Optimization of Wire Electric Discharge Machining Process of D-2 Steel using Response Surface Methodology

Vijayant Maan , Abhishake Chaudhary
Lecturer,Department of Mechanical Engineering,S.C.R.I.E.T,C.C.S University Meerut,Uttar Pradesh,India
Lecturer,Department of Mechanical Engineering,S.C.R.I.E.T,C.C.S University Meerut,Uttar Pradesh,India

ABSTRACT

In the present study,Response surface methodology was used to investigate the effect of four controllable variables on the material removal rate(MRR).The work piece material is D-2 tool steel and the four process variables are pulse on time,pulse off time,peak current and servo voltage.These parameters are varied to study their effect on the MRR of D-2 steel. The response surface methodology (RSM) in conjunction with central composite design has been used to develop the empirical models for response characteristics. Desirability functions have been used for simultaneous optimization of performance measures.It was found that the material removal rate (MRR) directly increases with increase in pulse on time and peak current while decreases with increase in pulse off time and servo voltage.

***Keywords*:**Pulse on time(Ton),Pulse off time(Toff),Material removal rate(MRR),Servo voltage(SV),Peak current(IP),Central composite design(CCD).

I. INTRODUCTION

Wire Electric Discharge Machining (WEDM) is a non-traditional process of material removal from electrically conductive materials to produce parts with intricate shapes and profiles. This process is done by using a series of spark erosion. 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. The wire electrical discharge machining (WEDM) has become an important non-traditional machining process because it can machine the difficult-to-machine materials like titanium alloys and zirconium which cannot be machined by conventional machining process.

Though EDM process is very demanding but the mechanism of process is very complex,therefore,it is troublesome to establish a model that can accurately predict the performance by co-relating the process parameters.The optimum processing parameters are very essenstial to establish to boost up the production rate to a large extent.In this paper a model is developed by using RSM methodology and Central Composite Design.

II. LITERATURE REVIEW

Author	Parameters	Factors	Material	Method	Remark
1.Liao et al.	MRR,SR and Gap Width	T_{on}, T_{off}, peak current and table feed	SKD11 alloy steel	Taguchi method	Pulse-on time have a significant influence on the metal removal rate and gape width
2.Jangra et al.	CS, SR value and dimensional lag	T_{on}, T_{off}, Peak current, Wire speed and Wire tension	D_3 tool steel	Taguchi and Grey Relational Analysis	The cutting speed was observed 3.80mm/min and surface finish was not good.
3.Mahapatra et al.	MRR and SR	Discharge current, pulse duration, dielectric flow rate	D2 tool steel	Taguchi method	Mathematical models were developed for optimization of MRR and surface finish using non linear regression method
4.Kanlaya	SR	T_{on},T_{off},wire	DC53 die	Full	Surface roughness increased

siri et al.		tension	steel	factorial method	when T_{on} peak current increased.
5.Tosun et al.	Wire electrode wear,MRR and SR	Pulse duration and open circuit voltage	AISI 4140 steel	Regressi-on analysis technique	It was observed that, the wear increases with the increase in pulse duration and open circuit voltage
6.Sanchez et al.	Accuracy of WEDM corner cutting	Influence of work thickness,corner radius and number of trim cuts	AISI D2 tool steel	Fuzzy logic	It was found that wire lag is responsible for the back-wheel effect in corner cutting
7.Haddad et al.	MRR	Power, voltage, T_{off}, and spindle rotational speed	AISI D3 tool steel	DOE and RSM	In order to obtain high MRR the T_{on} and voltage should be fixed high.
8.Guo et al.	Cutting Speed	Voltage, the machining current and the pulse interval.	Reinforc-ed matrial (Al2O3 in 6061 Al alloy)	Orthogon-al design	A large pulse duration, a high voltage,and a large machining current and a proper pulse interval provides high machining efficiency
9.Kuriakose et al.	Cutting speed	pulse-on time, pulse-off time, voltage	Titanium alloys	Sorting genetic algorithm	Velocity and the surface finish was no single optimal combination of cutting parameters, as their influences on the cutting are quite opposite
10.Ozdemer et al.	Cutting Speed	Machining voltage, current, wire speed and peak current	Nodular cast iron	Regression analysis method	Results indicates that increase in SR and CR clearly follows the trend indicated with increasing discharge energy
11.S.Sarkar et al.	Cutting speed	Pulse-on time, pulse-off time, peak current	γ-TiAl	Response surface methodol-ogy	The residual analysis and experimental result indicated that the proposed models could adequately describe the performance indicators
12.Hewidy et al.	MRR	peak current and water pressure	Inconel-601	Response surface methodology	The volumetric metal removal rate generally increased with the increase of the peak current value and water pressure
13.Ramakrishnan et al.	Material removal rate	T_{on},wiretension, delay time, wire feed speed and ignition current intensity	D3 tool steel	Taguchi's robust	It was indentified that the pulse on time and ignition current had influenced more than the other parameters.
14.Kozak et al.	Material removal rate	Clamp position silver coating	Si3N4	Design of experim-ent	A reduction in MRR occurs when the wire moves away from the clamp A significant increase in MRR was observed due to silver coating
15.Kanlayasiri et al.	Surface roughness	Pulse-on time and pulse-peak current	DC53 die steel	Full factorial	It was reported that the SR increases when T_{on}, and

