation. In this work, it is planned to study the

Table 3. Design factors and their levels for tool steel 2714 workpiece – Cu electrode.

Control parameter	Coding	Level 1 Minimum	Level 2 Intermediate	Level 3 Maximum
Pulse-on time (T_{ON}) in µs	A	50	100	150
Pulse-off time (T_{OFF}) in µs	B	40	50	60
Discharge current (I) in Amp	C	1	4	6
Average machining voltage (V) in V	D	40	50	60

Table 4. Design factors and their levels for tool steel 2714 workpiece – Gr electrode.

Control parameters	Coding	Level 1 Minimum	Level 2 Intermediate	Level 3 Maximum
Pulse-on time (T_{ON}) in µs	E	20	60	100
Pulse-off time (T_{OFF}) in µs	F	10	40	60
Discharge current (I) in Amp	G	1	5	10
Average machining voltage (V) in V	H	40	45	50

behavior of four control factors, (A, B, C, and D) for copper electrode and (E, F, G and H for graphite electrodes, and two interactions such as A×C and A×D for copper electrode and E×G and E×H for graphite electrode. The experimental observations are further transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on the type of characteristics. The characteristic of higher value represents better machining performance, such as MRR, and is termed 'higher is better, HB'. Inversely, the characteristic of lower value represents better machining performance, such as surface roughness, and is termed 'lower is better, LB. Therefore,"HB" for the MRR 'LB" for the SF and "LB" for the (GS) were selected for obtaining optimum machining performance characteristics. The loss function (L) for objective of HB and LB is defined as follows:

$$L_{HB} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{MRR}^2} \quad (3)$$

$$L_{LB} = \frac{1}{n}\sum_{i=1}^{n} y_{SF}^2 \quad (4)$$

$$L_{LB} = \frac{1}{n}\sum_{i=1}^{n} y_{GS}^2 \quad (5)$$

Where the terms y_{MRR}, y_{SF} and y_{GS} denote the response for metal removal rate, surface finish and gap size, respectively, and n denotes the number of performed experiments.

The S/N ratio response parameter can be calculated as a logarithmic transformation of the loss function as shown below.

$$\frac{S}{N}\, ratio\ for\ MRR = -10\ log_{10}(L_{HB}) \quad (6)$$

$$\frac{S}{N}\, ratio\ for\ SF = -10\ log_{10}(L_{LB}) \quad (7)$$

$$\frac{S}{N}\, ratio\ for\ GS = -10\ log_{10}(L_{LB}) \quad (8)$$

The orthogonal array chosen to set the control parameters and evaluate the process performance is the L_{27} (3^{13}), which has 27 rows corresponding to the number of experiments with 13 columns at three levels. It considers four process parameters (without interaction), (A, B, C, and D) for copper electrode and (E, F, G and H for graphite electrodes, to be varied in three discrete levels.

The plan of experiments when using copper electrodes is as follows: the first column was assigned to pulse-on time (A), the second column to pulse-off time (B), the third column to peak current (C), the sixth column to average machining voltage (D), the fourth column and fifth columns are assigned to (A×C) and (B×C), respectively, to estimate interaction between pulse-on time (A), pulse-off time (B) and discharge current (C), the seventh column and the eighth column are assigned to (A×D) and (B×D), respectively, to estimate interaction between the pulse-on time (A), pulse-off time (B) and average machining voltage (D). When using graphite electrodes, the plan of experiments look like it for copper electrodes. According to the Taguchi design concept, a L_{27} orthogonal array table was chosen for the experiments as shown in Table 5. The Taguchi analysis was made using the popular software specifically used for design of experiment applications known as MINITAB 15.

Table 5. Taguchi's L_{27} OA design.

Ex. No.	A or E	B or F	C or G	D or H
1	1	1	1	3
2	1	1	2	2
3	1	1	3	1
4	1	2	1	3
5	1	2	2	2
6	1	2	3	1
7	1	3	1	3
8	1	3	2	2
9	1	3	3	1
10	2	1	1	3
11	2	1	2	2
12	2	1	3	1
13	2	2	1	3
14	2	2	2	2
15	2	2	3	1
16	2	3	1	3
17	2	3	2	2
18	2	3	3	1
19	3	1	1	3
20	3	1	2	2
21	3	1	3	1
22	3	2	1	3
23	3	2	2	2
24	3	2	3	1
25	3	3	1	3
26	3	3	2	2
27	3	3	3	1

RESULTS AND DISCUSSION

Here, the use of an orthogonal array to reduce the number of cutting experiments for determination of optimal cutting parameters is presented. Results of the cutting experiments are studied by using the S/N and ANOVA analyses. Based on the results of these analyses, optimal cutting parameters for maximum material removal rate and minimum surface roughness and gap size are obtained and verified.

After DOE process, a set of 27 experiments are carried out in electrical discharge machine for each type of electrode. After each experiment material removal rate was calculated and also, surface roughness and gap size were measured. A quality characteristic for MRR is higher is better (HB) and lower is better (LB) is the quality characteristic for both surface roughness and gap size. Signal-to-noise (S/N) ratios were calculated for each experiment with the help of software Minitab 15 as shown in Tables 6 and 7. The output characteristic, MRR, SR and GS are analyzed by software Minitab 15 and ANOVA is formed, which shows the percentage contribution of each influencing factor on MRR, SR and GS.

Effect of input factors on MRR

Main effect plots for means and main effect plots for signal to noise ratio of material removal rate for copper and graphite electrodes are plotted with the help of Minitab 15 software as shown in Figures 2 and 3, respectively. The interaction plots for MRR between pulse-on time and both discharge current and average machining voltage for copper and graphite electrodes are also shown in Figures 4 and 5, respectively. In the main effects plot, if the line for a particular parameter is near horizontal, then the parameter has no significant effect. On the other hand, a parameter for which the line has the highest inclination will have the most significant effect. It is very much clear from the main effects plot that parameter pulse-on time (A) is the most significant parameter, while average machining voltage (D) has some contribution. As far as the interaction plots are concerned, estimating an interaction means determining the non-parallelism of the parameter effects. Thus, if the lines on the interaction plots are non-parallel, interaction occurs and if the lines cross, strong interactions occur between parameters.

