An Experimental Investigation of Electrode Wear Rate (EWR), Material Removal Rate (MRR) and Radial Overcut (ROC) in EDM of High Carbon-High Chromium Steel (AISI D3)

Pravin R. Kubade, V. S. Jadhav

***Abstract-** This study investigates the influence of EDM parameters on EWR, MRR and ROC while machining of AISI D3 material. The parameters considered are pulse-on time (T_{on}), peak current (I_p), duty factor (t) and gap voltage (V_g). The experiments were performed on the die-sinking EDM machine fitted with a copper electrode. The experiments planned, conducted and analyzed using Taguchi method. It is found that the MRR is mainly influenced by (I_p); where as other factors have very less effect on material removal rate. Electrode wear rate is mainly influenced by peak current (I_p) and pulse on time (T_{on}), duty cycle (t) and gap voltage (V_g) has very less effect on electrode wear rate. Peak current (I_p) has the most influence on radial overcut then followed by duty cycle (t) and pulse on time (T_{on}) with almost very less influence by gap voltage (V_g).*

***Index Terms**— AISI D3; EDM; Radial overcut, duty factor.*

I. INTRODUCTION

Electro-discharge machining (EDM) machining is a non-traditional manufacturing process based on removing material from a part by means of a series of repeated electrical discharges (created by electric pulse generators at short intervals) between a tool, called electrode, and the part being machined. Due to high temperature of the sparks not only work material is melted and vaporised but the electrode material is also melted and vaporised which is known as electrode wear (EW). At present EDM is widespread technique used in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite or even some ceramic materials of any hardness[1]. During EDM the main output parameters are the MRR, EW and surface finish. It is desirable to obtain the maximum MRR with minimum EW common electrode materials are graphite, brass, and copper-tungsten alloys. Efforts have been done to minimize EW. A.A. Khan found that electrode wear increases with an increase in both current and voltage, but wear along the cross-section of the electrode is more compared to the same along its length. It was also found that the wear ratio increases with an increase in current [2].

The adequate selection of manufacturing conditions is one of the most important aspects to take into consideration in the die-sinking electrical discharge machining (EDM) of conductive steel, as these conditions are the ones that are to determine such important characteristics: surface roughness, electrode wear (EW) and material removal rate (MRR). Approximately 50% of all carbide production is used for machining applications but tungsten carbides are also being increasingly used for non machining applications, such as mining, oil and gas drilling, metal forming and forestry tools [3-4]. The selection of conductive ceramic was made taking into account its wide range of applications in the industrial field due to its attractive physical characteristics together with chemical inertness at elevated temperature. Its inherent brittleness and low fracture toughness make its machining difficult and consequently limit its utilization. Considerable improvement in mechanical properties of the single-phase alumina ceramic has been achieved by incorporating Sic whisker, Tic particles into Al_2O_3, which also allow electrical discharge machining (EDM) to fabricate components with complex geometry and widen the applications [5]. In the past twenty years, materials R&D has shifted from monolithic to composite materials, adjusting to the global need for reduced weight, low cost, quality, and high performance available readily in structural materials [6-7].

II. EXPERIMENTATION

A. Materials

The material used for this work is High carbon-high chromium steel (AISI D3) plate of size 110×50×12 mm (density 7.7×100 kg/m^3) . The material is hardened to a hardness of 58 HRC. The electrode used is electrolytic copper (99.97% pure) of 8930 kgm^{-3} density with a melting point of 1083^0C. These electrodes are cylindrical in shape with a nominal diameter of 9.5 mm.

B. EDM machine

The machine used is Electronica- EMS 5535-R50 ZNC series 2000 machine with NC control in Z-direction. The dielectric fluid used for the EDM was a mineral oil EDM-30. Polarity of the electrode is negative and that of the work piece is positive.

Manuscript Received June, 2012.