				method	pulse-peak current are increased.
16. Rao et al.	Cutting Speed	Discharge current, voltage, wire speed	Brass	Design of experim-ent	It was observed that CS decreases as thickness of work piece inreases.
17. Romlay et al.	Cutting speed	Wire speed,wire tension	Brass	DOE	cutting speed of the wire-EDM has been affected by changing cutting parameters
18. Rozenek et al.	Cutting speed	Discharge current, pulse-on time, pulse-off time, voltage	Metal matrix composite	DOE technique	The machining feed rate of WEDM cutting composites significantly depends on the kind of reinforsement material
19. Saha et al.	Cutting speed	pulse-on time, pulse-off time, peak current and capacitance	Tungsten carbide cobalt composite	Neuralnetw ork model	It was observed that neural network architecture provide the best result prediction
20. Bamberg e et al.	SR	Different wire diameter	p-type gallium-doped germanium	Design of experiment	It was found that 50µm molybdenum wire achieved the fastest machining time
21. Shunmug am et al.	Cutting velocity and surface finish	Pulse-on time, pulse-off time, peak current	Titanium alloy	Sorting genetic algorithm	There was no single optimal combination of cutting parameters
22. Ramaswa my et al.	MRR and SR	T_{on},T_{off} ,wire tension, wire feed speed and ignition current intensity	Die steel	Taguchi's robust design approach	It was indentified that the pulse on time and ignition current had influenced more than the other parameters
23. Kumar et al.	MRR and SR	Gap voltage, T_{on}, T_{off} and Wire feed	Incoloy800 super alloy	Taguchi's L_9 Orthogonal Array	It is concluded that grey-tagauchi method is most suitable for parametric optimization
24. Lee etal.	MRR and SR	T_{on},$T_{off,}$ peak current	Ceramic material	Design of experiment	Optimal combination of process parameters are obtained
25. Palaniku marin et al.	Surface roughness	T_{on},$T_{off,}$ peak current	Glass fiber reinforced plastic	Response surface methodolog y	A model is developed and tested using anova

III. MATERIAL AND METHOD

The w/p material is a high carbon,high chromium D-2 steel,with exceelent resistance to wear and abrasion.D-2 steel is choosed due to it's incresing use in the making of press tools,forming rolls,blanking dies,bushes,punches etc.The chemical composition of the material is shown in the table given below-

S.NO	MATERIAL	%
1.	CARBON	1.50%
2.	SILICON	0.30%
3.	MAGANESE	0.30%
4.	SULPHUR	0.027%
5.	PHOSPHORUS	0.026%
6.	VANADIUM	0.90%
7.	CHROMIUM	11.50%
8.	MOLYBDENUM	0.78%
9.	COPPER	0.009%
10.	IRON	Rest

Table 1: Composition of work material.

