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"Parametric Optimization of Rotary Electro-Discharge Machining of Oil Hardened Non Shrinkage Steel" Material with Sensitivity Analysis

Rahul Shivajirao Desai[1], M. V. Kavade[2]

[1]Department of Mechanical Engineering, Rajarambapu Institute of Technology, Sakharale, Islampur, Sangli, Maharashtra, India

[2]Professor, Department of Mechanical Engineering, Rajarambapu Institute of Technology, Sakharale, Islampur, Sangli, Maharashtra, India.

Abstract: ***Optimization tool used in industrial area for increasing quality of product by reducing the cost of product. In this paper, the experimental investigation of material removal rate (MRR), electrode wear rate (EWR) and surface roughness during machining on OHNS Steel by using copper electrode on EDM machine. The input parameters used for experimental work are Peak Current (Ip), Pulse-On (Ton), Pulse-Off (Toff) and Rotation of ram. Based on the input parameters, the design of experiments are L9 orthogonal array. The optimization has been carried out by using Taguchi method as well as Grey relational analysis or Multi response optimization. Firstly single optimization has been carried out and then Multi response optimization has been carried out, for that Grey relational generation and coefficient are find out and then Grey relational grade is carried out. Then the confirmation experiments are carried out. According to this machining parameters are carried out to be optimized for combined objectives of higher MRR, lower EWR and lower SR. The results obtained from this optimization shows that GRA is very effective optimization technique than Taguchi method. Sensitivity analysis also used as a post analysis method***

Keywords: EDM, IP, Ton, Toff, MPR,EWR,SR Taguchi method, orthogonal array, G.R.A., Sensitivity analysis

1. Introduction

Electro Discharge Machining is a thermoelectric process in which removal of material takes place due to spark produced in between work-piece and electrode. For this spark production, both work piece and electrode are conductors of electricity. To understand experimental characteristics of OHNS Die steel, experimental study is carried out on it in this paper. K. Saraswathamma, Madhu Durgam [1] have carried out the study through statistical design of experiments were carried out to study the effect of machining parameters such as Pulse current, Pulse on time(Ton) and Pulse pause time(Toff) on responses variables such as Material RemovalRate(MRR) and Tool Wear Rate (TWR) on OHNS Tool Steel. The experiments were designed using Response surface methodology (RSM) - Central Composite Design (CCD) involving three variables with three levels. C. Mathalai Sundaram et.al. [2] Have investigated the effect *of various process parameters in Electrical Discharge Machining. Experimental results are discussed on electric discharge machining of OHNS (*Oil Hardening non-Shrinking Tool Steel) *Die material in Copper and Aluminum electrode. Statistical analysis is presented to identify the effect of process input factors (viz. current, voltage) on the output factors viz. Material Removal Rate (MRR), Electrode Wear Rate (EWR).* Trupti Raut *, Prof. M.Y. Shinde *[3] optimized to* increasing quality of product by lowering the cost of product. In this paper, the experimental investigation of material removal rate, electrode wear rate, surface roughness, radial overcut and half taper angle during machining on OHNS Die steel by using Copper electrode on EDM machine is done. The input parameters used for experimental work are Peak Current (Ip), Pulse-On Time (Ton), Gap Voltage (Vg) and Sensitivity (Sen).Based on the experiments conducted on L9 Orthogonal array , optimization has been carried out by using Taguchi method (Single optimization) as well as Grey Relational Analysis (Multi-response optimization). R. A. Kapgate et.al.[6] presented an experimental investigations and development of mathematical models using dimensional analysis for selection of WEDM process parameters. Sequential classical experimentation technique has been used to perform experiments for triangular, circular and rectangular shape cuts on Al/SiC10% MMC as majority of industrial products are manufactured by these shapes or combinations. An attempt of mini-max principle and linear programming (LPP) has been made to optimize the range bound process parameters for maximizing material removal rate and minimum surface finish to machine Al/SiC10% MMC

2. Materials and Methods

OHNS Steel is used as work piece and copper electrode is used as tool electrode. The photographic view of OHNS steel is shown in Fig.1 and material properties are shown in table 2.1

Figure 1: The photographic view of OHNS steel

Table 2.1: Properties of OHNS steel

Properties	*Value*
Melting Point	1421ºc
Elastic Modulus	193 GPa
Conductivity	30W/Mk
Density	7.81 g/cm^3

Machining was carried out by using Electronica-ZNC with NC control machine in the Rajarambapu Institute of Technology, Islampur following table 2.2 shows specification of machine and table 2.3 shows the condition and description of EDM Machine.