From Figure 3, it can be seen that there are moderate interaction between the parameters: pulse on time (A) and discharge current (C) and strong interaction between the parameters pulse-on time (A) and average machining voltage (D). Thus from the present analysis it is clear that the pulse-on time (A) is the most influencing parameter for the multiple parameters of EDM process. According to the higher-the-better quality characteristic for MRR of copper electrode, based from the maximum point on the graph, the optimum condition for each factor indicated is A3 (150 μs), B3 (60 μs), C3 (6 A), D1 (40 V). The optimal process parameter combination for maximum metal removing rate is found to be pulse on time (A) at highest level, pulse off time (B) at highest level, discharge current (C) at highest level and average machining voltage (D) at lowest level.

The S/N ratio corresponds to the larger variance of the output characteristics around the desired value. The mean S/N ratio for each level of the cutting parameters is summarized and called the mean S/N response table for material removal rate (Table 8). When using copper electrodes, the effect of cutting parameters can be ranked as follows (pulse-on time, discharge current, pulse-off time and average machining voltage). However, the effect of cutting parameters can be ranked as follows (pulse-on time, pulse-off time, discharge current and average machining voltage) when using graphite electrodes.

ANOVA is a statistical technique that can infer some important conclusions on the basis of analysis of the experimental data. The method is very useful for revealing the level of significance of influence of factor(s) or interaction of factors on a particular response. It separates the total variability of the response into

Table 6. Experimental design using L_{27} orthogonal array for copper electrodes.

Exp. no.	A	B	C	D	MRR	S/N ratio	SR	S/N ratio	GS	S/N ratio
1	50	40	1	60	0.005	-46.021	8.564	-18.654	37	-31.364
2	50	40	4	50	0.018	-34.895	10.216	-20.186	47	-33.442
3	50	40	6	40	0.027	-31.373	12.884	-22.201	52	-34.320
4	50	50	1	50	0.015	-36.478	10.006	-20.005	44	-32.869
5	50	50	4	40	0.025	-32.041	11.966	-21.559	50	-33.979
6	50	50	6	60	0.033	-29.63	13.288	-22.469	54	-34.648
7	50	60	1	40	0.035	-29.119	13.876	-22.845	55	-34.807
8	50	60	4	60	0.043	-27.331	14.548	-23.256	58	-35.269
9	50	60	6	50	0.054	-25.352	15.632	-23.880	61	-35.707
10	100	60	1	60	0.072	-22.853	16.998	-24.608	72	-37.147
11	100	60	4	50	0.082	-21.724	17.882	-25.048	80	-38.062
12	100	60	6	40	0.118	-18.562	20.098	-26.063	87	-38.790
13	100	40	1	50	0.062	-24.152	16.344	-24.267	67	-36.522
14	100	40	4	40	0.072	-22.853	17.000	-24.609	72	-37.147
15	100	40	6	60	0.079	-22.048	17.566	-24.894	75	-37.501
16	100	50	1	40	0.082	-21.724	17.88	-25.047	80	-38.062
17	100	50	4	60	0.091	-20.819	18.432	-25.311	82	-38.276
18	100	50	6	50	0.104	-19.659	19.002	-25.576	86	-38.690
19	150	50	1	60	0.158	-16.027	21.072	-26.474	92	-39.276
20	150	50	4	50	0.181	-14.846	22.987	-27.230	95	-39.555
21	150	50	6	40	0.228	-12.841	26.879	-28.588	98	-39.825
22	150	60	1	50	0.169	-15.442	21.611	-26.694	94	-39.463
23	150	60	4	40	0.188	-14.517	23.888	-27.564	96	-39.645
24	150	60	6	60	0.196	-14.155	24.662	-27.841	96	-39.645
25	150	40	1	40	0.168	-15.494	21.434	-26.622	94	-39.463
26	150	40	4	60	0.176	-15.09	22.144	-26.905	95	-39.555
27	150	40	6	50	0.189	-14.471	24.044	-27.620	96	-39.645

contributions of each of the factors and the error.

Using Minitab, ANOVA is performed to determine which parameter and interaction significantly affect the performance characteristics. Tables 9 and 10 show the ANOVA results for material removal rate for copper and graphite electrodes respectively. The ANOVA table shows the percentage contribution of each parameter. For MRR, the calculation of S/N ratio follows "Larger the Better" model**.** Therefore, pulse-on time (T_{ON}) has the maximum effect on material removal rate. Similarly, interaction between pulse-on time (T_{ON}) and discharge current (I) and pulse-on time (T_{ON}) and average machining voltage (V) have some influence on MRR of the EDM ~~of~~ process parameters.

It can be concluded that, pulse-on-time is a significant factor for material removal rate. Pulse-on-time is current discharge duration on the voltage gap. Short peak current duration or short pulse duration may cause less surface vaporization of the workpiece during machining, whereas long pulse duration may cause the plasma channel to expand in the machining gap (Wang, 1999). The increase in pulse-on-time means that the same heating flux is applied for a longer time. This will cause an increase of heat that is conducted into the workpiece as the plasma channel expands which will result in an increase in the MRR (Panda, 2008; Natsu et al., 2006).

Effect of input factors on surface roughness

Main effect plots for means and main effect plots for signal to noise ratio surface roughness for copper and graphite electrodes are shown in Figures 6 and 7, respectively. The interaction plots for surface roughness between pulse-on time and both discharge current and average machining voltage for copper and graphite electrodes are also shown in Figures 8 and 9, respectively. It is noticed from the main effects plot that the pulse-on-time parameter (A) is the most significant parameter, while the average machining voltage (D) has some contribution.

The response table for signal to noise ratio for surface roughness is shown in Table 11 and the corresponding ANOVA table is shown in Tables 12 and 13. For SR, the calculation of S/N ratio follows “Smaller the Better” model. Therefore, pulse-on-time (T_{ON}) has the maximum

Table 7. Experimental design using L_{27} orthogonal array for graphite electrodes.