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C. Design of experiment

This paper uses Taguchi method, which is very effective to deal with responses influenced by multi-variables. This method is a powerful Design of Experiments tool, which provides a simple, efficient and systematic approach to determine optimal machining parameters. Compared to the conventional approach to experimentation, this method reduces drastically the number of experiments that are required to model the response functions. Traditional experimentation involves one-factor-at-a-time experiments, wherein one variable is changed while the rest are held constant. The major disadvantage of this strategy is that it fails to consider any possible interactions between the parameters. An interaction is the failure of one factor to produce the same effect on the response at different levels of another factor. It is also impossible to study all the factors and determine their main effects (i.e., the individual effects) in a single experiment. Taguchi technique overcomes all these drawbacks. The main effect is the average value of the response function at a particular level of a parameter. The effect of a factor level is the deviation it causes from the overall mean response. The Taguchi method is devised for process optimization and identification of optimal combinations of factors for given responses. The steps involved are:

1. Identify the response functions and the process parameters to be evaluated.
2. Determine the number of levels for the process parameters and possible interaction between them.
3. Select the appropriate orthogonal array and assign the process parameters to the orthogonal array and conduct the experiments accordingly.
4. Analyze the experimental results and select the optimum level of process parameters.
5. Verify the optimal process parameters through a confirmation experiment.

The process parameters chosen for the experiments are:

(a) pulse-on time (T_{on}), (b) peak current (I_p), and (c) duty factor(t) and (d) gap voltage (Vg) while the response functions are: (a) electrode wear rate (EWR) and (b) material removal rate (MRR) and radial overcut (ROC). According to the capability of the commercial EDM machine available and general recommendations of machining conditions for AISI D3 the range and the number of levels of the parameters are selected as given in Table 1.

Table 1. Level values of input Factors

Sr. No.	Factors	Levels		
		1	2	3
1	T_{on} (µs)	75	100	150
2	I_p (Amp)	8	12	16
3	t	8	10	12
4	V_g (volts)	50	55	60

The total number of degrees of freedom needs to be computed to select an appropriate orthogonal array for the experiments. The degrees of freedom are defined, as the number of comparisons that needs to be made to determine which level is better. For example, a two-level parameter has one degree of freedom. The present analysis does not include the interaction between parameters. Hence, there are four degrees of freedom due to four process variables. The selection of the orthogonal array is subject to the condition that the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In the present analysis, an L9 orthogonal array with four columns and nine rows is used. This array can handle three-level process parameters and has eight degrees of freedom. Therefore only nine experiments are required to study the entire machining parameters using the L9 orthogonal array. The experimental layout for the machining parameters using the L9 orthogonal array is shown in Table 2. A statistical analysis of variance (ANOVA) is performed to identify the process parameters that are statistically significant. Based on ANOVA the optimal combination of the process parameters are predicted.

Table 2. Taguchi L9 Orthogonal Array Design Matrix:

Expt. No.	Factor1	Factor 2	Factor 3	Factor 4
E1	1	1	1	1
E2	1	2	2	2
E3	1	3	3	3
E4	2	1	2	3
E5	2	2	3	1
E6	2	3	1	2
E7	3	1	3	2
E8	3	2	1	3
E9	3	3	2	1

D. Experimental procedure

Experiments are performed, randomly, according to the L9 orthogonal array, on a AISI D3 plate of size 28mm×25mm×10 mm. For each experiment a separate electrode is used. The depth of machining is set at 8mm for all experiments. The machining time is noted from the timer of the machine. The electrode wear rate is calculated by weight difference of the electrodes using Precisa 125 A SCS with 80 g capacity with a precision of 0.0001g. The diameters of the electrode, before machining and the hole are measured, using Digimatic vernier and CMM respectively having a least count of 0.001 mm. The readings, at different angular positions of the electrode and top diameter of hole, are taken. The electrode and hole diameters are represented by the average value of their respective measured diameters. The experimental results for electrode wear rate, MRR and ROC based on L9 orthogonal array is shown in table 3.

Table3. Experimental results for MRR, EWR and ROC

Expt. No.	MRR (gm/min)	EW (gm/min)	ROC (mm)
1	0.0661	0.00344	0.140
2	0.0803	0.00420	0.145

3	0.1024	0.00592	0.165
4	0.0812	0.00287	0.145
5	0.0962	0.00339	0.150
6	0.1000	0.00650	0.200
7	0.07263	0.00136	0.135
8	0.0948	0.0033	0.185
9	0.1014	0.00317	0.195

III. RESULTS AND DISCUSSION

After the experimental procedure, different response factors like MRR, EWR and ROC of the drilled holes were calculated from the observed data.

Then a statistical analysis were performed on the calculated values and the signal to noise ratio values of three response factors are tabulated in table 4.

Table 4. Signal to noise ratio for various response factors.