Table 2.2: Specification of machine

Description	*Details*
Supply voltage	415 V
Discharge current	35A
Servo system	Electromechanical
Model	Electronica-ZNC

Table 2.3: Condition and description of EDM Machine

Conditions	*Description*
Work piece	OHNS steel
Electrode	Copper
Peak Current	5, 10, 15 A
Pulse-on Time	50, 100, 150 µs
Pulse-off Time	4,8,12 µs
Rotation of electrode	100,200,300 rpm

Table 2.4: Shows the four control parameters with three levels

Control Parameters	Levels		
	1	2	3
Peak Current	5	10	15
Pulse-on Time	500	100	150
Pulse-off Time	4	8	12
Rotation of electrode	100	200	300

3. Experimental Details

The design of experiment is an effective tool to design and conduct the experiments the Taguchi L9 orthogonal array and analysis was done by Taguchi as well as GRA, by carrying out total number of 9 experiments with 3 verification experiments. Table 3.1(a&b) shows L9 orthogonal array with experiments conducted represented by four columns and three levels.

Table 3.1(a): L9 orthogonal array design matrix

Expt.No.	Factor(1)	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

Table 3.1(b): L9 orthogonal array design matrix

Expt.No.	Factor(1)	Factor(2)	Factor(3)	Factor(4)
E1	5	50	4	100
E2	5	100	8	200
E3	5	150	12	300
E4	10	50	8	300
E5	10	100	12	100
E6	10	150	4	200
E7	15	50	12	200
E8	15	100	4	300
E9	15	150	8	100

The material used for this work OHNS plate of size 100mm x 50 mm x 11mm and cured under appropriate pressure and temperature. The specimen is polished to get a plane surface. The electrode is electrolytic copper (99.97% pure) of 8930-kgm^3 densities with a melting point of 1083^{0}C. These electrodes are cylindrical in shape with a nominal diameter of 16 mm. EDM machine used is Electronica-EZMC with NC control in the Z-direction. The dielectric fluid used is IPOL. Polarity of the electrode is negative and that of the composite is positive. The process parameters chosen for study were Peak Current (Ip), Pulse-On Time (Ton), Pulse-Off Time (Toff) and Rotation of electrode with above three different levels. Following were the performance parameters considered in this study: Material Removal Rate (MRR), Electrode Wear Rate (EWR), and Surface Roughness (SR). For these parameters, weights of work-piece and electrode were measured before and after machining by using weighing machine. Surface Roughness were measured by Surface Roughness Tester.

4. Experimental Results

The results found by above formulae were tabulated in the following table 4.1:-

Table 4.1: Experimental Results

Expt. No	MRR (mm^3/ min)	EWR (mm^3/ min)	SR (µm)
E1	12.9526	0.0112	5.119
E2	13.9739	0.0337	5.641
E3	15.4506	0.0187	6.138
E4	18.8651	0.2322	5.179
E5	23.4020	0.5194	6.632
E6	21.2526	0.0486	9.839
E7	25.4862	0.5617	5.623
E8	26.4174	0.1872	9.203
E9	22.0964	0.4531	9.680

5. Analysis of Experiments

From the experimental results, optimization was done by Taguchi method (Single Optimization) and Grey Relational Analysis (Multi-Response Optimization) and according to that verification experiments were carried out and from that objective of this study was to obtain higher MRR, lower EWR and SR.

Table 5.1: Signal-to-Noise Ratios

Expt.No	MRR (mm^3/ min)	EWR (mm^3/ min)	SR (µm)
E1	22.24714	39.01564	-14.1837
E2	22.90635	29.4474	-15.0271
E3	23.77891	34.56317	-15.7605
E4	25.51318	12.68276	-14.2849
E5	27.38506	5.689961	-16.4328
E6	26.54824	26.26727	-19.8590
E7	28.1261	5.009912	-14.9993
E8	28.4378	14.55388	-19.2785
E9	26.88643	6.876119	-19.7175

5.1 Effect of input factors on MRR:

Table 5.2: Response Table for Signal to Noise Ratios Larger is better (MRR)

Level	Current	Pulse On	Pulse Off	Rotation
1	22.98	25.30	25.74	25.51
2	26.48	**26.24**	25.10	25.86
3	**27.82**	25.74	**26.43**	**25.91**
Delta	4.84	0.95	1.33	0.40
Rank	1	2	3	4

Table 5.3: Analysis of Variance for SN ratios (MRR)

Source	DF	Seq SS	Adj MS	% OF Contribution
Current	2	172,984	86.4919	**77.6528**
Pulse On	2	7.698	3.8492	3.9121
Pulse Off	2	14.953	7.4766	7.5988
Rotation	2	1.147	0.5735	0.5828
Total	8	196.782	98.3912	100

Therefore, peak current has maximum effect on MRR.

5.2. Effect of input factors on EWR:

Table 5.4: Response Table for Signal to Noise Ratios Smaller is Better (EWR):

Level	Current	Pulse On	Pulse Off	Rotation
1	**34.342**	18.903	**26.612**	17.194
2	14.880	16.564	16.335	20.242
3	8.813	**22.569**	15.088	**20.600**
Delta	25.529	6.005	11.525	3.406
Rank	1	3	2	4

Table 5.5: Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj MS	% of Contribution
Current	2	1067.29	533.647	**77.1570**
Pulse On	2	54.97	27.486	3.9744
Pulse Off	2	239.99	119.933	17.3420
Rotation	2	21.02	10.509	1.5195
Total	8	1383.27	691.575	100

Therefore, peak current has maximum effect on EWR.