Exp. no.	E	F	G	H	MRR	S/N ratio	SR	S/N ratio	GS	S/N ratio
1	20	10	1	50	0.014	-37.077	8.026	-18.090	33	-30.370
2	20	10	5	45	0.062	-24.152	10.800	-20.669	37	-31.364
3	20	10	10	40	0.088	-21.110	12.033	-21.608	41	-32.256
4	20	40	1	45	0.094	-20.537	13.756	-22.770	43	-32.669
5	20	40	5	40	0.101	-19.914	15.066	-23.560	46	-33.255
6	20	40	10	50	0.108	-19.332	16.989	-24.603	50	-33.979
7	20	60	1	40	0.121	-18.344	18.222	-25.212	52	-34.320
8	20	60	5	50	0.129	-17.788	19.011	-25.580	54	-34.648
9	20	60	10	45	0.144	-16.833	19.889	-25.972	55	-34.807
10	60	60	1	50	0.377	-8.4732	23.632	-27.470	73	-37.267
11	60	60	5	45	0.408	-7.7868	24.092	-27.638	76	-37.616
12	60	60	10	40	0.442	-7.0916	24.881	-27.917	80	-38.062
13	60	10	1	45	0.152	-16.363	20.688	-26.314	58	-35.269
14	60	10	5	40	0.173	-15.239	21.020	-26.453	62	-35.848
15	60	10	10	50	0.198	-14.067	21.872	-26.798	65	-36.258
16	60	40	1	40	0.221	-13.112	22.078	-26.879	67	-36.522
17	60	40	5	50	0.265	-11.535	22.874	-27.187	69	-36.777
18	60	40	10	45	0.352	-9.0692	23.122	-27.281	72	-37.147
19	100	40	1	50	0.588	-4.6125	28.678	-29.151	90	-39.085
20	100	40	5	45	0.608	-4.3219	29.065	-29.267	92	-39.276
21	100	40	10	40	0.648	-3.7685	29.867	-29.504	94	-39.463
22	100	60	1	45	0.692	-3.1979	30.602	-29.715	96	-39.645
23	100	60	5	40	0.712	-2.9504	31.089	-29.852	98	-39.825
24	100	60	10	50	0.800	-1.9382	32.224	-30.164	101	-40.086
25	100	10	1	40	0.488	-6.2316	25.438	-28.110	83	-38.382
26	100	10	5	50	0.501	-6.0033	26.534	-28.476	85	-38.588
27	100	10	10	45	0.528	-5.5473	27.843	-28.894	87	-38.790

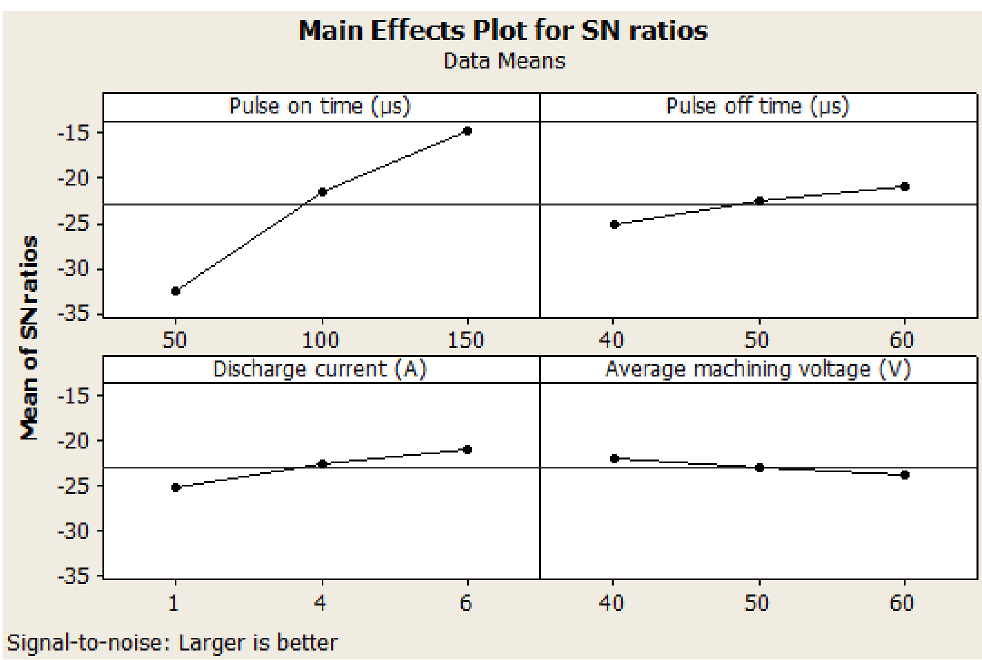

Figure 2. Main effects plot for S/N ratios of each factor on MRR with Cu electrode.

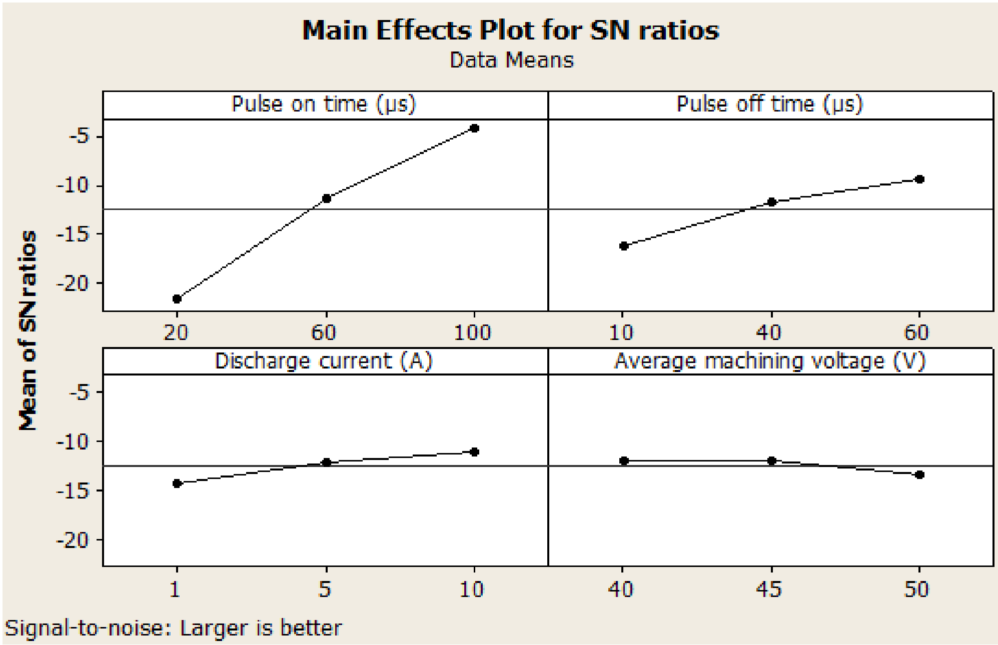

Figure 3. Main effects plot for S/N ratios of each factor on MRR with graphite electrode.