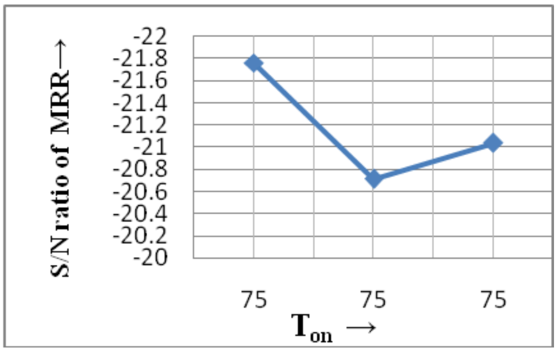
Expt. No.	S/N Ratio for MRR	S/N Ratio for EWR	S/N Ratio for ROC
1	-23.5959	49.2688	17.0774
2	-21.9057	47.5350	16.7726
3	-19.7940	44.5535	15.6503
4	-21.8089	50.8423	16.7729
5	-20.3364	49.3960	16.4782
6	-20.000	43.7417	13.9794
7	-22.7776	57.3292	17.3933
8	-20.4638	49.6297	14.6566
9	-19.8792	49.5478	14.1993

A. Effect of input factors on MRR

The response table for signal to noise ratio for MRR is shown in table 4 and corresponding analysis variances (ANOVA) table is shown in table 5 for MRR, the calculation of S/N ratio follows “Larger the better model”.

Table 5. Response table for signal-to- noise ratio for MRR.

Levels	Pulse-on Time (T_{on})	Peak Current (I_p)	Duty Cycle (t)	Gap voltage (V_g)
1	-21.7652	-22.7274	-21.3532	-21.2705
2	-20.7151	-20.9019	-21.1979	-21.5611
3	-21.0402	-19.8911	-20.9693	-20.6889
Delta	1.0501	2.8363	0.3839	0.8722
Rank	2	1	4	3



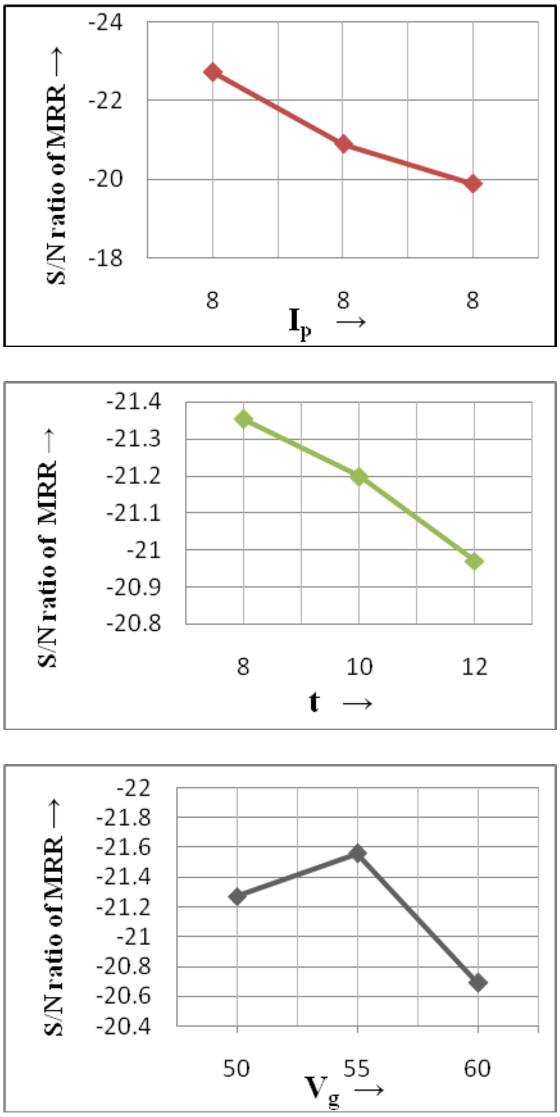


Fig 1. S/N Ratio curve for MRR with V_g,I_p,t and V_g

Table 6. Analysis Of Variance (ANOVA) for MRR

Sources	D.O.F.	Sum of squares	Mean square	%Contribution
T_{on}	2	1.7340	0.867	11.1541
I_p	2	12.3987	6.19935	79.7559
t	2	0.2237	0.11185	1.43
V_g	2	1.1834	0.5917	7.612
Total	8	15.5458	7.7699	100

Referring table 6 it is noticed that factor peak current (I_p) has largest contribution to the total sum of squares i.e. 79.75%. The factor pulse-on time (T_{on}) and gap voltage (V_g) also have the considerable contribution in total sum of the squares which is 11.15% and 7.61% respectively. The factor duty cycle (t) has much less contribution of 1.43%. The larger the contribution of any factor to the total sum of squares, the larger is the ability of that factor to influence material removal rate (MRR).

