Experimental Investigation on EDM of Titanium Alloy using Taguchi Method

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Abstract— Electro Discharge Machining (EDM) is a newly developed non-traditional machining technique for "difficult to machine" conducting materials. In EDM, the material removal of the electrode is achieved through high frequency sparks between the tool and the work-piece immersed into the dielectric. In the present work, an investigation has been made into the electrical discharge machining process during machining of Titanium alloy (Ti-6Al-4V). Taguchi method is used to formulate the experimental layout, to analyze the effect of each process parameters peak current (I), pulse on time (T_{on}) and pulse off time (T_{off}); varied in three different levels to predict the optimal choice for each Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Roughness(SR). L9 Orthogonal array is used to conduct Experimentation. To identify the significance of parameters on measured responses, the analysis of variance (ANOVA) has been done. It is found that parameters peak current and pulse on time have the significant affect on material removal rate, tool wear rate and surface roughness. However, parameter pulse off time has less significant affect compared to the former on material removal rate. Optimal combination of process parameters was obtained to yield max MRR, min TWR and SR separately using Taguchi method. The optimal parametric setting for Maximum MRR (2.30248 mm³/min) is at Peak current: 28A (Level 3), pulse on time; 100 µs (Level 1) and pulse off time: 185 µs (Level 3). The optimal parametric setting for Minimum TWR (0.0149 mm³/min) is at Peak current: 12A (Level 1), pulse on time; 200 µs (Level 3) and pulse off time: 185 µs (Level 3) and for minimum SR (3.3505 µm) it is at Peak current: 12A (Level 1), pulse on time; 100 µs (Level 1) and pulse off time: 65 µs (Level 1). Confirmation tests are conducted at their respective optimum parametric settings to verify the predicted optimal values of each performance characteristics. The results obtained were in good agreement with the experimental values.

Key words: Electro Discharge Machining, EDM of Titanium Alloy

I. INTRODUCTION

Traditional machining processes work on the principle that the tool is harder than the work piece. Some materials, however, are too hard or too brittle to be machined by conventional methods. The use of Titanium super alloy by so many industries, for example, finds extensive use in gas turbines, rocket motors, spacecraft, nuclear reactors, pumps and cutting tools. By conventional methods their machining is not only costly but also results into poor surface finish and shorter tool life. To overcome these difficulties, a number of Newer Machining Methods have been developed. These methods are not conventional in the sense that material removal does not occur due to plastic deformation and with the formation of chips .These methods have found successful applications in several important industries for machining of components having complicated shapes made of hard materials like tungsten carbides, super-alloys, ceramics, refractory materials etc.

II. LITERATURE SURVEY

Literature provides a strong impression in relation to the scope as well as interest in the field of Electro Discharge Machining (EDM) and it reveals that traditional methods are very straightforward (consisting of a number of assumptions) and not free from limitations. Various aspects on EDM were addressed by pioneer researchers throughout the World. Dr.V.V. Reddy et.al, (2015) [1] have investigated the EDM process when both graphite powder and surfactant-mixed dielectric fluid were used during EDM of hardening stainless steel PH17-4. Taguchi parameter design approach was used to get an optimal parametric setting of EDM process parameters namely peak current, surfactant concentration and graphite powder concentration that yields to optimal process performance characteristics such as MRR, SR, white layer thickness and surface crack density. Varinder Khurana, et.al (2015) [2] reported machining mechanism of Wire cut Electrical Discharge machining. This process is based on the a continuously moving conductive wire acts as an electrode and material is eroded from the work piece by series of discrete sparks between the work piece and wire electrode separated by a thin film of dielectric fluid. The dielectric is continuously fed to the spark zone to flush away the eroded material and it acts as a coolant. This Review Research paper is based on the development and processes of WEDM.

III. DESIGN OF EXPERIMENTS AND EXPERIMENTAL DETAILS

The objective of conducting experiments is to investigate the effect of process parameters such as peak current, pulse on time and pulse off time on performance measures of EDM of Ti-6AL-4V alloy. The number of levels to use for each process parameter and level settings will depend on how much is known about the process. If a new process is being investigated, it may be desirable to run three levels to evaluate nonlinearity over the range of the process parameters. When uncertainty exists about the number of levels to choose for a given process parameter, then three levels might provide sufficient information. A lot depends on the cost of experimentation and the scope of the experiment when increased from two to three levels. When two levels are used, we can fit only a linear function. When three levels are used, we can fit a quadratic function. Similarly, when four levels are used, we can fit a cubic function. Since cost is usually a constraint in studying many levels of a factor, it would be more economical to study two level factors. If however, the quality characteristic is a very important one, then it is necessary to study 3-level factors. Hence, three levels of each factor are selected in this case. Trial experiments were conducted using one factor-at-a-time approach. The working range of peak current, pulse on time and pulse off time was investigated by checking the blind hole produced on the work piece by the tool. The working range of the selected process parameters under the present study is shown in Table. 1 when EDM Oil grade SAE240 was used as dielectric fluid. The experiments were conducted as per the OA shown in Table. 2, In Taguchi method, the effects of process parameters on performance measures are evaluated under optimal conditions. It is used to determine appropriate combination of process parameters to maximize MRR, and minimize TWR and SR. The experimental results of MRR, TWR, and SR are further transformed into a signal-to-noise ratio (S/N ratio).