5.3. Effect of input factors on SR:

Table 5.6: Response Table for Signal to Noise Ratios Smaller is better (SR):

Level	Current	Pulse On	Pulse Off	Rotation
1	**-14.99**	**-14.49**	-17.77	-16.78
2	-16.86	-16.91	-16.34	-16.63
3	-18.00	-18.45	**-15.73**	**-16.44**
Delta	3.01	3.96	2.04	0.34
Rank	2	1	3	4

Table 5.7: Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj MS	% of Contribution
Current	2	13.8381	6.9190	31.1111
Pulse On	2	23.8759	11.9379	**38.3717**
Pulse Off	2	6.5946	3.2973	8.5930
Rotation	2	0.1707	0.0854	0.9938
Total	8	44.4793	22.2396	100

Therefore, pulse on time has maximum effect on SR.

6. Verification Experiments

After performing statistical analysis on the experimental data. It has been observed that there is one level for each factor for which responses are either maximum in case of MRR, minimum in case of EWR and SR. According to that we get three different levels for which we get maximum MRR and minimum EWR and SR. The table of verification experiments as follows.

Table 6.1: Verification experiments

Physical requirement	Optimal combination			
	Peak current	Pulse on time	Pulse off time	Rotation of electrode
Max .MRR	15	100	12	300
Min EWR	5	150	4	300
Min. SR	5	50	12	300

7. Grey Relational Analysis

Optimization by using Grey Relational analysis Technique

In this technique, orthogonal array with Grey Relational analysis was discussed. The optimization process was done by following steps:

7.1 In Grey Relational analysis experimental data was firstly normalized in the range of 0 to 1. This is called as Grey Relational generation.

According to normalization there are two types of data normalization.

For lower better criteria:

$$Xi\ (k) = \frac{max\ yi(k) - yi(k)}{max\ yi(k) - min yi(k)} \text{---7.1}$$

For higher better criteria:

$$Xi\ (k) = \frac{yi(k) - min\ yi(k)}{max\ yi(k) - min\ yi(k)} \text{----7.2}$$

Where,

The xi (k) is the value of grey relational generation, min yi(k) is the minimum value for the (k^{th}) response and max yi(k) is the maximum value for the (k^{th}) response.

Table 7.1: Shows normalized value.

Expt. No.	MRR	EWR	SR
1	0.0000	0.0000	0.0000
2	0.106485	0.281371	0.148612
3	0.247432	0.130933	0.277841
4	0.527576	0.774366	0.017834
5	0.829947	0.980002	0.396311
6	0.694773	0.374889	1.0000
7	0.94965	1.0000	0.14372
8	1.0000	0.719342	0.897727
9	0.749401	0.945121	0.975065

7.2 Calculate the deviation sequence:-

$$\triangle oi(k) = |\ yo(k) - yi(k)\ | \text{---7.3}$$

Where,

yo(k) – Max. Value of o/p of Normalized S/N

yi(k) – Value of o/p of Normalized S/N

Table 7.2: Deviation Sequence

Expt. No.	MRR	EWR	SR
1	1.0000	1.0000	1.0000
2	0.893515	0.718629	0.851388
3	0.752568	0.869067	0.722159
4	0.472424	0.225634	0.982166
5	0.170053	0.019998	0.603689
6	0.305227	0.625111	0.0000
7	0.05035	0.0000	0.85628
8	0.0000	0.280658	0.102273
9	0.250599	0.054879	0.024935

7.3 Calculate the Grey Relational coefficient.

$$\xi i\ (k) = \frac{\Delta min + \psi \Delta max}{\Delta oi(k) + \psi \Delta max} m \text{ ---7.4}$$

Where,
$\Delta 0i\ (k)$ is the deviation sequence
Ψ is distinguishing coefficient which
generally lies between 0 and 1. (It mostly 0.5)

Table 7.3: Grey Relational coefficient

Expt. No.	MRR	EWR	SR
1	0.3333	0.3333	0.3333
2	0.358805	0.410297	0.36999
3	0.39918	0.365212	0.409112
4	0.514179	0.689053	0.337344
5	0.746209	0.961542	0.453026
6	0.620943	0.4444	1.0000
7	0.908513	1.0000	0.368656
8	1.0000	0.640486	0.830189
9	0.666135	0.901097	0.9525

7.4. Now calculate Grey Relational Grade by Averaging the Grey Relational coefficient.

$$\gamma i = \frac{1}{n} \sum_{k=1}^{n} \xi i(k) \text{ ---7.5}$$

where n = number of process responses.

