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Effect of Process Parameters on MRR for HCHCr in WEDM using RSM

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*Abstract***:** Wire electrical discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts of hard materials with complex shapes. Response surface methodology (RSM) with central composite design is selected for experimentation. In the present work, four factors are taken as input parameters, and the effect of these parameters on MRR are studied. The influence of the input parameters on response in WEDM process has been examined. The input parameters are Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) and peak current (IP). The experiments have been performed on high chromium high carbon steel with a wire of diameter 0.2 mm and the obtained data has been analyzed with the help of RSM using design expert software. The work piece material was a high carbon high chromium (HCHCr) die steel with excellent wear resistance, hot toughness and good thermal shock resistance. The experiments shows that Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) and peak current (IP) influence MRR. Results show that machining speed increases with increase in the pulse on-time and the pulse off-time increases as the number of discharges within given period of time decreases. Moreover, there is not much influence of servo voltage on MRR and it increases very slightly with increase in peak current. Also, as the Ton increases the MRR increases and as Toff increases MRR decreases. This is because as Ton increases number of sparks per unit time increases and as Toff increases the sparks per unit time decreases.

Keywords: Wire Electric Discharge Machining, Material Removal Rate, Central Composite Design, Response Surface Methodology

I. INTRODUCTION

Wire Electric Discharge Machining (WEDM) has become an important machining because it can machine the difficult-to-machine materials like titanium alloys and zirconium which cannot be machined by conventional machining processes. It can produce parts with complex shapes and profiles and performed by a series of spark erosions. These sparks are produced between the work piece and a wire electrode (usually less than 0.30 mm diameter) separated by a dielectric fluid and erodes the work piece to produce complex two and three dimensional shapes according to a numerically controlled pre-programmed path. The sparks produce heating and melt work piece surface to form debris which is then flushed away by dielectric pressure. During the cutting process there is no direct contact between the work piece and the wire electrode [1, 14].

In recent years an extensive research has been carried out on WEDM relating to improving performance measures, optimizing the process variables, monitoring and controlling the sparking process, simplifying the wire design and manufacture, improving spark efficiency by various researchers. Patil and Waghmare [14] presented the good amount of literature on WEDM. Some of the contributions related to the present study are discussed below.

Spedding and Wang [1] made an attempt at modeling the process through RSM and ANN. RSM model based on a central composite rotatable experimental design, and a 4-16-3 size back-propagation neural network has been developed. The pulse-width, time between two pulses, wire mechanical tension and injection set-point were selected as the factors (input parameters); whilst the cutting speed, surface roughness and surface waviness were the responses (output parameters). Both models were compared and verification experiments have been carried out to check validity of models. They concluded that both models provide accurate results for the process. Mohri et al [2] carried out an investigation on the dynamic wire vibration mechanism and a mathematical model was derived. The measured displacement of a wire electrode in machining a thin plate was analyzed with impulsive force measured through impulse response by a single discharge. They concluded that the force acting on wire depends on direction of wire movement in vibration. Huang et al [3] made an attempt to unveil the influence of machining parameters (pulse-on time, pulse-off time, table feed-rate, flushing pressure, distance between wire periphery and work piece surface) on machining performance of WEDM in finish cutting operations. Mathematical models relating machining parameters and performance were established by regression and non-linear programming using feasible-direction algorithm to obtain optimal machining parameters. Experimental results show that the proposed approach can achieve better performance than that achieved by a well-skilled operator.

Puri and Bhattacharya [4] carried out an extensive study of wire lag phenomenon in WEDM and established trend of variation of geometrical inaccuracy caused due to wire lag with various machine control parameters. Guo et al [5] adopted a method of computer simulation to study the vibration of wire electrode under the action of successive discharges, by which the effect of wire fluctuation on distribution of discharge points was also analyzed.