Fig 1: Machine Tool

During machining,on the basis of literature review ,the following process parameters have been selected for study in the range shown in table 2

S.No	Input Parameters	Range
1.	Pulse on time (Ton)	112-127 machine units
2.	Pulse off time (Toff)	42-55 machine units
3.	Peak current (IP)	170-215 Amp
4.	Servo voltage (SV)	40-60Volts

Table 2 :Process parameters with their Range

IV. RESPONSE SURFACE METHODOLOGY

Response surface methodology (RSM) is defined as a collection of mathematical and statistical methods that are used to develop, improve, or optimize a product or process. The independent variables are controlled by the experimenter, in a designed experiment, while the response variable is an observed output of the experiment. Fig. 4.1 illustrates the estimated relationship between a response variable and the two independent variables x_1 and x_2.

The experiments were performed on the Sprintcut WEDM machine from Electronica India Pvt Ltd.A brass wire of 0.25 mm was used as a cutting tool. Work pieces are cut into specimens of size 20mmX10mmX10mm.

Apart from these the following parameters are kept constant during experimentation-

Wire Tension- 4-7-10 unit
Wire feed - 4-7-10m/min
Servo Feed- 2050 unit

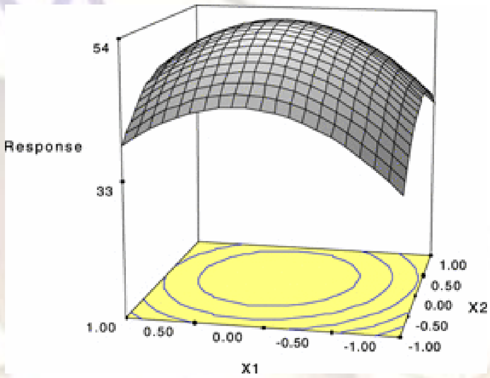

Fig 2 : An example of a response surface.

The field of response surface methodology consists of the experimental strategy for exploring the space of the process or independent variables, empirical statistical modelling to develop an appropriate approximating relationship between the yield and the process variables, and optimization methods for finding the values of the process variables that produce desirable values of the response.In general, the relationship between the response y and independent variables, $\xi_1, \xi2, \ldots, \xi_k$

$y=f(\xi_1,\xi2,\ldots,\xi_k)+\varepsilon$ (1)

Usually ε is treated as a statistical error, often assuming it to have a normal distribution with mean zero and variance σ^2. Then

$E(y) = \eta = E\,[f\,(\xi_1, \xi2,\ldots,\xi_k)] + E\,(\varepsilon) = f\,(\xi_1, \xi2,\ldots,\xi_k)$ (2)

The variables $\xi_1, \xi2,\ldots,\xi_k$ in Equation (2) are usually called the **natural variables**.In much RSM work it is convenient to transform the natural variables to **coded variables** $X_1, X_2 \ldots X_k$, which are usually defined to be dimensionless with mean zero and the same standard deviation. In terms of the coded variables, the response function (3) will be written as

$\eta=f(X_1,X_2\ldots X_k)$ (3)

In many cases, either a **first-order** or a **second order** model is used.For the case of two independent variables, the first-order model in terms of the coded variables is

$\eta=\beta_0+\beta_1X_1+\beta_2X_2$ (4)

The form of the first-order model in Equation (4) is sometimes called **main effects model**, because it includes only the main effects of the two variables X_1 and X_2. If there is an **interaction** between these variables, it can be added to the model easily as follows:

$\eta=\beta_0+\beta_1X_1+\beta_2X_2+\beta_{12}X_1X_2$ (5)

This is the first-order model with interaction.Often the curvature in the true response surface is strong enough that the first-order model (even with the interaction term included) is inadequate. A second-order model will likely be required in these situations. For the case of two variables, the second-order model is

$\eta = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1X_2$ (6)

This model would likely be useful as an approximation to the true response surface in a relatively small region. The second-order model is widely used in response surface methodology.