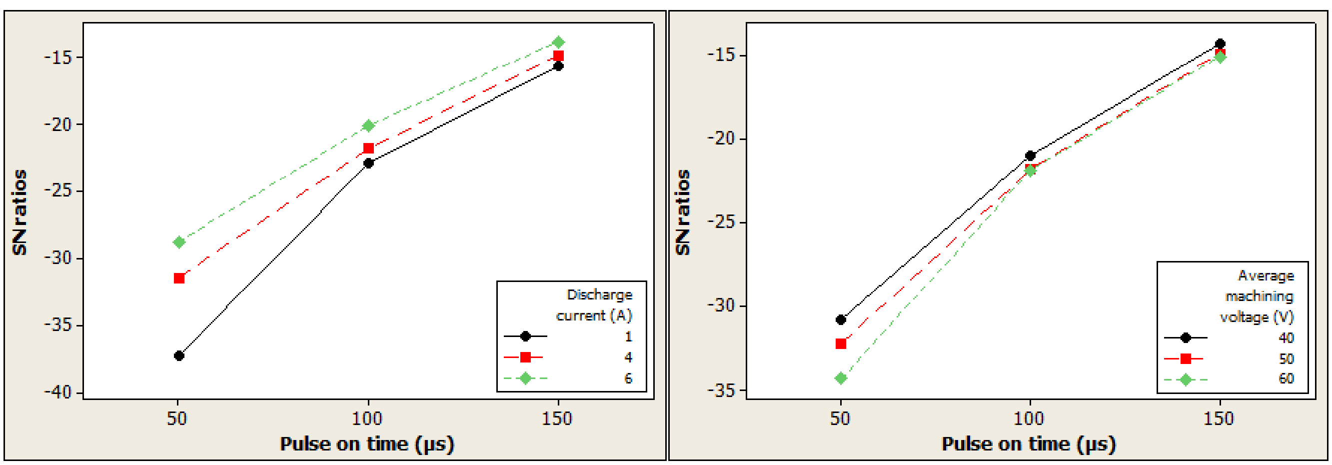

Figure 4. Interaction graphs for MRR between pulse-on time and both discharge current and average machining voltage for Cu electrode.

effect on surface roughness.

When using copper electrode, pulse-on-time (T_{ON}) with a contribution of 86.33% has the greatest effect on the machining output characteristics. Parameter C that is,. discharge current (I) with a 7.51% share is the next most significant influence on the output parameters, followed by parameter B that is, machine's pulse-off-time, (T_{OFF}) 4.7%. However, for graphite electrode, pulse-on-time with a contribution of 80.12% has the greatest effect on the machining output characteristics. Parameter B i.e. machine's pulse-off-time, with 15.16% share is the next most significant influence parameter, followed by parameter C, that is, discharge current with a 2.1%. Surface finish quality was better when applying smaller pulse-on-time. This is because of small particle size and crater depths formed by electrical discharge. As a result, the best surface finish will be produced. The selection of these machining parameters for EDM of any material should be used for a higher surface quality is required.

It was observed that when discharge current and particularly pulse-on time increased with pulse-off time, machined work piece surface exhibited a higher surface roughness due to irregular topography. Discharge current had an effect on surface roughness at low pulse time, but the influence of pulse-on time was more significant than discharge current at higher pulse times. It was noticed

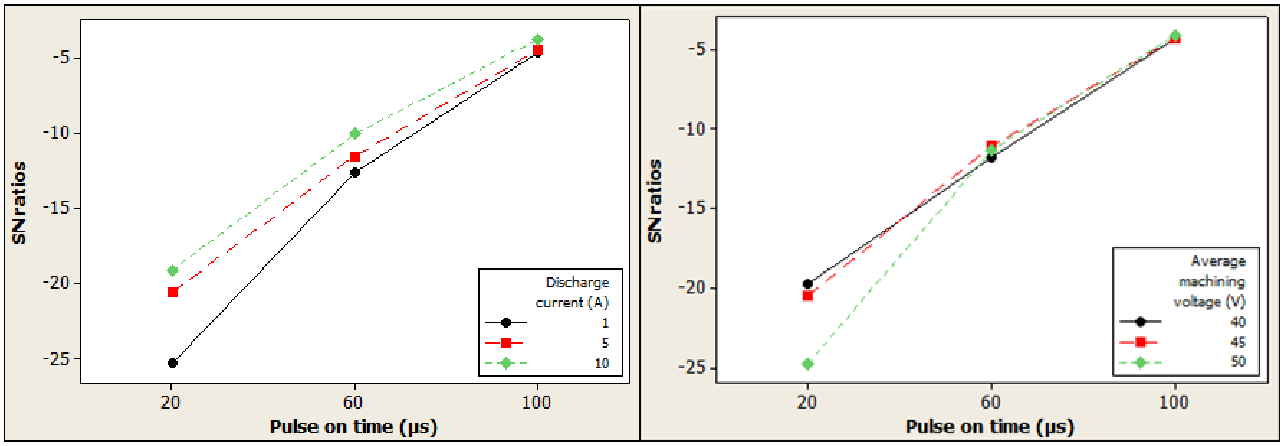

Figure 5. Interaction graphs for MRR between pulse-on time and both discharge current and average machining voltage for Graphite electrode.

Table 8.S/N ratio response table for material removal rate.

Level	Cu electrode				Gr electrode			
	T_{ON}	T_{OFF}	I	V	T_{ON}	T_{OFF}	I	V
1	-32.47	-25.16	-22.06	-25.26	-21.676	-16.199	-14.217	-11.974
2	-21.60	-22.67	-22.68	-23.00	-11.415	-11.800	-12.188	-11.979
3	-14.76	-21.01	-20.90	-23.77	-4.286	-9.378	-10.973	-13.425
Delta	17.71	4.15	4.36	1.72	17.391	6.821	3.244	1.452
Rank	1	3	2	4	1	2	3	4

Table 9. ANOVA results for material removal rate using Cu electrode.