Tosun et al [6] carried out an investigation on the effect and optimization of machining parameters on the kerf (cutting width) and MRR in WEDM operations. The experimental studies were conducted under varying pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. The settings of machining parameters were determined by using Taguchi experimentation. The level of importance of machining parameters on cutting kerf and MRR was determined by using ANOVA. The optimum machining parameter combination was obtained by using analysis of signal-to-noise ratio. The variation of kerf and MRR with machining parameters was mathematically modeled by using regression analysis method. The optimal search for machining parameters for the objective of minimum kerf together with maximum MRR was performed by using the established mathematical models. Hasçalýk and Çaydaş **[7]** adopted an experimental investigation of the machining characteristics of AISI D5 tool steel in WEDM. During experiments, parameters such as open circuit voltage, pulse duration, wire speed and dielectric fluid pressure were changed to explore their effect on the surface roughness and metallurgical structure. Optical and scanning electron microscopy, surface roughness and micro hardness tests were used to study the characteristics of the machined specimens. Taking into consideration the experimental results, it is found that the intensity of process energy does affect the amount of recast and surface roughness as well as micro cracking, wire speed and dielectric fluid pressure not seeming to have much of an influence.

Hewidy et al [8] highlighted the development of mathematical models for correlating various WEDM machining parameters of Inconel 601 material such as: peak current, duty factor, wire tension and water pressure with the MRR, wear ratio and surface roughness. This work has been established based on RSM. Mahapatra and Patnaik [9] described the development of a model and its application to optimize WEDM machining parameters. This paper outlines the development of a model and its application to optimize WEDM machining parameters. Experiments were conducted to test the model and satisfactory results were obtained.

Kanlayasiri and Boonmung [10] presented an investigation of the effects of machining variables on surface roughness of WEDMed DC53 die steel. Result shows that pulse-on time and pulse-peak current were significant variables to the surface roughness of WEDMed DC53 die steel. The surface roughness of test specimen increases when these two parameters increase. The developed mathematical model was validated with a new set of experimental data and maximum prediction error of the model was less than 7% . Haddad and Tehrani [11] carried out a surface roughness (Ra), roundness and MRR study on the cylindrical wire electrical discharge turning. The material chosen in this case was AISI D3 tool steel due to its growing range of applications in the field of manufacturing tools dies and moulds. This study was conducted only for the finishing stages to investigate the influence of four design factors power, voltage, and pulse off time and spindle rotational speed, over the three previously mentioned response variables. For MRR, Ra and roundness, regression models have been developed by using RSM.

Portillo [12] presented the design and development of a real-time monitoring and diagnostic system for diagnosing the degraded behavior in WEDM. The detection in advance of degraded behavior was crucial since this can lead to the breakage of cutting tool (wire), reducing process productivity and required accuracy. Singh and Garg [13] investigated the effects of various process parameters of WEDM like pulse on time (TON), pulse off time (TOFF), gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) to reveal their impact on MRR of hot die steel (H-11) using one variable at a time approach. The optimal set of process parameters has also been predicted to maximize the MRR .

II. METHODOLOGY AND EXPERMENTATION

RSM methodology with central composite design is selected for experimentation. RSM is a compilation of mathematical and statistical methods which is used to build up, advance and optimise a process or product. This methodology was initially presented by Box and Wilson in 1951. The key scheme of RSM is to use a series of planned experiments in order to find an optimal answer (response). It comprises statistical experimental designs, regression modeling techniques, and optimization methods. Most applications of RSM involve experimental situations where several independent (or control) variables potentially impact one or more response variable. The independent variables are controlled by the experimenter, in a designed experiment, while the response variable is an observed output of the experiment. The most popular response surface design is the central composite design (CCD). A CCD has three groups of design points: (a) Factorial points (b) Axial points (c) Center points. CCD's are designed to estimate the coefficients of a quadratic model. In the present work, four factors are taken as input parameters and the effect of these parameters on MRR are calculated. There are various process parameters of WEDM affecting the machining characteristics. On the basis of literature review and some pilot investigations (not reported here), the following process parameters have been selected for study in the range shown in table 1.