5. DESIGN OF EXPERIMENT

The experiments were designed by using Design expert software.Response surface methodology was used and central composite design was applied.Total 30 runs were obtained by applying given procees parameters. The value of input parameters were set according to this design for each run.The value of MRR was calculated for each run.The design is shown in table 5.1 with response MRR and SR.

Std	Run	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	Response SR µm
14	1	123	44	55	215	22.1	2.61
2	2	124	44	45	185	23.6	2.92
9	3	116	44	45	200	12.5	1.8
5	4	116	44	55	215	12.4	1.71
3	5	116	51	45	215	12.1	1.62
17	6	120	47	50	185	18.3	2.09
8	7	123	51	55	200	21.7	2.50
15	8	123	51	55	185	21.5	2.51
12	9	120	51	45	215	18.2	2.02
18	10	123	47	50	185	21.7	2.58
6	11	123	43	55	200	22.1	2.62
16	12	120	51	55	185	17.9	2.01
20	13	116	47	50	200	12.2	1.66
11	14	123	51	45	215	21.9	2.52
10	15	123	43	45	185	22.3	2.64
4	16	116	51	45	185	12.1	1.61
7	17	116	51	55	215	11.9	1.61
1	18	116	43	45	215	12.8	1.85
13	19	120	43	55	215	18.8	2.35
19	20	120	47	50	185	18.8	2.10
23	21	119	40	50	200	18.1	2.18
29	22	120	47	50	200	18.2	2.09
30	23	120	47	50	200	18.6	2.09
26	24	119	47	60	200	17.1	1.98
24	25	120	55	50	230	17.8	1.98
28	26	120	47	50	200	18.3	2.10
27	27	119	47	50	170	16.9	2.11
25	28	127	47	40	200	25	3.08
22	29	120	47	50	200	18.2	2.10
21	30	112	47	50	200	6.8	1.40

Table 3 : Experimental design with response data(MRR and SR)

6. RESULT AND DISCUSSION

In this study models as well as experimental results of the responses have been analyzed.Model analysis was made by using Design-Expert version 8.0.3 while the analysis of MRR is done in line with the behaviour of machining parameters on the responses.

6.1 Material Removal Rate(MRR) and Surface Roughness(SR) model-

The regression equation for MRR and SR as a function of four input process variables- Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV), peak current (IP) was developed using experimental data and is given below.

Final Equation in Terms of Coded Factors for MRR-

MRR=+17.70+5.00*A-0.33*B+0.055*C-0.41* A^2-0.14* C^2

Final Equation in Terms of Actual Factors for MRR-

MRR=-571.92416 +8.36169* ton -0.087745 * toff+0.5708* sv-0.029410* ton^2-5.59881E-003* sv^2

Final Equation in Terms of Coded Factors for SR-

SR=+2.03+0.46*A-0.089*B-0.011*D+0.056* A^2+0.018* B^2 +0.021* D^2

Final Equation in Terms of Actual Factors for SR-

SR=+52.76687-0.83824* ton -0.14747 * toff*-0.037761* peak current+4.01619E-003*ton^2+1.30198E-003* $toff^2$+9.26250E-005* peak $current^2$

6.2 Effect of process parameters on MRR and SR-

The figure 6.1-6.3 shows the effect of input parameters Pulse on time (Ton), Pulse off time (Toff), Servo voltage (SV) on the MRR and figure 6.4-6.6 shows the effect of input parameters Pulse on time (Ton), Pulse off time (Toff),Peak current on the SR.The MRR and SR increased with Pulse on time,and decreased with Pulse off time and servo voltage.The peak current has a very small influence on the MRR and servo voltage has very less influence on SR,But the Ton is the most influential parameter among them.In this process spark energy affects the MRR.And it is a function of Pulse on time and peak current.In The view point of industrial economy it is desirable to obtain higher value of MRR and low value of SR.