Input Parameters	Peak Current I, (amp)	Pulse on Time T_{on}, (µs)	Pulse off Time T_{off},(µs)
Level 1	12	100	65
Level 2	20	150	125
Level 3	28	200	185

Table 1: Working range of the process parameters and their levels

Test case	Parameter 1 I	Parameter 2 T_{on}	Parameter 3 T_{off},
1.	1	1	1
2.	1	2	2
3.	1	3	3
4.	2	1	2
5.	2	2	3
6.	2	3	1
7.	3	1	3
8.	3	2	1
9.	3	3	2

Table 2: Experimental layout using an L9 (34) OA

The characteristic that has higher value represents better machining performance as such for MRR "higher-the-better" is appropriate. The characteristic that should has lower values for better machining performance, such as TWR and SR, is called "lower-the-better". Therefore, "higher-the-better" for the MRR and SH "lower-the-better" for TWR, and SR are selected for obtaining machining performance. Taguchi method uses the S/N ratio to measure the quality characteristic deviating from the desired value.

The S/N ratio η is defined as

$$\eta = -10 \log_{10}(MSD) \quad (1)$$

$$MSD_{MRR} = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{MRR_i^2} \quad (2)$$

$$MSD_{TWR} = \frac{1}{m}\sum_{i=1}^{m} TWR_i^2 \quad (3)$$

$$MSD_{SR} = \frac{1}{m}\sum_{i=1}^{m} SR_i^2 \quad (4)$$

After calculation of S/N ratio, the effect of each machining parameter at different levels was separated. The mean S/N ratio for each process parameter at each level was calculated by averaging the S/N ratios for the experiments at the same level for that particular parameter. Mean of means response tables and mean of means graphs for MRR, TWR, and SR are prepared by using MINITAB software.

A. Work Material

Titanium super alloy (Ti-6Al-4V) has been used as work material for experimentation. Titanium based super alloy which has excellent creep-rupture strength at temperatures up to 700°C (1300 °F).

B. Tool Material

Electrolytic copper (99.9%) of diameter ø14mm and length 60 mm was used as tool material to machine the Titanium alloy (Ti-6Al-4V).

C. Machine Tool

All the experiments were conducted on EDM machine model MOLD MASTERS605. The dielectric fluid used to conduct all the experiments is commercial EDM oil grade SAE240, and for flushing purpose, side flushing has been used during all experimental runs. The experimental set up is shown in Fig 1.

Fig. 1: Experimental set up

The experimental runs were performed based on the basis of orthogonal array L_9 (3^4). Machining time considered for conducting each experiment is 5 min. The work pieces and electrodes were cleaned and polished before machining. The work piece was firmly clamped in the vice and immersed in the dielectric.

D. Performance Characteristics

Material removal rate (MRR), tool wear rate TWR), and surface roughness (SR) were chosen to evaluate machining performance. A digital weighing balance (citizen) having capacity up to 300 grams with a resolution of 0.1gms was used for weighing the work pieces and electrodes before machining and after machining. Then the material removal rate (MRR) and tool wear rate are calculated as follows.

$$MRR\ (mm^3/\min) = \frac{\Delta T}{\rho_t \times t} \quad (5)$$

$$TWR\ (mm^3/\min) = \frac{\Delta T}{\rho_t \times t} \quad (6)$$

Where ΔW is the weight difference of work piece before and after machining (g), ρ_w is density of work material (g/mm³), ΔT is the weight difference of electrode before and after machining (g), ρ_t is density of electrode material (g/mm³) and t is machining time in minutes.

IV. RESULTS & DISCUSSIONS

Statistical analysis of various parameters has been carried out using Minitab software. Minitab 16 was used because of its wide acceptance among researchers, user friendliness and easy availability. This software is available with Minitab worksheet which is similar to the Excel worksheet in tabulated form. It can save the data in worksheet, graph format and project form. It can be used for Taguchi design as per the required levels and factor selections. Once results are stored in the worksheet then the analysis of Taguchi design can be performed. In this analysis means and signal to noise ratios are tabulated, factors are given rank based on delta values and main effects plots are extracted. The main effects plots for signal to noise ratios would be utilized for optimization purpose.