Table 7.4: Grey Relational Grade

Expt. No.	Grey Relational Grade	Rank
1	0.333333	9
2	0.379697	8
3	0.391168	7
4	0.513525	6
5	0.720259	4
6	0.688448	5
7	0.759056	3
8	0.823558	2
9	0.839911	1

7.5. Performing statistical analysis of variance (ANOVA) for the input parameters with the Grey relational grade and to find which parameter significantly affects the process.

Table 7.5: Shows ANOVA table for G.R.G.

Input Factor	Average G.R.G. by Factor Level				
	Level-1	Level-2	Level-3	Max-Min	Rank
Current	0.368066	0.640744	**0.807508**	0.439442	1
Pulse On	0.535305	**0.641172**	0.639842	0.105867	2
Pulse Off	0.615113	0.577711	**0.623494**	0.045783	4
Rotation	**0.631168**	0.609067	0.576084	0.055084	3

7.6 Selecting the optimum levels of parameters.

Table 7.6: Shows the initial and optimal setting of Parameters

	Initial Parameter	Optimal Parameters	
		Prediction	Experiment
Setting Level	A1B1C1D1	A3B2C3D1	A3B2C3D1
MRR	12.9526	20.09	23.4020
EWR	0.0112	0.4622	0.5194
SR	5.119	6.208	6.632
GRG	0.333333	0.887022	0.720259
Improvement in Grey Relational Grade = 0.16676			

7.7 Conduct confirmation experiment and verify

After the optimal level of machining parameters has been identified, a verification test needs to be carried out in order to check the accuracy of analysis. The estimated grey relational grade,α , using the optimal level of the process parameters can be calculated as

$$\alpha = \alpha m + \sum_{i=1}^{q} (\alpha i - \alpha m) \text{ ----7.6}$$

Where,
αm is the total mean of the Grey relational grade αi is the mean of the Grey relational grade at the optimal level and q is the number of the machining parameters that significantly affects the multiple response characteristics. Table 7.6 shows the comparison of the estimated grey relational grade with the actual grey relational grade obtained in experiment using the optimal cutting parameters. It may be noted that there is good agreement between the estimated value (0.887022) and experiment value (0.720259). The improvement grey relational grade from initial parameter combination (A1B1C1D1) to the optimal parameter combination (A3B2C3D1) is 0.16676. This is about 28% of the mean grey relational grade and thus there is significant improvement. Here, it may conclude that the multiple performance characteristic of the EDM process such as material removal rate and surface finish are improved together by using this approach.

8. Sensitivity Analysis

"Sensitivity analysis is the first and the most important step in the optimization problems, because it yields the information about the increment or decrement tendency of the design objective function with respect to the design parameter. Therefore, sensitivity analysis plays an important role in determining which parameter of the process should be modified for effective improvement" this study focuses on the sensitivity analysis of parameters and fine tuning requirements of the parameters for optimum MRR,EWR and SR. Changeable process parameters such as current, Pulse-On, Pulse-Off, Rotation of electrode are taken as design variables. In order to investigate the effects of input (process) parameters on output parameters, which determine the MRR, EWR and SR a mathematical model is constructed by using regression analysis.

In this work, investigation is carried out to study the effect of the Process parameter on OHNS material and their sensitivity. The quantitative and qualitative effectiveness of the process parameters can be determined using sensitive analysis, by his analysis, critical parameter can be identified and ranked by their order of importance. This will help the engineer to select the process parameter effectively and to control the EWR and SR effectively without much trial and error, resulting in saving of time and material.

8.1 Sensitivity analysis for MRR, EWR and SR

From the above developed mathematical equation to be used for the estimation of the MRR, EWR and SR. The sensitivity equation are obtained by differentiating them with respect to process parameter of interest, such as current, Pulse-On, Pulse-Off, and Rotation of electrode. The sensitivity equation for current were obtained by differentiating equation respect to current, are given below.

8.1.1Regression Analysis: MRR versus CURRENT, TON, TOFF, ROTA

The regression equation is

MRR = 6.95 + 1.05 CURRENT + 0.0050 TON + 0.155 TOFF + 0.0038 ROTA

The Sensitivity equation for welding current as below respectively.

$$\frac{dR}{dI} = 1.05 \qquad 8.1$$

The Sensitivity equation for PULSE ON

$$\frac{dR}{dTon} = 0.0050 \qquad 8.2$$

The Sensitivity equation for PULSE OFF

$$\frac{dR}{dToff} = 0.155 \qquad 8.3$$

The Sensitivity equation for SPEED OF ELECTRODE

$$\frac{dR}{ds} = 0.0038 \qquad 8.4$$

8.1.2 Regression Analysis: EWR versus CURRENT, TON, TOFF, ROTA

The regression equation is

EWR = - 0.157 + 0.0379 CURRENT - 0.000949 TON + 0.0355 TOFF - 0.000909 ROTA

The Sensitivity equation for welding current as below respectively.