Table 1: Process parameters with their ranges

S. No.	Input Parameters	Range
1.	Pulse on time (Ton)	100-135 machine units
2.	Pulse off time (Toff)	30-65 machine units
3.	Peak current (IP)	70-230 Amps
4.	Servo voltage (SV)	10-70 Volts

The experimental study was performed on ELECTRONICA© SPRINTCUT WEDM machine installed at AMT Lab of the Mechanical Engineering Department, NIT Kurukshetra. WEDM is a four axes machine and capable to control all four axes simultaneously. The machine performs multiplicity of operations in one setup. The work piece material is a high carbon high chromium (HCHCr) die steel with excellent wear resistance, hot toughness and good thermal shock resistance. The chemical composition of the material is shown in table 2.

The experimental work is carried out as per the central composite design using RSM methodology. The design is prepared with the help of Design expert software version 8.0.3 which is used to create experimental designs. The design is shown in table 3.

Table 2: Composition of work material

S. NO.	MATERIAL	PERCENTAGE
1.	CARBON	2.02
2.	SILICON	0.33
3.	MAGANESE	0.37
4.	SULPHUR	0.027
5.	PHOSPHORUS	0.026
6.	NICKEL	0.062
7.	CHROMIUM	11.55
8.	MOLYBDENUM	0.023
9.	COPPER	0.009
10.	IRON	Rest

Table 3: Experimental Design

Std	Run	Block	Factor 1 A: Ton Machine units	Factor 2 B: Toff Machine units	Factor 3 C: SV Volts	Factor 4 D: IP Amp
17	1	DAY 1	125	55	20	230
18	2	DAY 1	105	30	10	70
5	3	DAY 1	125	63	50	70
8	4	DAY 1	125	52	30	150
3	5	DAY 1	105	63	10	70
2	6	DAY 1	105	40	50	70
15	7	DAY 1	125	40	10	70
12	8	DAY 1	105	63	50	230
14	9	DAY 1	115	52	30	150
9	10	DAY 1	105	40	10	230
10	11	DAY 2	105	40	10	70
13	12	DAY 2	105	63	10	230
11	13	DAY 2	125	40	50	70
1	14	DAY 2	125	63	50	230
16	15	DAY 2	115	52	30	150
6	16	DAY 2	125	63	10	70
20	17	DAY 2	105	40	50	230
7	18	DAY 2	115	52	30	120
19	19	DAY 2	125	40	10	230
4	20	DAY 2	105	63	50	70
27	21	DAY 3	115	52	30	120
30	22	DAY 3	135	52	30	150
24	23	DAY 3	115	52	30	230
26	24	DAY 3	115	63	30	150

Table Continue on Next Page….

21	25	DAY 3	105	52	30	150
28	26	DAY 3	105	63	70	150
22	27	DAY 3	125	52	30	230
25	28	DAY 3	125	52	20	230
23	29	DAY 3	125	40	20	230
29	30	DAY 3	95	40	20	120

Based on the experimental design as given in table 3 the specimens were prepared and the values of selected machining characteristics i.e. MRR are reported in table 4.