Published By:
Blue Eyes Intelligence Engineering
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So peak current (I_p) has maximum effect on material removal rate, Pulse on time (T_{on}) and gap voltage (V_g) have considerable effect on material removal rate whereas duty cycle (t) has very less effect on MRR (fig. 1).

The experimental results are analyzed, to see the main effects and the difference between the main effect of level 1, 2 and 3of the variables on the EWR, MRR and ROC using the MINITAB 15.

Table 7. Statistical values for Regression Analysis for MRR

Predictor	Coefficient	SE Coefficient	T	P
Constant	0.00346	0.03675	0.09	0.929
Pulse on time (T_{on})	0.00006814	0.00007521	0.91	0.416
Peak current (I_p)	0.0034946	0.0007180	4.87	0.008
Duty cycle (t)	0.000861	0.001436	0.60	0.581
Gap voltage (V_g)	0.0004900	0.0005744	0.85	0.442

S = 0.00703498 R-Sq = 86.5% R-Sq(adj) = 73.0%

The regression equation is-

$$MRR = 0.0035 + 0.000068\, T_{on} + 0.00349\, I_p + 0.00086\, t + 0.000490\, V_g$$

B. Effect of input factors on EWR

The response table for signal-to-noise ratio for electrode wear rate (EWR) is shown in table 8 and corresponding analysis of variances (ANOVA) table is shown in table 9.

For electrode wear rate (EWR), the calculation of S/N ratio follows “Smaller the Better” model.

Table 8. Response table for Signal-to-Noise Ratios for EWR

Levels	Pulse-on Time (T_{on})	Peak Current (I_p)	Duty Cycle (t)	Gap voltage (V_g)
1	47.1191	52.4801	47.5467	49.5478
2	47.9933	48.8535	49.3083	49.535.
3	52.1689	45.9476	50.4262	48.3418
Delta	5.0498	6.5325	2.8795	1.206
Rank	2	1	3	4

Referring to table 9 it is noted that factor peak current (I_p) has the largest contribution to total sum of squares i.e. 52.04%. The factor pulse on time (T_{on}) has also some contribution of 35.38% in total sum of the square. The other two factors have negligible contribution in total sum of squares. Duty cycle (t)