$$\frac{dR}{dI} = 0.0379 \qquad 8.5$$

The Sensitivity equation for PULSE ON

$$\frac{dR}{dTon} = -0.000949 \qquad 8.6$$

The Sensitivity equation for PULSE OFF

$$\frac{dR}{dToff} = 0.0355 \qquad 8.7$$

The Sensitivity equation for SPEED OF ELECTRODE

$$\frac{dR}{ds} = -0.000909 \qquad 8.8$$

8.1.3 Regression Analysis: SR versus CURRENT, TON, TOFF, ROTA

The regression equation is

SR = 3.45 + 0.254 CURRENT + 0.0325 TON - 0.240 TOFF - 0.00152 ROTA

The Sensitivity equation for welding current as below respectively.

$$\frac{dR}{dI} = 0.254 \qquad 8.9$$

The Sensitivity equation for PULSE ON

$$\frac{dR}{dTon} = 0.0325 \qquad 9.0$$

The Sensitivity equation for PULSE OFF

$$\frac{dR}{dToff} = -0.240 \qquad 9.1$$

The Sensitivity equation for SPEED OF ELECTRODE

$$\frac{dR}{ds} = -0.00152 \qquad 9.2$$

8.2 MRR Sensitivity of the Process parameters

Pulse-on= 100 µs
Pulse-off= 12 µs
Rotation of electrode = 100 rpm.

Table 8.1: MRR sensitivity of process parameters

Current	dR/dI	dR/dTon	dR/dToff	dR/ds
5	1.05	0.0050	0.155	0.0038
10	1.05	0.0050	0.155	0.0038
15	1.05	0.0050	0.155	0.0038

8.3 EWR Sensitivity of the Process parameters

Pulse-on= 100 µs
Pulse-off= 12 µs
Rotation of electrode = 100 rpm.

Table 8.2: EWR sensitivity of process parameters

Current	dR/dI	dR/dTon	dR/dToff	dR/ds
5	0.0379	-0.000949	0.0355	-0.000909
10	0.0379	-0.000949	0.0355	-0.000909
15	0.0379	-0.000949	0.0355	-0.000909

8.4 SR Sensitivity of the Process parameters

Pulse-on= 100 µs
Pulse-off= 12 µs
Rotation of electrode = 100 rpm.

Table 8.3: SR sensitivity of process parameters

Current	dR/dI	dR/dTon	dR/dToff	dR/ds
5	0.254	0.0325	- 0.240	- 0.00152
10	0.254	0.0325	- 0.240	- 0.00152
15	0.254	0.0325	- 0.240	- 0.00152

9. Adequacy of Model

The adequacy of the models was tested using the analysis-of-variance technique (ANOVA). As per this technique [2,8]:The calculated value of the F-ratio of the model developed should not exceed the standard tabulated value of *F*-ratio for a desired level of confidence (say 95%) if the calculated value of the *R*-ratio of the model developed exceeds the standard tabulated value of the R-ratio for a desired level of Confidence (Say 95%) then the model may be considered adequate within the confidence limit.

9.1 The regression equation of MRR:-

MRR = 6.95 + 1.05 CURRENT + 0.0050 TON + 0.155 TOFF + 0.0038 ROTA

Table 8.4

Predictor	Coef SE	Coef	T	P
Constant	6.950	4.296	1.62	0.181
CURRENT	1.0541	0.2104	5.01	0.007
TON	0.00499	0.02104	0.24	0.824
TOFF	0.1548	0.2631	0.59	0.588
ROTA	0.00380	0.01052	0.36	0.736

S = 2.57740 R-Sq = 86.5% R-Sq(adj) = 73.0%
From the above table is taken for sensitivity analysis because it's R^2=86.5% and R^2 (adj) =73.0% which is best fit

9.2 The regression equation of EWR:-

EWR = - 0.157 + 0.0379 CURRENT - 0.000949 TON + 0.0355 TOFF - 0.000909 ROTA

Table 8.5

Predictor	Coef SE	Coef	T	P
Constant	-0.15743	0.07915	-1.99	0.118
CURRENT	0.037947	0.003877	9.79	0.001
TON	-0.0009490	0.0003877	-2.45	0.071
TOFF	0.035533	0.004847	7.33	0.002
ROTA	-0.0009093	0.0001939	-4.69	0.009

S = 0.0474879 R-Sq = 97.8% R-Sq(adj) = 95.6%
From the above table is taken for sensitivity analysis because it's R^2=97.8% and R^2 (adj) =95.6% which is best fit

9.3 The regression equation of SR:-

SR = 3.45 + 0.254 CURRENT + 0.0325 TON - 0.240 TOFF - 0.00152 ROTA

Table 8.6

Predictor	Coef SE	Coef	T	P
Constant	3.4510	0.5543	6.23	0.003
CURRENT	0.25360	0.02715	9.34	0.001
TON	0.032453	0.002715	11.95	0.000
TOFF	-0.24033	0.03394	-7.08	0.002
ROTA	-0.001518	0.001358	--1.12	0.326