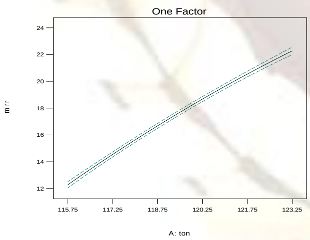

Fig 2:Showing the effect of Ton on M.R.R

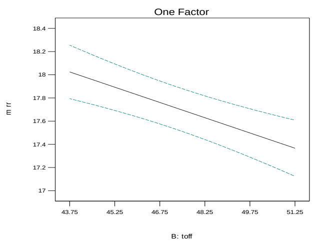

Fig3 :Showing the effect of Toff on M.R.R

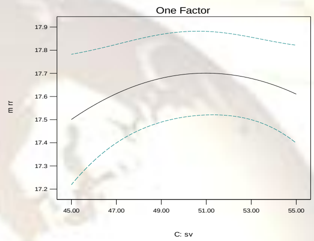

Fig4:Showing the effect of S.V on M.R.R

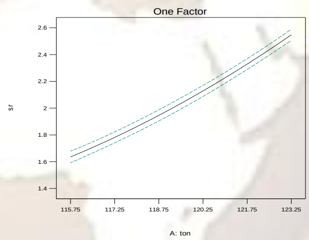

Fig 5 : Showing the effect of Ton S.R

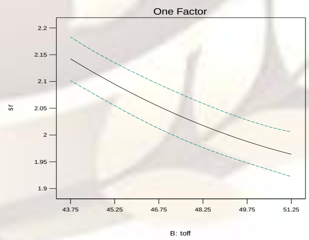

Fig 6 : Showing the effect of Toff on S.R

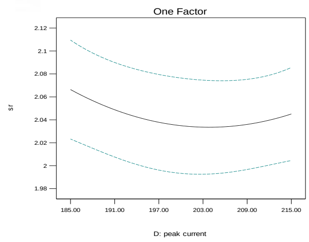

Fig 7 : Showing the effect of Peak Current on S.R

The effects of process parameters are taken two at a time on MRR is shown in the Fig 6.7-6.8.Fig 6.7 shows the combined effect of Ton and Toff on MRR.Fig 6.8 shows the combined effect of peak current and SV on MRR.

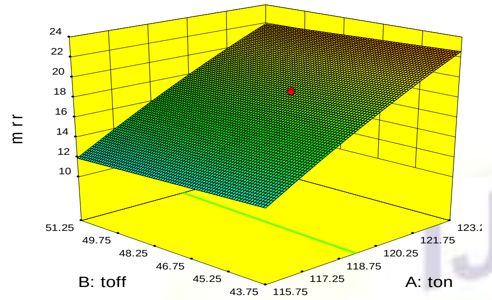

Fig 8 : Showing the combined effect of Ton and Toff on MRR

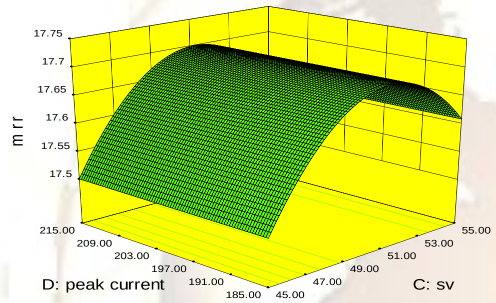

Fig 9 : Showing the combined effect of SV and Peak Current on MRR

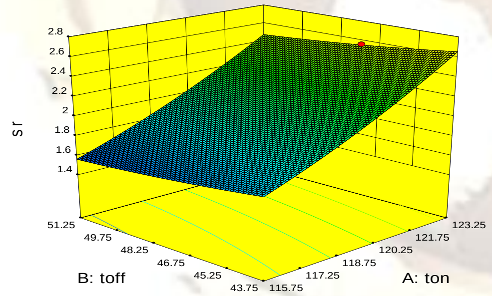

Fig 10: Showing the combined effect of Ton and Toff on SR

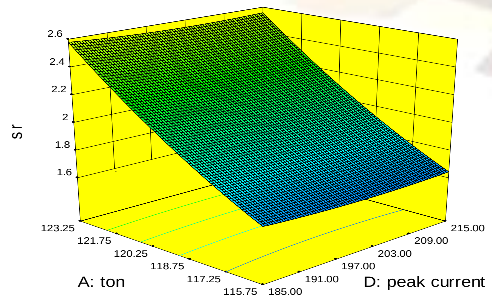

Fig 11: Showing the combined effect of Ton and Peak Current on SR

6.3 Residual Analysis-

The residual analysis as a primary diagnostic tool is also done. Normal probability plot of residuals has been drawn (Fig 611,6.12). All the data points are following the straight line. Thus the data is normally distributed. It can be seen from Figure 6.13 and 6.14 that all the actual values are following the predicted values and thus declaring model assumptions are correct.