A. *Effect of process parameters on MRR*

The average values of MRR, TWR, and SR for each trial (run) and their respective S/N ratio values are presented in Table.3. Figure.2 presents main effects plot for means of MRR. Figure.3 shows main effects plot for S/N ratios of MRR. A main effects plot is a plot of the means at each level of a factor. One can use these plots to compare the magnitudes of the various main effects and compare the relative strengths of the effects across factors. However it is important to proceed to evaluate significance by looking at the effects in the analysis of variance Table. From Figures.2 and 3 it has been observed that MRR increases with increasing in peak current.

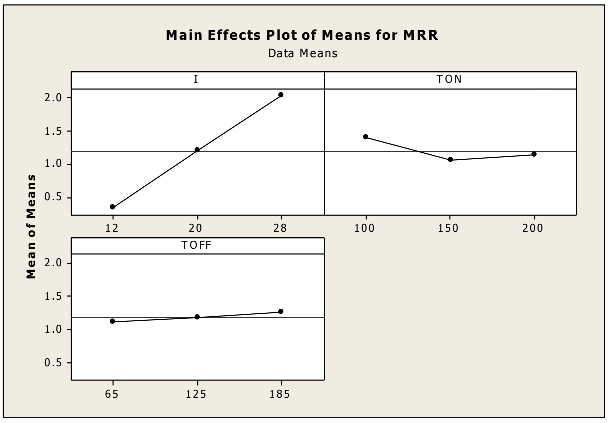

Fig. 2: Effect of process parameters on mean data of MRR

Sl. No	I	T_{on}	T_{off}	MRR		TWR		SR	
				Mean mm^3/min	S/NdB	Mean mm^3/min	S/N dB	Mean μm	S/N Db
1	12	100	65	0.49661	-6.0797	0.2942	10.626	3.351	-10.5022
2	12	150	125	0.18811	-14.512	0.3687	8.6662	3.38	-10.5783
3	12	200	185	0.35365	-9.0285	0.0149	36.537	3.48	-10.8316
4	20	100	125	1.36945	2.7309	0.3240	9.7885	3.986	-12.0107
5	20	150	185	1.15124	1.2233	0.4432	7.0679	4.572	-13.2028
6	20	200	65	1.06847	0.5753	0.4059	7.8304	5.912	-15.4336
7	28	100	185	2.30248	7.2439	0.8454	1.4584	7.023	-16.9305
8	28	150	65	1.81339	5.1698	1.0838	-0.699	8.167	-18.241
9	28	200	125	1.97141	5.8955	0.9013	0.9026	8.556	-18.6454

Table 3: Average experimental values and S/N ratios of MRR, TWR, and SR

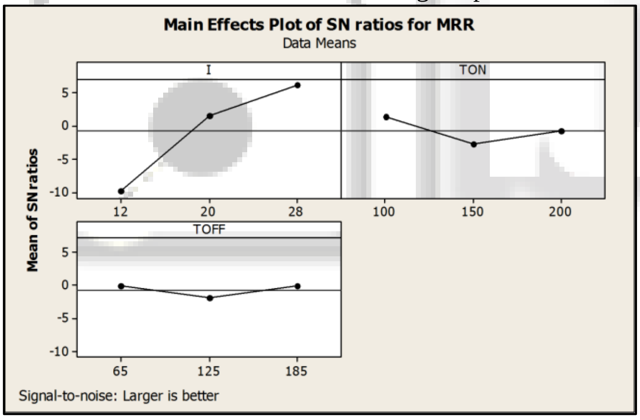

Fig. 3: Effect of process parameters on S/N Ratios of MRR

The increase in peak current causes increase in spark energy resulting in higher current density. This rapidly over heats the work piece and increases MRR with peak current. Further as current increases, discharge strikes the surface of work piece intensively which creates an impact force on the molten material in the molten puddle and this results into ejection of more material out of the crater (V.V Reddy et al, 2014). Another observation from the present experiment is that the MRR increases with increase in pulse on time. The discharge energy in the plasma channel and the period of transferring this energy in to the electrodes increases with increase in pulse on time. This phenomenon leads to formation of bigger molten material crater on the work which results in increase in MRR (V.V Reddy et al, 2014). However MRR decreases with increase in pulse off time. Since it is always desirable to maximize the MRR larger the better option is selected. Figure.3.