Sequence of Variation	Degrees of freedom (DF)	Sum of squares (SS)	Mean square (variance) MS = SS/DF	Contribution (%)
T_{ON}	2	1435.23	717.616	86.49
T_{OFF}	2	78.45	39.227	4.73
I	2	86.40	43.202	5.21
V	2	13.30	6.651	0.8
T_{ON} * I	4	42.07	10.517	1.27
T_{ON} * V	4	7.59	1.899	0.23
Residual Error	10	105.91	10.591	1.28
Total	26	1768.96		

that high discharge current and pulse times will produce a poor surface finish due to deeper and wider crates on the machined surface. Excellent machined surface quality could be obtained by setting machining parameters at a low short pulse-on-time and pulse-off-time.

Effect of input factors on gap size

Main effect plots for means and main effect plots for signal to noise ratio of gap size for copper and graphite electrodes are shown in Figures 10 and 11, respectively. The interaction plots for gap size between pulse-on time and both discharge current and average machining voltage for copper and graphite electrodes are also shown in Figures 12 and 13, respectively. It was observed that, the gap size has highly affected with pulse-on-time and being slightly affected with average machining voltage. This may be due to that in EDM process the values of gap size are proportional to

Table 10. ANOVA results for material removal rate using graphite electrode.

Sequence of variation	Degrees of freedom (DF)	Sum of squares (SS)	Mean square (variance) MS = SS/DF	Contribution (%)
T_{ON}	2	1375.67	687.837	81.1
T_{OFF}	2	215.22	107.610	12.68
I	2	48.34	24.171	2.85
V	2	12.60	6.299	0.74
T_{ON} * I	4	26.25	6.563	0.77
T_{ON} * V	4	31.09	7.772	0.92
Residual Error	10	81.95	8.195	0.97
Total	26	1791.13		

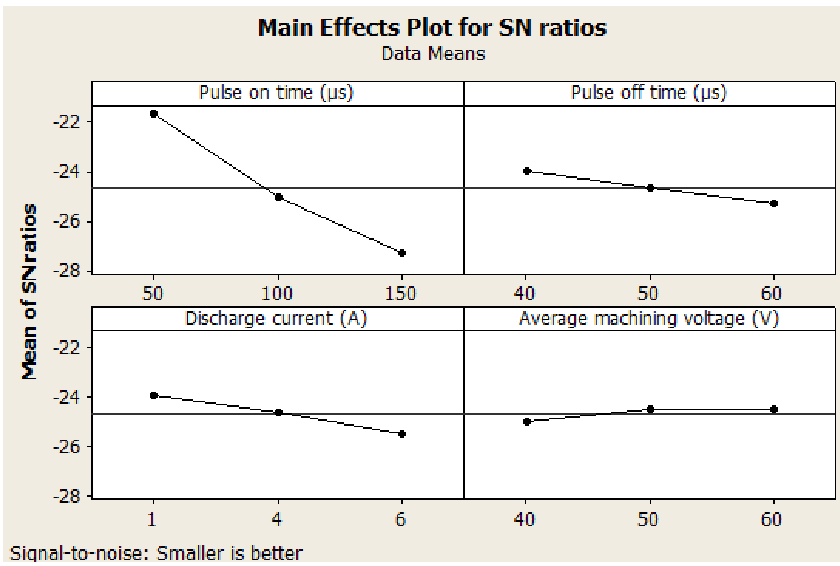

Figure 6. Main effects plot for SN ratios of each factor on SR with Cu electrode.

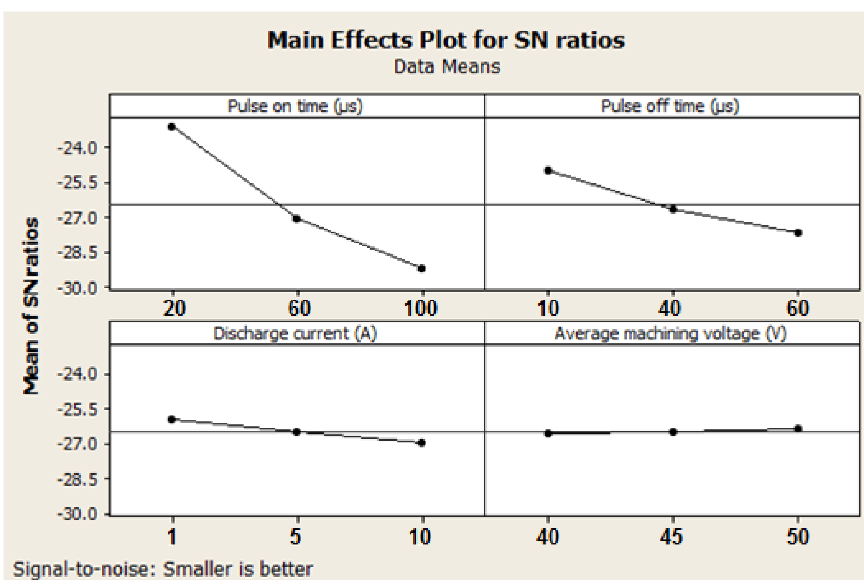

Figure 7. Main effects plot for SN ratios of each factor on SR with graphite electrode.