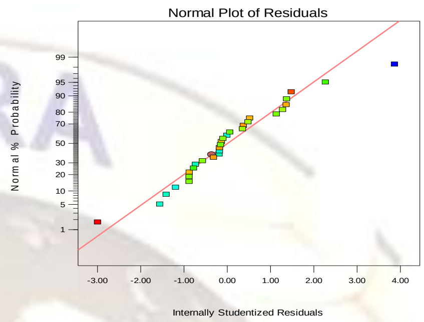

Fig 12 :Normal plot of residulals for MRR

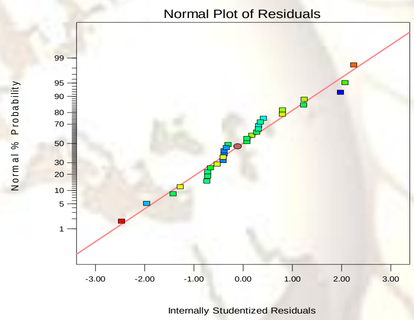

Fig 13: Normal plot of residulals for SR

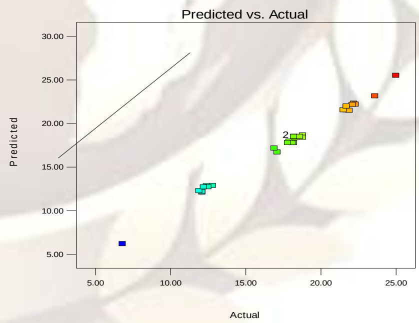

Fig 14 : Predicted v/s Actual for MRR

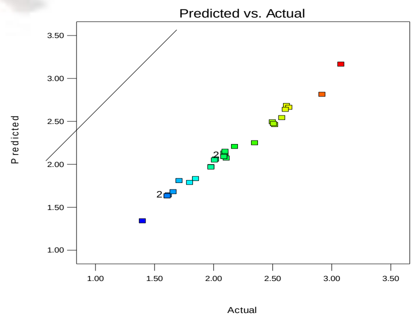

Fig 15 : Predicted v/s Actual for SR

6.4 Analysis of variance-

In order to statistically analyze the results, ANOVA was performed. Process variables having p-value<0.05 are considered significant terms for the requisite response characteristics. The insignificant parameters were pooled using backward elimination.

Table 4 : Anova table for MRR-

Source	**Sum Of Squares**	**Df**	**Mean Square**	**F-Value**	**p-Value Prob>f**	
Block	9.13	2	4.56			
Model	531.58	5	106.32	873.12	<0.0001	Significant
A-ton	467.42	1	467.42	3838.71	<0.0001	
B-toff	2.60	1	2.60	21.31	0.0001	
C-sv	0.060	1	0.060	0.49	0.4895	
A^2	3.48	1	3.48	28.62	<0.0001	
C^2	0.42	1	0.42	3.47	0.0759	
Residual	2.68	22	0.12			
Lack of Fit	2.57	20	0.13	2.41	0.3339	Not-significant
Pure Error	0.11	2	0.053			
Cor Total	543.49	29				

Table 5 : Anova table for SR-

Source	**Sum Of Squares**	**Df**	**Mean Square**	**F-Value**	**p-Value Prob>f**	
Block	0.12	2	0.059			
Model	4.75	6	0.79	253.30	<0.0001	Significant
A-ton	4.16	1	4.16	1332.02	<0.0001	
B-toff	0.19	1	0.19	60.86	0.0001	
D-Peak current	2.532E-003	1	2.532E-003	0.81	0.4895	
A^2	0.082	1	0.082	26.25	<0.0001	
B^2	9.192E-003	1	9.192E-003	2.94	0.0759	
D^2	0.012	1	0.012	3.77		
Residual	0.066	21	3.125E-003			
Lack of Fit	0.066	19	3.450E-003	2.40	0.1692	Not-significant
Pure Error	6.667E-005	2	3.333E-005			
Cor Total	4.93	29				