Table 4: Experimental Design with Response Data

Std	Run	Block	Factor 1 A: Ton Machine units	Factor 2 B: Toff Machine units	Factor 3 C: SV Volts	Factor 4 D: IP Amp	Response MRR mm^2/min
17	1	DAY 1	125	55	20	230	33.75
18	2	DAY 1	105	30	10	70	17.5
5	3	DAY 1	125	63	50	70	8.75
8	4	DAY 1	125	52	30	150	24.25
3	5	DAY 1	105	63	10	70	4
2	6	DAY 1	105	40	50	70	8.75
15	7	DAY 1	125	40	10	70	43
12	8	DAY 1	105	63	50	230	3.5
14	9	DAY 1	115	52	30	150	23.75
9	10	DAY 1	105	40	10	230	21.5
10	11	DAY 2	105	40	10	70	15.25
13	12	DAY 2	105	63	10	230	6.25
11	13	DAY 2	125	40	50	70	23.25
1	14	DAY 2	125	63	50	230	21.25
16	15	DAY 2	115	52	30	150	18.75
6	16	DAY 2	125	63	10	70	12
20	17	DAY 2	105	40	50	230	10
7	18	DAY 2	115	52	30	120	18
19	19	DAY 2	125	40	10	230	58.25
4	20	DAY 2	105	63	50	70	2.75
27	21	DAY 3	115	52	30	120	20.25
30	22	DAY 3	135	52	30	150	42
24	23	DAY 3	115	52	30	230	25.50
26	24	DAY 3	115	63	30	150	13.50
21	25	DAY 3	105	52	30	150	8
28	26	DAY 3	105	63	70	150	10
22	27	DAY 3	125	52	30	230	34
25	28	DAY 3	125	52	20	230	58
23	29	DAY 3	125	40	20	230	58.75
29	30	DAY 3	95	40	20	120	13

III. ANALYSIS OF EXPERIMENTAL RESULTS

The influence of the input parameters on response in WEDM process has been examined. The input parameters are Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) and peak current (IP). The experiments have been performed on high chromium high carbon steel with a wire of diameter 0.2 mm and the obtained data has been analyzed with the help of RSM using design expert software. The result of experiment shows that Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) and peak current (IP) are influencing MRR.

Figure 1 revealed that machining speed increases with increase in the pulse on-time. It means that the number of sparks in unit time increases which increase in discharge energy. As a result machining speed becomes faster with increase in pulse on time. So the pulse on time can be adjusted to get the desired MRR. Figure 2 presenting that the pulse off-time is increases as the number of discharges within given period of time decreases. This will lead to a lower machining speed. Figure 3 presents that there is not much influence of servo voltage on MRR. It can be seen from figure 4 that MRR increases very slightly with increase in peak current. So the peak current should be high to obtain higher MRR.