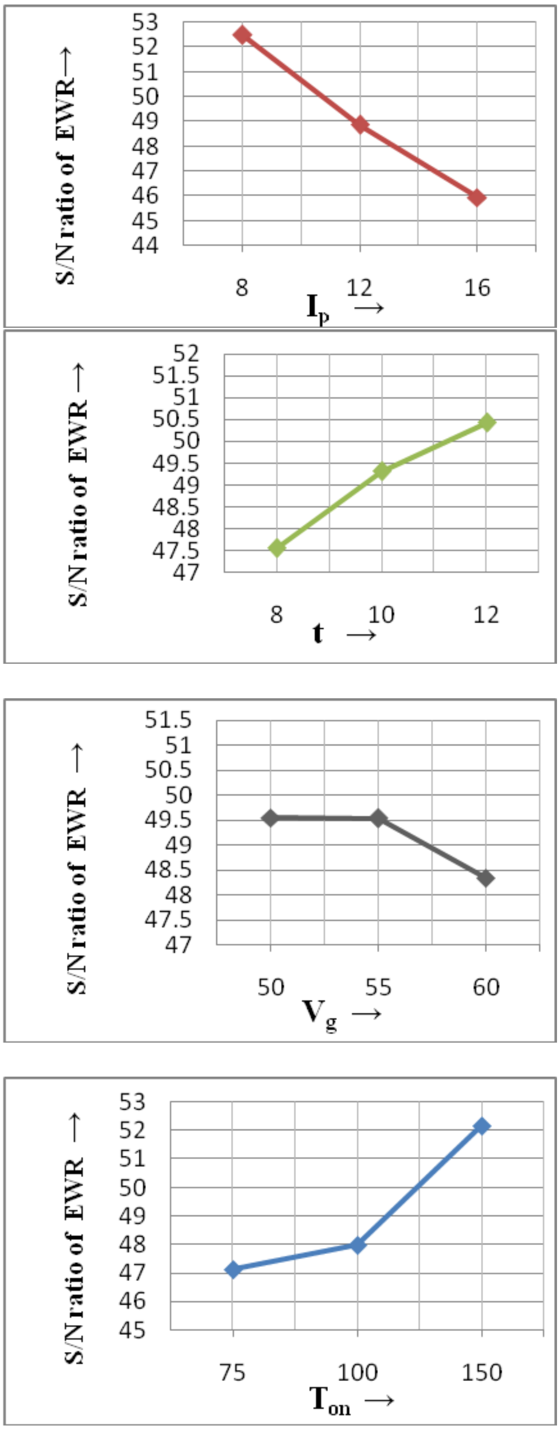

Fig 2. S/N Ratio curve for EWR with V_g,I_p,t and V_g

Table 9. Analysis of Variance (ANOVA) for EWR

Sources	D.O.F	Sum of squares	Mean square	%Contribution
T_{on}	2	43.7003	21.85015	35.38
I_P	2	64.2700	32.135	52.04
t	2	12.6444	6.3222	10.23
V_g	2	2.8790	1.4395	2.331
Total	8	540.2698	270.1349	100

Has very much less contribution of 10.23% and factor gap voltage (V_g) has almost no contribution with only 2.33% of total contribution. The larger the contribution of any factor to total sum of squares, larger is its ability to influence electrode wear rate (EWR). Electrode wear rate is mainly influenced by peak current (I_p) and pulse on time (T_{on}). Duty cycle (t) and gap voltage (V_g) has very less effect on electrode wear rate (fig. 2).

Table 10. Statistical values for Regression Analysis for EWR

Predictor	Coefficient	SE Coefficient	T	P
Constant	0.001018	0.002941	0.35	0.747
Pulse on time (T_{on})	-0.00002652	0.00000602	-4.41	0.012
Peak current (I_p)	0.00033000	0.00005747	5.74	0.005
Duty cycle (t)	-0.0002142	0.0001149	-1.86	0.136
Gap voltage (V_g)	0.00006967	0.00004598	1.52	0.204

S = 0.000563084 R-Sq = 93.6% R-Sq(adj) = 87.1%

The Regression Equation is-

EWR= 0.00102-0.000027 T_{on} + 0.000330 I_p - 0.000214 t + 0.000070 V_g

A. Effect of input factors on radial overcut ROC.

The response table for signal-to-noise ratio for radial overcut (ROC) is shown in table 11 and corresponding analysis of variances (ANOVA) table is shown in table 12.

For radial overcut (ROC), the calculation of S/N ratio follows "Smaller the Better" model.

Table 11. Response table for Signal-to- Noise Ratios for ROC

Levels	Pulse-on Time (T_{on})	Peak Current (I_p)	Duty Cycle (t)	Gap voltage (V_g)
1	16.5001	17.0811	15.2378	15.9183
2	15.7434	15.9691	15.9148	16.0484
3	15.4164	14.6097	16.5073	15.6932
Delta	1.0837	2.4714	1.2695	0.3552
Rank	3	1	2	4