6.5 Multi Response Optimization Using Desirability Function-

The goal of optimization is to find a good set of conditions that will meet all the goals. It is not necessary that the desirability value is 1.0 as the value is completely dependent on how closely the lower and upper limits are set relative to the actual optimum.The constraints for the optimization of individual response chracteristics are given in table 6.1.Goals and limits are established for the response in order to accurately determine their impact on it's desirability.A set of 30 optimal solutions is derived with specific design constraints for MRR and SR.The set of condition possessing highest desirability is selectrd as optimium condition and is given in table 6.2.Desirability Plots are drawn keeping Input parameters in range,MRR maximum and SR minimum.The plots showing the effect of input parameters are shown in fig. 6.14.

Table 6 :Range of Input Parameters,MRR and SR for Desirability-

Process Parameter	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Ton	is in range	116	123	1	1	3
Toff	is in range	44	51	1	1	3
Servo Voltage	is in range	45	55	1	1	3
Peak Current	is in range	185	215	1	1	3
MRR	maximize	6.8	25	1	1	5
SR	minimize	1.4	3.08	1	1	3

Table 7 : Optimal Set of Condition with highest desirability-

S. No.	Ton	Toff	Servo-Voltage	Peak-Current	MRR	SR	Desirability	
1	**123**	**51**	**45**	**215**	**21**	**2.32**	**0.662**	**selected**

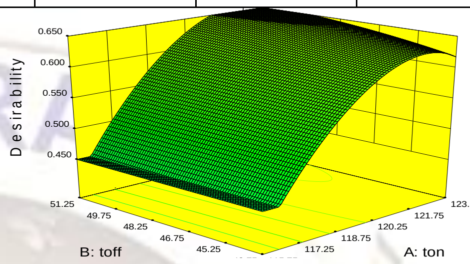

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Fig 16 : 3D Surface Graph of Desirability for MRR and SR(Ton, Toff)

6.6 Ramp function and bar function graphs-

The ramp function graphs and bar graphs drawn using Design expert shows the desirability for each factor and each response. The dot on each ramp reflects the factor setting or response prediction for that response characteristic.Bar graph shows the individual Desirability of each objective function.

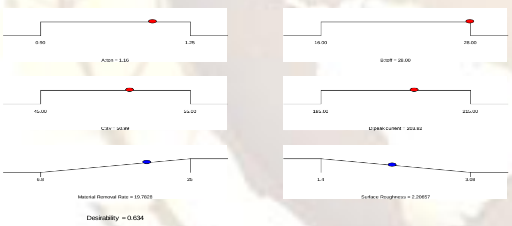

Fig 17: Ramp Graph showing desirability for MRR and SR

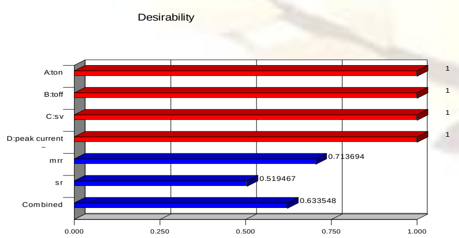

**Fig 18 : Bar Graph showing desirability for MRR
and SR**

7. CONCLUSION

In this research an experimental investigation was performed to consider the machining chracteristics of D-2 steel and following results are obtained-
1.Results shows that the Central composite design is a powerful tool for providing
experimental diagrams and statstical-mathematical models,to perform the experiments
appropriately and economically.
2.The ANOVA shows that Ton, Toff,SV has maximum influence on MRR,and Ton, Toff,
3.The peak current has a very less influence on the MRR and servo voltage has very less
Influence on SR.
4.The methodology adopted establishes the optimization of D-2 steel machining in WEDM.And facilitates the effective use of D-2 steel in industrial applications by reducing the cost of machining.

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