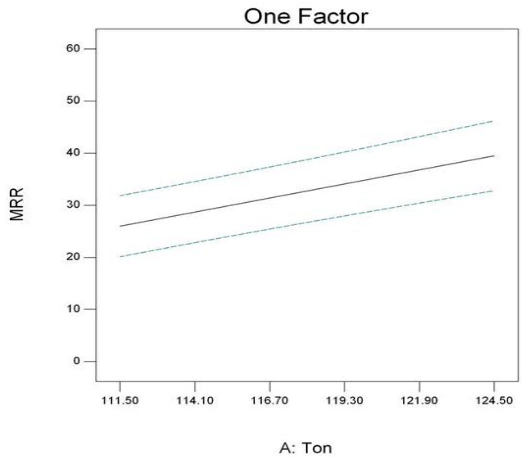

Figure 1: Effect of Ton on MRR

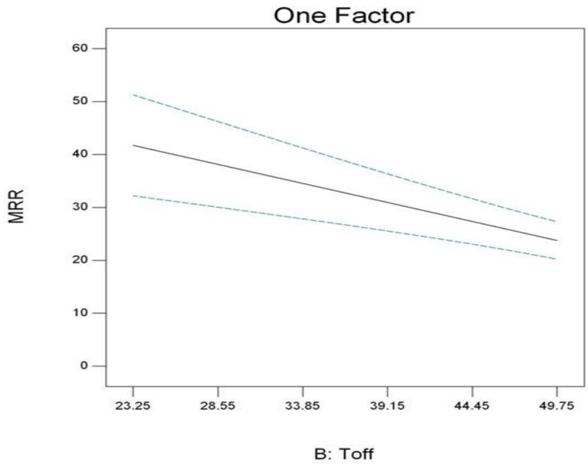

Figure 2: Effect of Toff on MRR

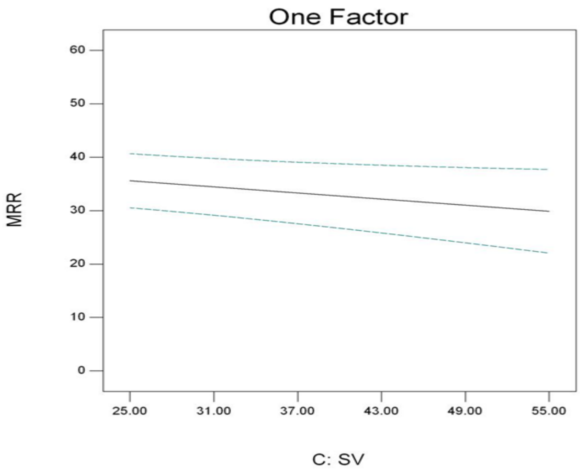

Figure 3: Effect of SV on MRR

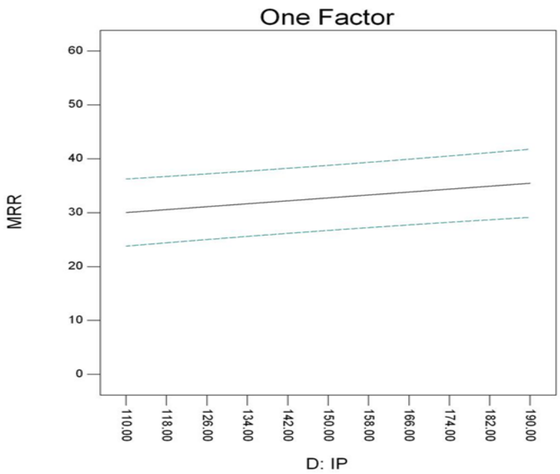

Figure 4: Effect of IP on MRR

IV. 3-D Graph Of Effects Of Machining Parameters On MRR

The effects of process parameters are taken two at a time on MRR as shown in figures 5-7. Figure 5 shows the 3-D response surface of effects of Ton and Toff on MRR. It revealed that as Ton increases the MRR increases and as Toff increases MRR decreases. This is because as Ton increases number of sparks per unit time increases and as Toff increases the sparks per unit time decreases. Figure 6 shows the 3-D response surface of effects of IP and SV on MRR. It revealed that as IP increases the MRR increases and as SV increases MRR slightly decreases. This is because as IP increases, spark energy increases and as SV increases spark energy decreases. Figure 7 shows the 3-D response surface of effects of Ton and IP on MRR. It revealed that as Ton increases the MRR increases and as IP increases MRR increases.This is because as Ton increases number of sparks per unit time increases and as IP increases, spark energy increases which results in increased MRR.