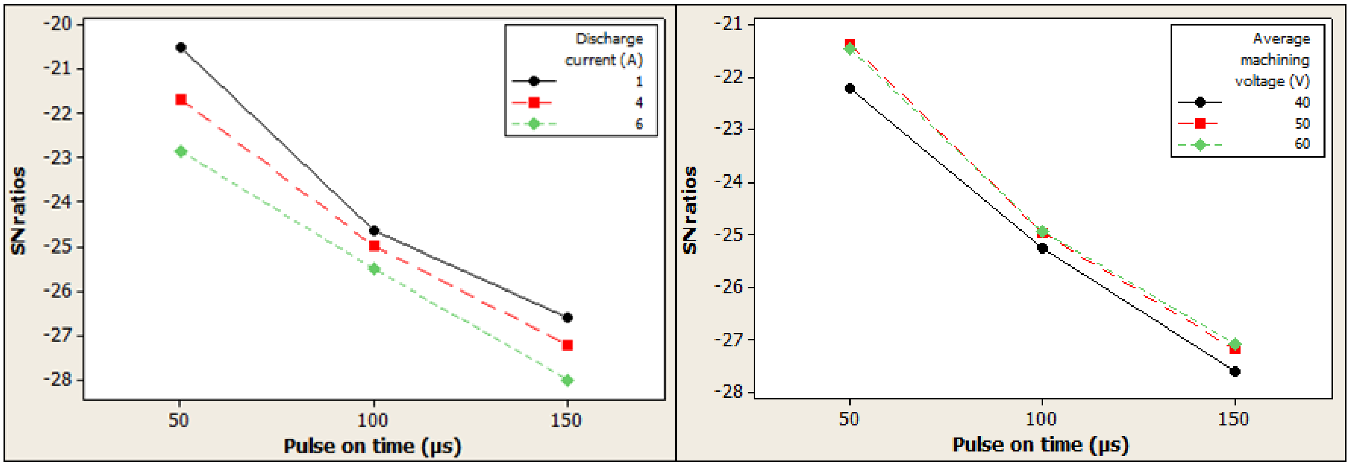

Figure 8. Interaction graphs for SR between pulse-on time and both discharge current and average machining voltage for Cu electrode.

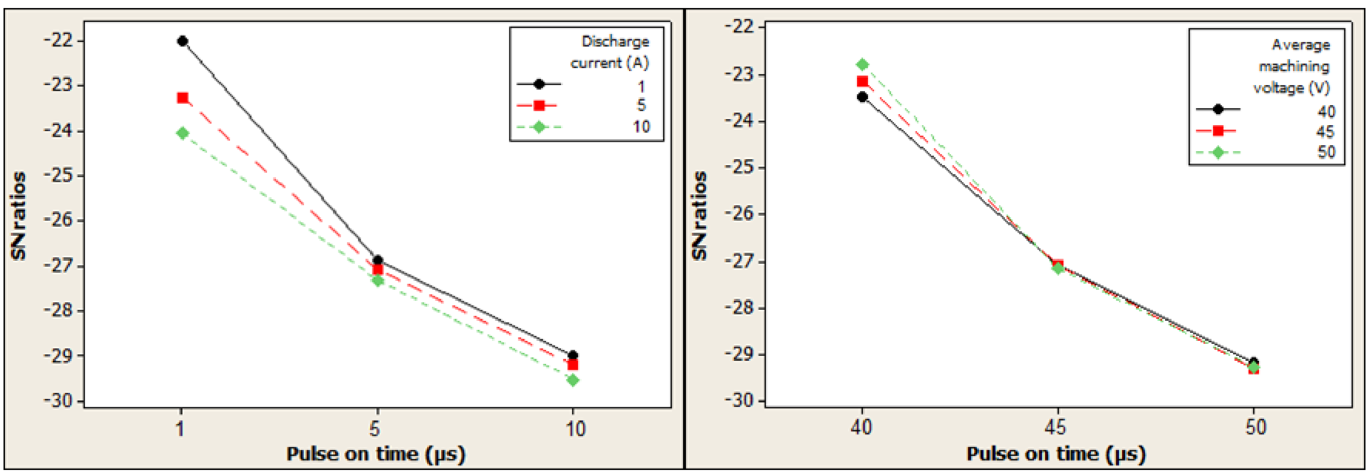

Figure 9. Interaction graphs for SR between pulse-on time and both discharge current and average machining voltage for graphite electrode.

Table 11. S/N ratio response table for surface roughness.

Level	Cu electrode				Gr electrode			
	T_{ON}	T_{OFF}	I	V	T_{ON}	T_{OFF}	I	V
1	-21.67	-24.00	-23.91	-25.01	-23.12	-25.05	-25.97	-26.57
2	-25.05	-24.70	-24.63	-24.50	-27.10	-26.69	-26.52	-26.50
3	-27.28	-25.31	-25.46	-24.49	-29.24	-27.72	-26.97	-26.39
Delta	5.61	1.32	1.55	0.52	6.12	2.68	1.00	0.18
Rank	1	3	2	4	1	2	3	4

material removal rate. Long pulse-on-time may cause the plasma channel to expand in the machining gap. This will cause an increase of heat that is conducted into the workpiece (Wang, 1999; Panda, 2008; Natsu et al., 2006) which leads to increase in the material removal rate and gap size.

The response table for signal to noise ratio for gap size is shown in Table 14 and the corresponding ANOVA analysis is shown in Tables 15 and 16 for the two types of electrodes. For gap size, the calculation of S/N ratio

Table 12. ANOVA results for surface roughness using Cu electrode.

Sequence of Variation	Degrees of freedom (DF)	Sum of squares (SS)	Mean square (variance) MS = SS/DF	Contribution (%)
T_{ON}	2	143.526	71.7631	86.33
T_{OFF}	2	7.801	3.9005	4.7
I	2	10.777	5.3886	7.51
V	2	1.595	0.7976	0.96
T_{ON} * I	4	1.683	0.4208	0.51
T_{ON} * V	4	0.296	0.0740	0.09
Residual Error	10	7.826	0.7826	0.94
Total	26	173.505	83.1272	

Table 13. ANOVA results for surface roughness using graphite electrode.