S = 0.332554 R-Sq = 98.6% R-Sq(adj) = 97.2%
From the above table is taken for sensitivity analysis because it's R^2=98.6% and R^2 (adj) =97.2% which is best fit

9.4 Error Calculation

Sensitivity analysis of the wear model could be done to assess the percentage variation in wear based on the assumed variation in the parametric values by using the method of partial derivatives

$$\frac{dR}{R} = \frac{1}{R}\left[\frac{\partial R}{\partial I}\right]\Delta I + \frac{1}{R}\left[\frac{\partial R}{\partial Ton}\right]\Delta Ton + \frac{1}{R}\left[\frac{\partial R}{\partial Toff}\right]\Delta Toff + \frac{1}{R}\left[\frac{\partial R}{\partial S}\right]\Delta S$$

This is in reference to the generalized wear equation of the materials under dry condition. $\frac{\Delta I}{I}, \frac{\Delta Ton}{Ton}, \frac{\Delta Toff}{Toff}$ *and* $\frac{\Delta S}{S}$ are the percentage variation in the parameters current, Pulse-On, Pulse-Off, and Rotation of electrode. Respectively, expressed in decimals. Assuming equation for MRR as

$R=6.92\ I^{1.05} Ton^{0.0050} Toff^{0.155}\ S^{0.0038}$

If we assume the percentage variation is 5% in each case of the parameters current, Pulse-On, Pulse-Off, and Rotation of electrode, then MRR becomes

$$\frac{dR}{R} = (1.05+0.0050+0.155+0.0038) \times 0.05$$
$$= 0.06069$$
$$= \pm 6.0\%$$

This is to say that, the error we may expect in predicting the value of MRR lies in the range± 6.0%
Equation for EWR
EWR = - 0.157 + 0.0379 CURRENT - 0.000949 TON + 0.0355 TOFF - 0.000909 ROTA

$$\frac{dW}{W} = (0.0379 - 0.000949 + 0.0355 - 0.000909) \times 0.05$$
$$=0.0036$$
$$=\pm 0.4\%$$

This is to say that, the error, we may expect in predicting the value of EWR lies in the range±0.4%

Equation for SR
SR = 3.45 + 0.254 CURRENT + 0.0325 TON - 0.240 TOFF - 0.00152 ROTA

$$\frac{dS}{S} = (0.254+0.0325 - 0.240 - 0.00152) \times 0.05$$
$$=0.0022$$
$$=\pm 0.2\%$$

This is to say that, the error, we may expect in predicting the value of SR lies in the range±0.2%

10. Results and Discussion

[1] Results are discussed here which are obtained from optimization by Taguchi Method i.e. by Single Optimization Technique:
Experimental study was conducted to see the effect of Peak current, Pulse-on time, Pulse-off time and rotation of electrode on the EDM performance of OHNS material. The variation of MRR, EWR & SR with respect to independent parameter considered for this study has being carried out.

MRR Main Effects Plot (data means) for SN ratios

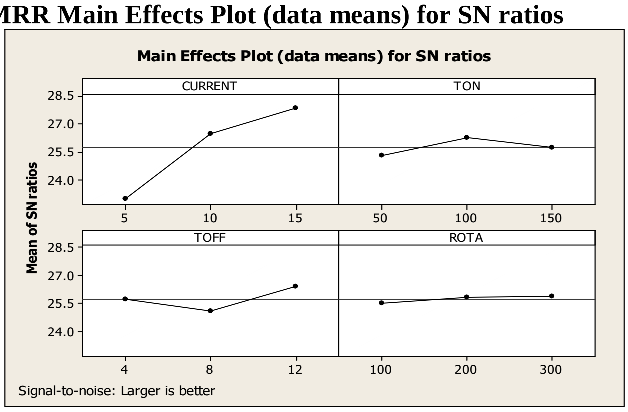

Fig 10.1 MRR Main Effects Plot (data means) for SN ratios

From fig. 10.1, it is observed that in case of Peak current, it is minimum for 5 Amp and it goes on increasing up to 15 Amp. In case of Pulse-on Time, it goes on increasing from 50 to 100 µs and again decreases from 100 to 150 µs. In case of Pulse-off Time, from 4 µs it comes down to 8 µs and then increases up to 12 µs. Similarly, in case of Rotation of electrode, it is minimum for 100 rpm and it goes on increasing up to 300 rpm. For higher MRR, Peak current has maximum contribution i.e. **77.6528** %. And it is followed by Pulse –on Time and Pulse –off Time. And it is less affected by Rotation of electrode i.e. 0.5828%.