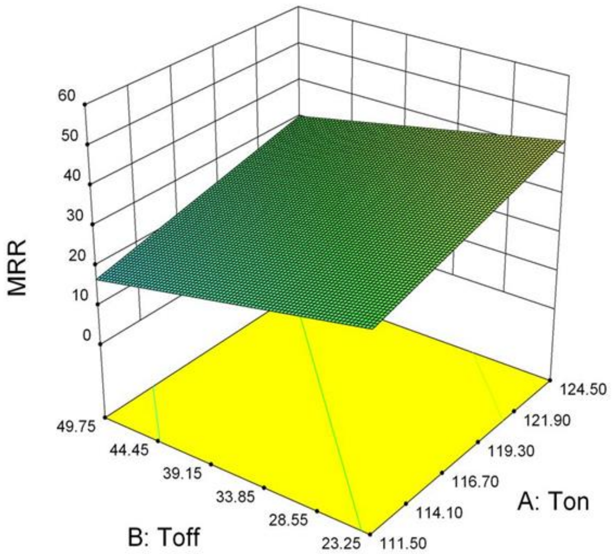

Figure 5: 3-D graph of Effects of Ton and Toff on MRR

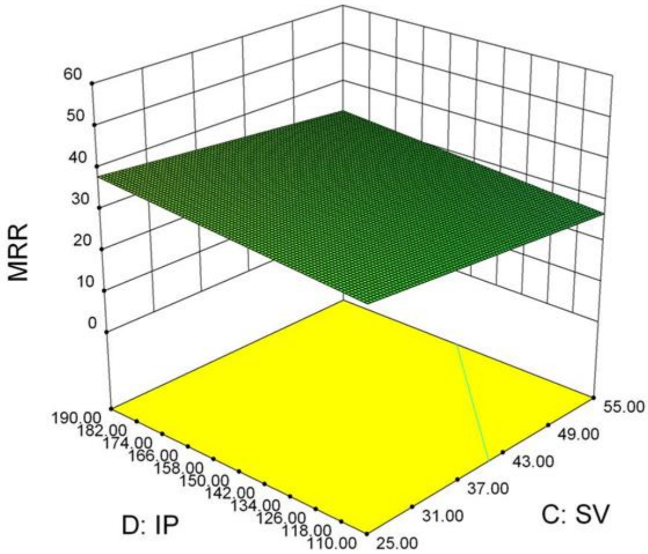

Figure 6: 3-D graph of Effects of IP and SV on MRR

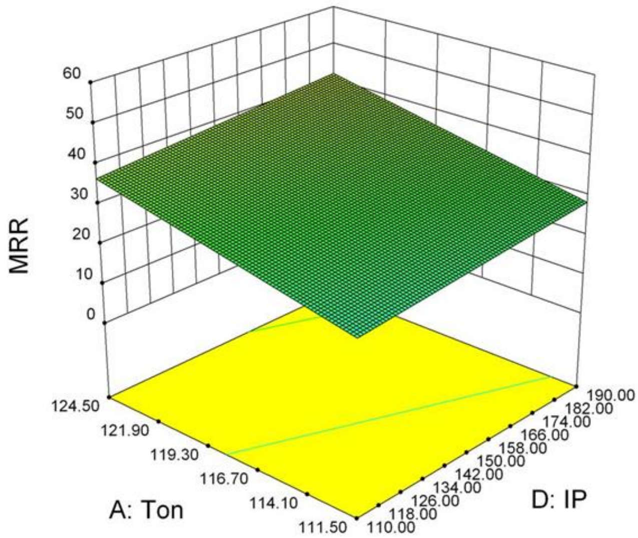

Figure 7: 3-D graph of Effects of Ton and IP on MRR

V. DISCUSSION OF RESULTS

The experimentation was carried out according to the CCD design and the analysis was accomplished using design expert software version 8.0.3. The analysis of variance for MRR using software is given in table 5. Model F-value (28.39) implies that the model is noteworthy. There is only a 0.01% chance that a "Model F-Value" this much magnitude could occur due to noise. p- values less than 0.0500 indicate model terms are significant. Here, A, B, C, D represent important model conditions. Values > 0.1000 show the model terms are not important. If there are many unimportant model conditions, model lessening may advance our model.

Table 5: ANOVA for Response Surface Linear Model

Source	Sum of Squares	df	Mean Square	F-Value	p-Value	
Block	608.33	2	304.16			
Model	5823.52	4	1455.88	28.39	<0.0001	Significant
A-Ton	3112.93	1	3112.93	60.69	<0.0001	
B-Toff	1152.54	1	1152.54	22.47	<0.0001	
C-SV	255.31	1	255.31	4.98	0.0357	
D-IP	546.24	1	546.24	10.65	0.0034	
Residual	1179.64	23	51.29			
Cor Total	7611.49	29				

The results are optimized for desirability objective function that ranges from 0 to 1 (i.e (outside limit to goal). Optimization finds a point that maximizes the desirability function. The characteristics of a goal may be altered by adjusting the weight or importance. One desirability function contains various goals of factors and responses. The value is dependent on settings of lower and upper limits corresponding to real optimum. Optimization finds a superior set of conditions that will meet all the goals, not to acquire to a desirability value of 1.0. According to desirability the solutions are reported in table 6.