Sequence of variation	Degrees of freedom (DF)	Sum of squares (SS)	Mean square (variance) MS = SS/DF	Contribution (%)
T_{ON}	2	173.631	86.8155	80.12
T_{OFF}	2	32.846	16.4231	15.16
I	2	4.545	2.2725	2.1
V	2	0.141	0.0706	0.07
T_{ON} * I	4	2.505	0.6263	0.58
T_{ON} * V	4	0.641	0.1603	0.15
Residual Error	10	19.823	1.9823	1.83
Total	26	234.132		

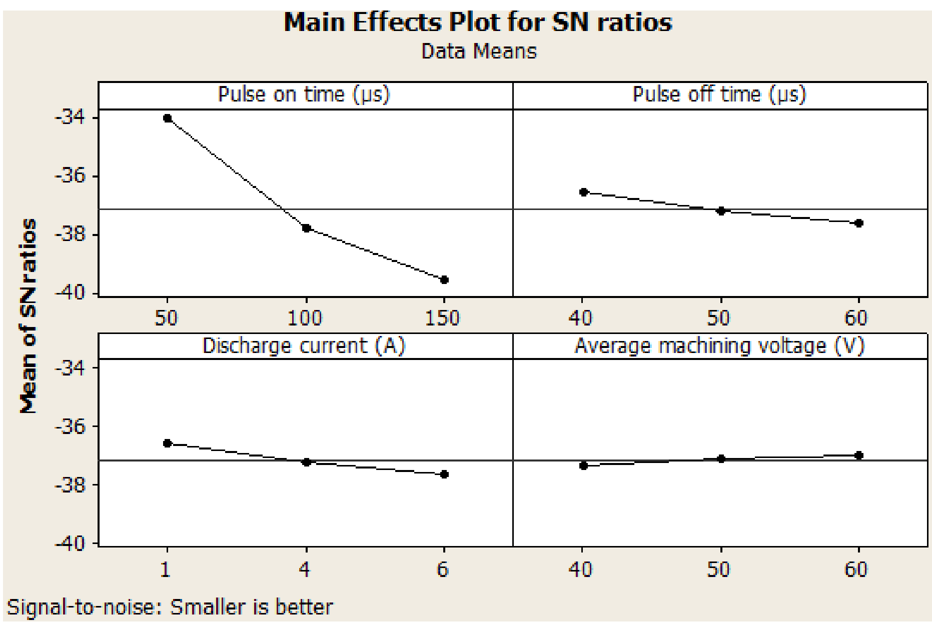

Figure 10. Main effects plot for SN ratios of each factor on GS with Cu electrode.

follows "Smaller the Better" model. Therefore, pulse-on-time (T_{ON}) has the maximum effect on gap size. Also, Tables 15 and 16 show that, the contribution amounts of pulse-on-time for copper and graphite electrodes are 91.4

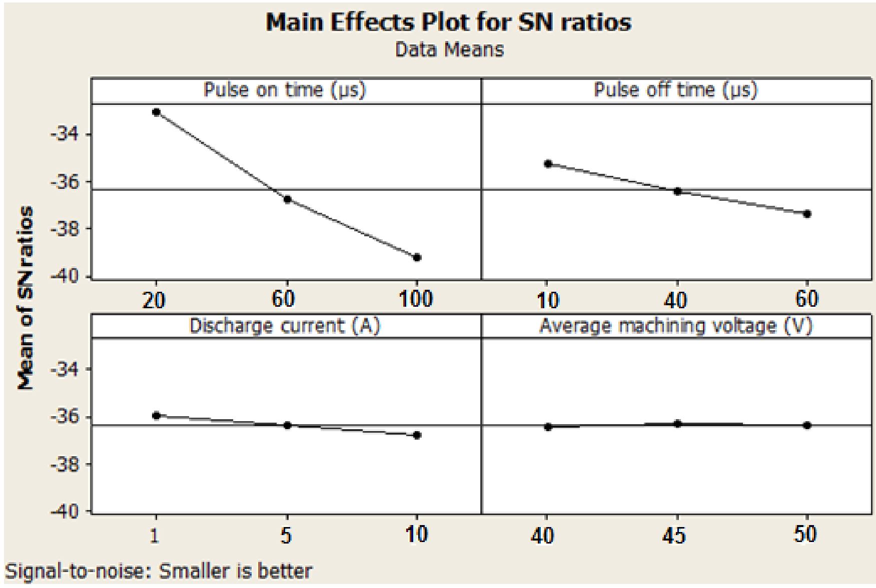

Figure 11. Main effects plot for SN ratios of each factor on GS with graphite electrode.

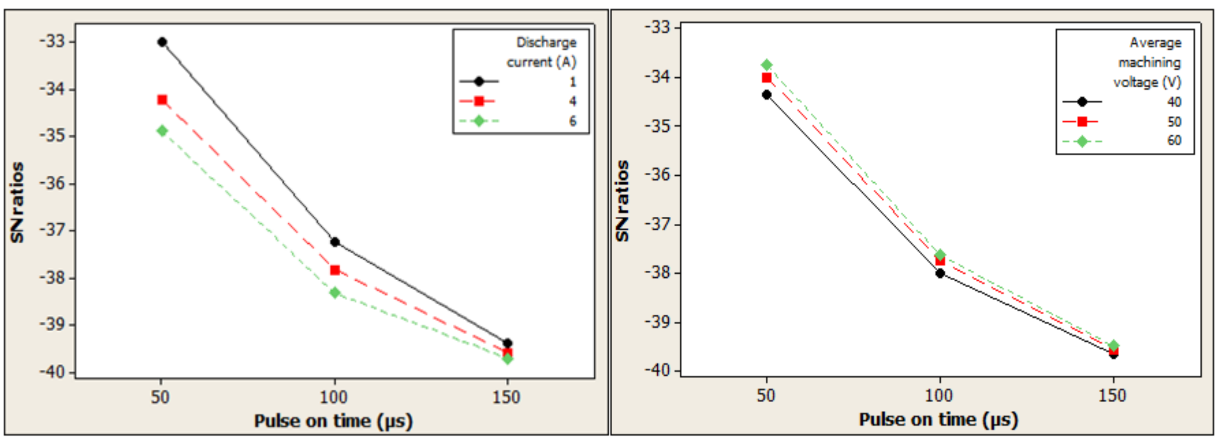

Figure 12. Interaction graphs for GS between pulse-on time and both discharge current and average machining voltage for Cu electrode.