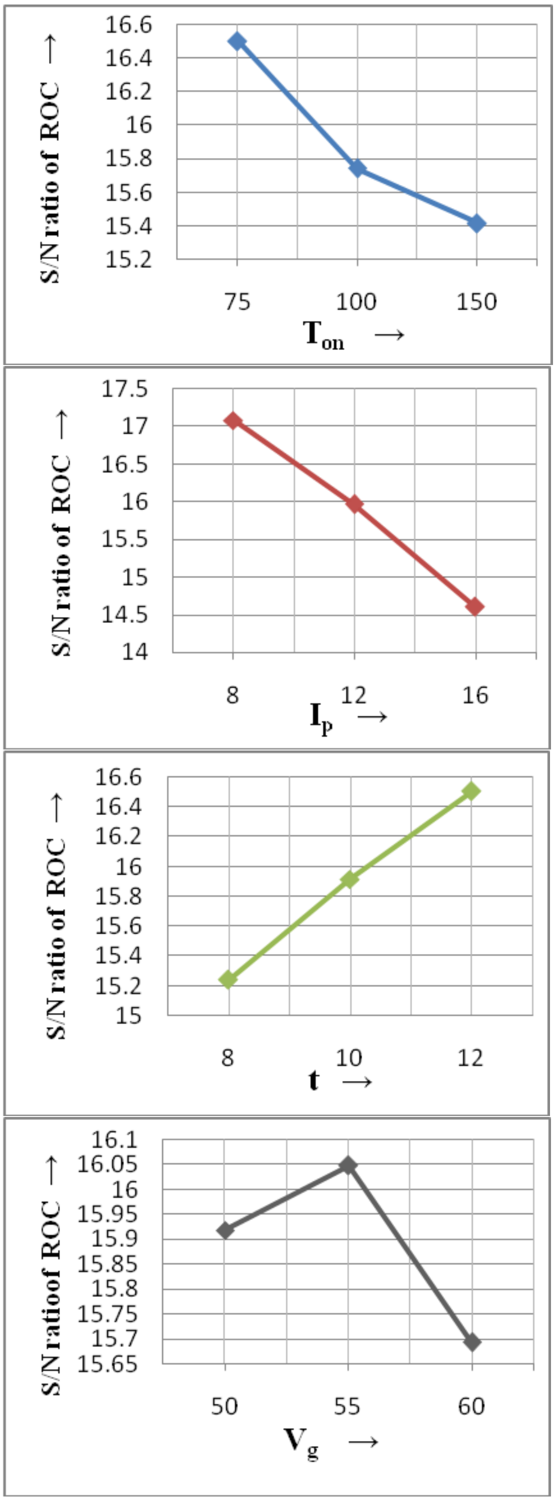

Fig. 3. S/N Ratio curve for ROC with V_g,I_p,t and V_g

Referring to table 12 it is noted that factor peak current (I_p) has the largest contribution to total sum of squares i.e. 67.29 %. The other two factors duty cycle (t) and pulse on time (T_{on}) has contribution of 17.72 % and 13.57 % respectively. The other factor gap voltage (V_g) has almost no contribution with

Table 12. Analysis of Variance (ANOVA) for ROC

Sources	D.O.F	Sum of squares	Mean square	%Contribution
T_{on}	2	1.8539	0.9269	13.57
I_P	2	9.1923	4.5961	67.29
t	2	2.4210	1.2105	17.72
V_g	2	0.1938	0.0969	1.42
Total	8	13.661	6.8304	100

only 1.42%. The larger the contribution of any factor to total sum of squares, larger is its ability to influence electrode wear rate (ROC). Thus Peak current (I_p) has the most influence on radial overcut then followed by duty cycle (t) and pulse on time (T_{on}) with almost very less influence by gap voltage (V_g) (fig. 3).

Table13. Statistical values for Regression Analysis for ROC

Predictor	Coefficient	SE Coefficient	T	P
Constant	0.10750	0.03329	3.23	0.032
Pulse on time (T_{on})	0.00026667	0.00006814	3.91	0.017
Peak current (I_p)	0.0058333	0.0006505	8.97	0.001
Duty cycle (t)	-0.006250	0.001301	-4.80	0.009
Gap voltage (V_g)	0.0003333	0.0005204	0.64	0.557

The Regression Equation is-

$$ROC = 0.108 + 0.000267\ T_{on} + 0.00583\ I_p – 0.00625\ t + 0.000333\ V_g$$

The calculated values of prediction error have been shown in table14 along with the prediction error variance. The experimental and predicted values shown below represent the specific values for the particular response factors mentioned in the table for which the corresponding verification experiment has been carried out.

Table 14. Prediction Error Percentage and Prediction Error Variance

Verf. Expt. No.	Verf. Expt. For	T_{on}	I_p	t	V_g	Pred. Value	% of Pred. Error
1	Max. MRR	100	16	12	60	0.10586	8
2	Min. EWR	150	8	12	50	0.000542	54
3	Min. ROC	75	8	12	55	0.117	2

IV. CONCLUSION

1) The material removal rate (MRR) is mainly affected by peak current (I_p). Pulse on time (T_{on}) and gap voltage (V_g) have considerable effect on MRR. The effect of duty cycle (t) on MRR is negligible.
2) Electrode wear rate is mainly influenced by peak current (I_p) and pulse on time (T_{on}).Duty cycle (t) and gap voltage has very less effect on electrode wear rate.
3) Peak current (I_p) has maximum effect on radial overcut (ROC). Duty cycle (t) and pulse on time (T_{on}) also have considerable effect on radial overcut. Gap voltage (V_g) has negligible effect on ROC.
4) The optimum parameter can be considered for which maximum material removal rate, minimum electrode wear rate and radial overcut is obtained.

Physical requirement	Optimal combinations			
	T_{on}	I_p	t	V_g
Maximum MRR	100	16	12	60
Minimum EWR	150	8	12	50
Minimum ROC	75	8	12	55

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