Table 6: Solutions according to desirability

S.No	Ton	Toff	SV	IP	MRR	Desirability	
1	124.99	30.00	10.05	230.00	55.4488	0.941	SELECTED
2	125.00	30.04	10.00	230.00	55.4374	0.941	
3	125.00	30.00	10.61	229.99	55.3489	0.939	
4	124.97	30.00	10.99	230.00	55.2483	0.937	
5	125.00	30.00	10.00	225.00	55.1308	0.935	
6	125.00	30.00	10.00	224.33	55.086	0.935	
7	125.00	30.00	12.04	229.97	55.0805	0.934	
8	125.00	30.00	12.59	230.00	54.9773	0.933	
9	124.46	30.00	10.00	229.83	54.9007	0.931	
10	125.00	30.00	14.57	230.00	54.6004	0.926	
11	125.00	30.00	10.00	213.19	54.333	0.921	
12	125.00	30.00	16.01	229.97	54.3256	0.921	
13	124.99	30.00	16.26	230.00	54.2665	0.920	
14	125.00	30.00	10.01	210.46	54.1468	0.918	
15	125.00	30.00	10.00	209.97	54.1159	0.917	
16	125.00	30.02	17.37	230.00	54.0586	0.916	
17	125.00	31.19	13.35	230.00	54.0288	0.916	
18	125.00	30.01	10.00	207.93	53.9741	0.915	
19	125.00	30.00	18.14	229.99	53.9217	0.914	
20	125.00	30.00	17.20	227.25	53.9176	0.914	
21	125.00	30.00	10.00	206.47	53.8788	0.913	
22	123.42	30.00	10.01	230.00	53.8288	0.912	
23	125.00	32.47	10.00	230.00	53.8005	0.912	
24	125.00	30.00	10.00	201.18	53.5213	0.907	
25	124.96	30.01	10.00	200.71	53.443	0.905	
26	125.00	33.22	10.00	230.00	53.2881	0.902	
27	123.33	30.07	12.40	230.00	53.2308	0.901	

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28	122.73	30.09	10.00	230.00	53.0584	0.898
29	122.65	30.00	10.00	230.00	53.0339	0.898
30	125.00	30.00	10.00	192.55	52.9367	0.896
31	124.99	30.00	10.06	191.79	52.8682	0.895
32	125.00	32.96	13.54	230.00	52.7976	0.894
33	125.00	30.00	25.26	230.00	52.5727	0.890
34	124.26	30.00	21.40	230.00	52.5362	0.889
35	125.00	30.00	10.00	182.77	52.2772	0.884
36	121.43	30.00	10.00	230.00	51.7609	0.875
37	123.65	30.00	10.00	185.02	51.0321	0.862
38	125.00	30.00	37.00	230.00	50.3382	0.850
39	125.00	30.00	10.72	155.36	50.2882	0.849
40	119.93	30.00	10.42	230.00	50.1295	0.846
41	125.00	30.00	38.76	230.00	50.009	0.844
42	120.48	30.00	10.35	217.33	49.8562	0.841
43	125.00	30.01	10.00	143.85	49.6378	0.837
44	125.00	30.00	10.10	137.44	49.1938	0.829
45	125.00	30.00	43.41	230.00	49.1264	0.828
46	118.94	30.00	10.04	227.21	48.9841	0.826
47	125.00	30.02	10.00	125.48	48.3919	0.815
48	125.00	30.00	48.12	230.00	48.2337	0.812
49	125.00	30.03	49.69	230.00	47.9137	0.806
50	124.96	30.00	10.00	116.19	47.731	0.803
51	125.00	41.95	10.00	230.00	47.3881	0.797
52	124.64	30.00	10.00	115.41	47.3514	0.796
53	124.91	30.00	10.00	106.66	47.0399	0.791
54	124.57	54.19	10.00	230.00	38.6565	0.641
55	120.02	30.18	70.00	70.00	27.9702	0.450