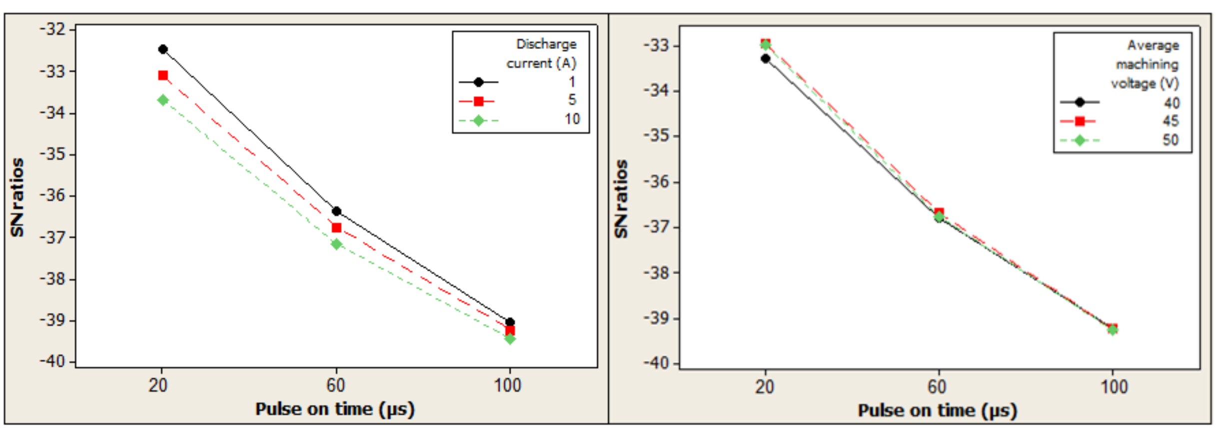

Figure 13. Interaction graphs for GS between pulse-on time and both discharge current and average machining voltage for graphite electrode.

Table 14. S/N ratio response table for gap size.

Level	Cu electrode				Graphite electrode			
	T_{ON}	T_{OFF}	I	V	T_{ON}	T_{OFF}	I	V
1	-34.04	-36.55	-36.55	-37.34	-33.07	-35.24	-35.95	-36.44
2	-37.80	-37.24	-37.21	-37.11	-36.75	-36.46	-36.36	-36.29
3	-39.56	-37.61	-37.64	-36.96	-39.24	-37.36	-36.76	-36.34
Delta	5.52	1.06	1.09	0.37	6.16	2.13	0.81	0.15
Rank	1	3	2	4	1	2	3	4

Table 15. ANOVA results for gap size using Cu electrode.

Sequence of variation	Degrees of freedom (DF)	Sum of squares (SS)	Mean square MS = SS/DF	Contribution (%)
T_{ON}	2	142.983	71.4917	91.4
T_{OFF}	2	5.247	2.6237	3.35
I	2	5.419	2.7094	3.46
V	2	0.639	0.3193	0.41
T_{ON} * I	4	1.933	0.4833	0.62
T_{ON} * V	4	0.160	0.0399	0.05
Residual Error	10	5.725	0.5725	0.73
Total	26	162.106	78.2398	

Table 16. ANOVA results for gap size using Graphite electrode.

Sequence of variation	Degrees of freedom (DF)	Sum of squares (SS)	Mean square MS = SS/DF	Contribution (%)
T_{ON}	2	173.073	86.5363	87.54
T_{OFF}	2	20.536	10.2681	10.39
I	2	2.977	1.4885	1.51
V	2	0.104	0.0519	0.05
T_{ON} * I	4	0.504	0.1260	0.13
T_{ON} * V	4	0.114	0.0286	0.03
Residual Error	10	3.578	0.3578	0.36
Total	26	200.886		

and 87.54% respectively.

Experimental verification

After performing the statistical analysis on the experimental data, it has been observed that there is one particular level for each factor for which the responses are either maximum (in case of material removal rate) or minimum (in case of surface roughness and gap size). The signal to noise ratio (S/N ratio) of each responses corresponding to each factor level also has a maximum and a minimum value. The optimal parameter setting for copper and graphite electrodes have been evaluated from the Figures 2 and 3 for material removal rate, Figures 6 and 7 for surface roughness and Figures 10 and 11 for gap size. The optimal setting comes as shown in Table 17. The optimal process parameters that have been identified to yield the best combination of process variables are A3B3C3D1 (highest level of pulse-on time, highest level of pulse-off time, highest level of discharge current and lowest level of average machining voltage) for copper and graphite electrodes. Using these optimum parameter settings, verification experiments have been carried out and the experimental results are shown in Table 18.

Conclusion

This research investigates the parameter optimization of electrical discharge machining on tool steel 2714

Table 17. Optimal parameter settings of input factors.

Physical requirement	Optimal combination Cu-electrode				Optimal combination Gr-electrode			
	T_{ON}	T_{OFF}	I	V	T_{ON}	T_{OFF}	I	V
Max. MRR	150	60	6	40	100	60	10	40
Min. SF	50	40	1	60	20	10	1	50
Min. GS	50	40	1	60	20	10	1	50

Table 18. Verification experimental results and calculation of various response factors.

Verification exp. for	Cu-electrode			Graphite-electrode		
	MRR	SF	GS	MRR	SF	GS
Max. MRR	**0.428**	27.956	99	**0.82**	32.441	101
Min. SF	0.005	**8.564**	37	0.014	**8.026**	33
Min. GS	0.005	8.564	**37**	0.014	8.026	**33**

workpiece with copper and graphite tool electrodes using Taguchi approach. The main conclusions of this research are as follows:

(1) Machining performance of the electrical discharge machining process can be improved effectively by using optimum factors as determined within this work.
(2) Pulse-on-time (T_{ON}) has the most significant influence on material removal rate, surface roughness and gap size within the specific test range for copper and graphite electrodes.
(3) Material removal rate, surface roughness and gap size are slightly affected with average machining voltage for both copper and graphite electrodes.
(4) The mean S/N ratio for each level of the cutting parameters reveals that, when using copper electrodes, the effect of cutting parameters can be ranked as follows: pulse-on-time, discharge current, pulse-off-time and average machining voltage.
(5) The effect of cutting parameters can be ranked as follows: pulse-on-time, pulse-off-time, discharge current and average machining voltage, when using graphite electrodes.
(6) The optimal process parameters that have been identified to yield the best combination of process variables are A3B3C3D1 for copper electrode and E3F3G3H1 for graphite electrode (highest level of pulse-on-time, highest level of pulse-off-time, highest level of discharge current and lowest level of average machining voltage).

Conflict of Interests

The author(s) have not declared any conflict of interests.

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