EWR Main Effects Plot (data means) for SN ratios

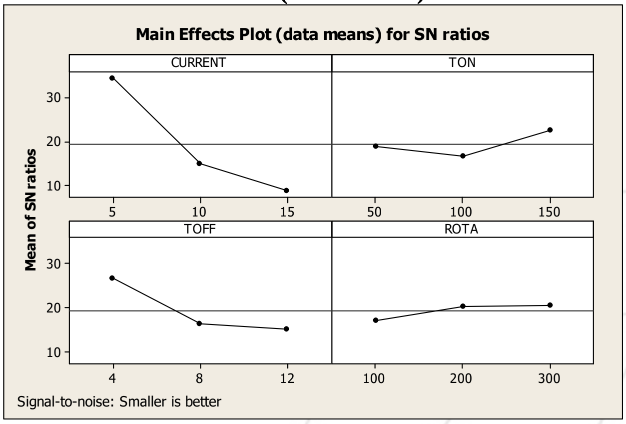

Fig 10.2 EWR Main Effects Plot (data means) for SN ratios

From fig. 10.2, it is observed that in case of Peak current, it is maximum for 5 Amp and it goes on decreases up to 15 Amp. In case of Pulse-on Time, from 50 µs it comes down to 100 µs and then increases up to 150 µs. In case of Pulse-off Time, it is maximum for 4 µs and it goes on decreases up to 12 µs. Similarly, in case of Rotation of electrode, it is minimum for 100 rpm and it goes on increasing up to 300 rpm. For lower EWR, Peak current has maximum contribution i.e. **77.1570**%. And it is followed by Pulse–on Time and Pulse–off Time. And it is less affected by Rotation of electrode i.e. 1.5195%.

SR. Main Effects Plot (data means) for SN ratios

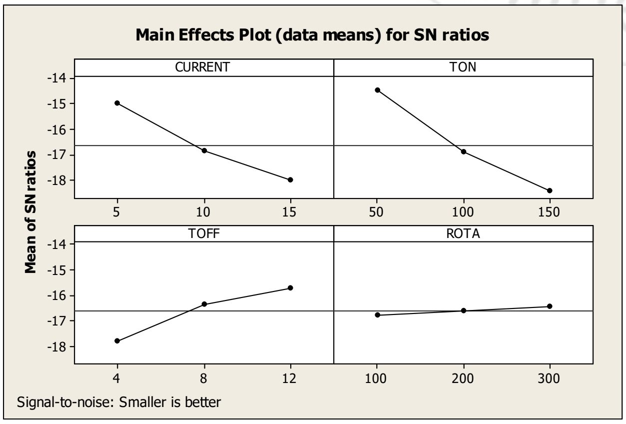

Fig 10.3 SR Main Effects Plot (data means) for SN ratios

From fig. 10.3, it is observed that in case of Peak current, it is maximum for 5 Amp and it goes on decreases up to 15 Amp. In case of Pulse-on Time, it is maximum for 50 µs and it goes on decreases up to 150 µs. In case of Pulse-off Time, it is minimum for 4 µs and it goes on increasing up to 12 µs. Similarly, in case of Rotation of electrode, it is minimum for 100 rpm and it goes on increasing up to 300 rpm. For lower SR, Pulse On Time has maximum contribution i.e. **38.3717**%. And it is followed by Pulse–on Time and Pulse–off Time. And it is less affected by Rotation of electrode i.e. 0.9938%.

[2] **Results are discussed here which are obtained from optimization by Grey Relational Method i.e. by Multi-response Optimization Technique:-**
Max. MRR, min. EWR & Min. SR,

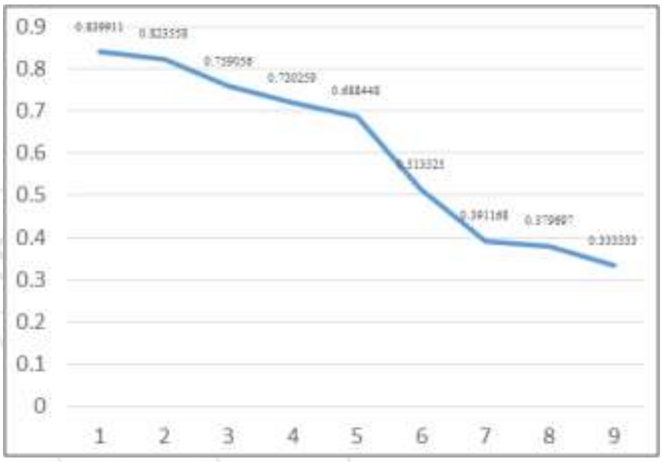

Figure 10.4: Grey relational grade for Max MRR, Min EWR, SR

From above graph, it is clear that highest value of G.R.G. is at experiment no. 1 i.e. that experimental parameters obtained results which we require i.e. Higher MRR and Lower EWR & SR

[3] **Results are discussed here which are obtained from optimization by SENSITIVITY ANALYSIS post analysis Technique:-**

MRR:

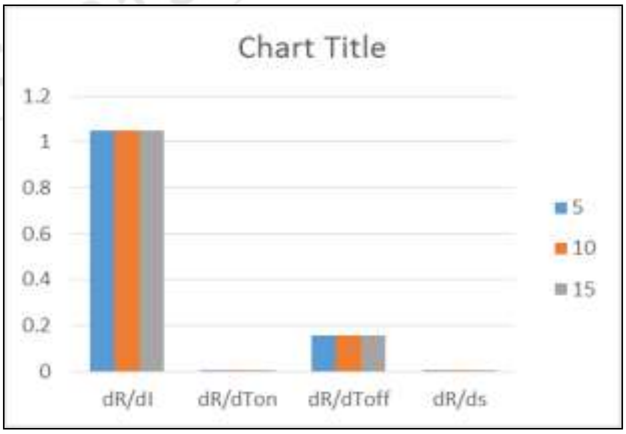

Figure 10.5: MRR Sensitivity

By considering ANOVA table 8.4 is taken for MRR sensitivity. From figure 10.5 it is clear that height of MRR is more sensible to change in discharge current than other process parameters. Hence it is reasonable to control the discharge current to get desired value of MRR. All parameter having positive effect on MRR. Whereas pulse on and rotation of the electrode having positive but small effect on MRR.

EWR:-

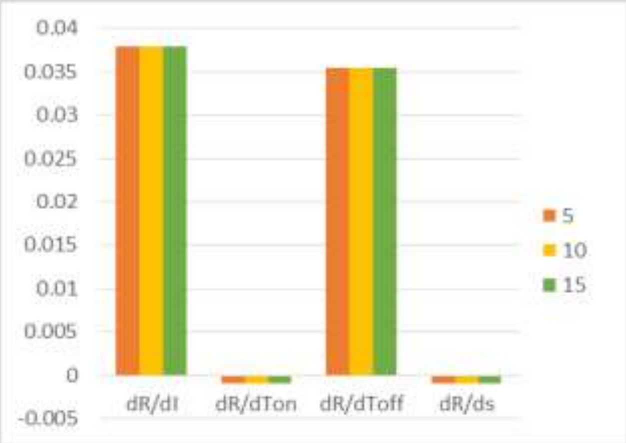

Figure 10.6: EWR Sensitivity

By considering ANOVA table 8.5 is taken for EWR sensitivity**.** From figure 10.6 it is clear that the EWR is more sensible to change in current and pulse off. Hence it is reasonable to control the current and pulse off to get desired value of EWR. From figure it is clear that current and pulse off having positive effect on EWR, whereas pulse on and rotation of the electrode having negative effect on EWR.

SR:-

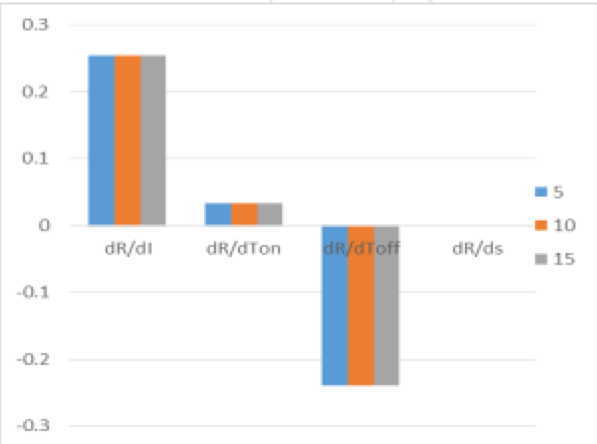

Figure 10.7: SR Sensitivity

By considering ANOVA table 8.6 is taken for SR sensitivity**.** From figure 10.7 it is clear that the SR is more sensible to change in current and pulse off. Hence it is reasonable to control the current and pulse off to get desired value of SR. From figure it is clear that current and pulse on having positive effect on SR, whereas pulse off and rotation of the electrode having negative effect on SR.

11. Conclusion

1) **The analysis was done by Taguchi Method i.e. by Single Optimization Technique:-**
   a) The **MRR** is mainly affected by Peak current (Ip) and Pulse-on Time. And less affected by Sensitivity.
   b) The **EWR** is mainly affected by Peak current (Ip) and Sensitivity. And less affected by Pulse-on Time.
   c) The **SR** is mainly affected by Peak current (Ip) and Sensitivity. And less affected by Pulse-on Time.

The analysis was done by Grey Relational Grade and hence multiple response characteristics i.e. MRR, EWR & SR, were improved by using Grey relational optimization technique. The optimal parameter combination determined by using this Grey Relational Analysis method as A3B2C3D1 i.e. Peak Current at 15A, Pulse-on Time at 100µs, Pulse-off Time at 12µs and rotation of the electrode at 100rpm. Hence, Grey Relational Analysis method simplifies the optimization procedure.

2) **The analysis was done by Sensitivity analysis**
   a) All parameter having positive effect on MRR. Whereas pulse on and rotation of the electrode having positive but small effect on MRR.
   b) The current and pulse off having positive effect on EWR, whereas pulse on and rotation of the electrode having negative effect on EWR.
   c) The current and pulse on having positive effect on SR, whereas pulse off and rotation of the electrode having negative effect on SR.

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