The optimal values of process parameters and response (MRR) using desirability are as shown in ramp graphs (Figure 8 to 12). The correlation between the four input process parameters - Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV), peak current (IP), and the MRR has been ascertained through RSM. Final equation in terms of coded factors can be given by; *MRR= +32.74 + 6.76 * A- 8.99 * B - 2.86 * C +2.72 * D* and the final equation in terms of actual factors is *MRR= -67.72224+1.03954*Ton-0.67843*Toff-0.19063*SV+0.06791*IP*. Three confirmation experiments were conducted at the pridicted optimal setting of the process parameters and there average values have been reported in table 7.

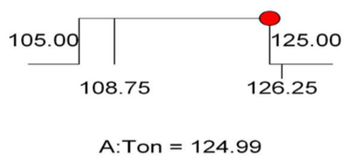

Figure 8: The optimum value of Ton from desirability

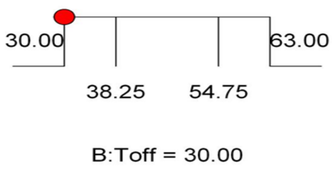

Figure 9: The optimum value of Toff from desirability

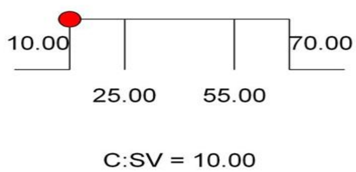

Figure 10: The optimum value of SV from desirability

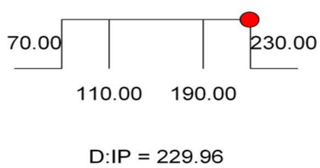

Figure 11: The optimum value of IP from desirability

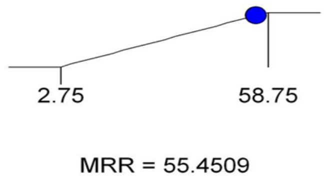

Figure 12: The optimum value of MRR from desirability

Table 7: Point prediction at optimal value of response (MRR)

Response	Prediction	95% CI low	95% CI high	95% PI low	95% PI high	Actual value (average of three confirmation experiments)
MRR	55.4488	47.4969	63.4007	38.7024	72.1951	58.65

VI. CONCLUSIONS AND FUTURE SCOPES

The following conclusions are drawn from the experimental study: (1) when pulse on time is increased the MRR increases, (2) when pulse off time is increased the MRR decreases, (3) when servo voltage is increased the MRR decreases, (4) when peak current is increased the MRR is increases, (5) the mathematical model for MRR is given by (-67.72224+1.03954*Ton-0.67843*Toff-0.19063*SV+0.06791*IP) and (6) the optimum value of four process parameters are: (i) the optimum value of Ton = 125, (ii) the optimum value of Toff = 30, (iii) the optimum value of SV = 10, (iv) the optimum value of IP = 230 and (v) the optimum value of MRR is 55.4509 mm2/min.

Analysis of the results obtained from the current work suggests several feasible extensions to the research. Some of them are; (1) the process parameters can be increased for investigation, (2) multiple response optimizations may be carried out instead of single response study, (3) in this work de-ionized water is used as dielectric. It would be interesting to compare the process performance of other gaseous dielectrics, (4) in terms of applications, the WEDM process may be implemented for micromachining. Not much work has been done in this field so far and it would require building up a knowledge base for the process at the micro-level to make Wire Electric Discharge Micromachining feasible.

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