Suggested that when peak current is at 28A (level 3), pulse on time is at 150µs (level 1) and pulse off time is at 185µs (level 3), provide maximum MRR. Optimum value of MRR is calculated as 2.30248 (mm³/min) and corresponding S/N ratio is 7.2439 at the optimal parameter settings. Table.4 shows response Table for means of MRR. Table.5 presents response Table for S/N ratios for MRR.

Level	I	T_{on}	T_{off}
1	0.3461	1.3895	1.1262
2	1.1964	1.0509	1.1763
3	2.0291	1.1312	1.2691
Delta	1.6830	0.3386	0.1430
Rank	1	2	3

Table 4: Response Table for Means of MRR

Level	I	T_{on}	T_{off}
1	-9.8733	1.2984	-0.1115
2	1.5098	-2.7062	-1.9618
3	6.1031	-0.8526	-0.1871
Delta	15.9764	4.0046	1.8502
Rank	1	2	3

Table 5: Response Table for Signal to Noise Ratios of MRR Larger the better

The rank represents directly the level of effect of input based on the values of delta. Here according to ranks, the effects of various machining parameters on MRR in sequence are peak current, pulse on time and pulse off time.

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F	P
Current	2	4.24874	4.24874	2.12437	3481.75	0.000
Pulse on time	2	0.18783	0.18783	0.09392	153.92	0.006

Pulse off time	2	0.03157	0.03157	0.01578	25.87	0.037
Residual error	2	0.00122	0.00122	0.00061		
Total	8	4.46936				

Table 6: ANOVA for MRR (mm³/min), using Adjusted SS for Tests

S = 0.0247011 R-Sq = 99.97% R-Sq(adj) = 99.89%

Table.6 presents the ANOVA for MRR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on MRR which is as follows. The peak current, pulse on time and pulse off time are significant factors affecting the MRR since respective F values are higher than the F_{cr}.

B. *Effect of process parameters on TWR*

The average values of TWR for each trial and their respective S/N ratio values are presented in Table.3 Figure.4 presents main effects plot for means of TWR. Figure.5 shows main effects plot for S/N ratios of TWR. It is observed from Figure.4 and 5 that the increase in tool wear rate with increase in peak current as well as pulse on time. This can be explained as increase in peak current causes increase in spark energy resulting in increase in TWR. Further spark energy and the period to transfer this energy in to the electrodes increases with increase in pulse on time which results in increase in TWR. However slight increase in TWR is noticed with increase in pulse off time due to overshoot effect for some time.

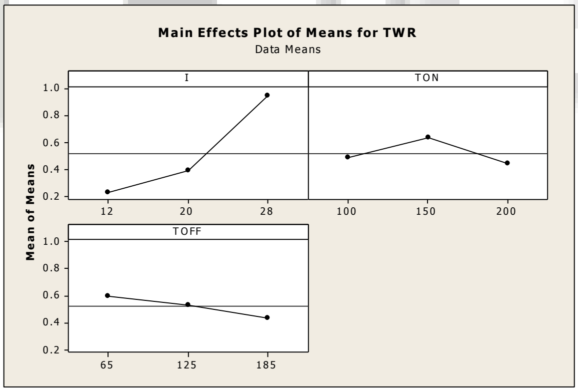

Fig. 4: Effect of process parameters on mean data of TWR

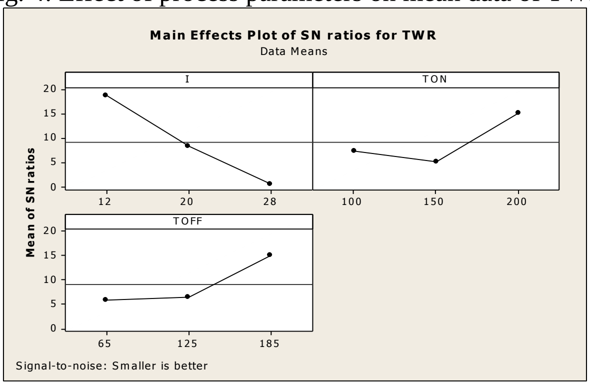

Fig. 5: Effect of process parameters on S/N ratio data of TWR

Since it is always desirable to minimize the TWR smaller the better option is selected. From the Figure.4 it is observed that minimum TWR value was achieved when peak current was at 12A (level 1), pulse on time at 200μs (level 3) and pulse of time at 185μs (Level 3). Further optimum TWR value was calculated as 0.0149mm³/min and corresponding S/N ratio is 36.5377.

Table.7 shows response Table for means of TWR.

Table 8 presents response Table for S/N ratios for TWR.

Level	I	T_{on}	T_{off}
1	0.2259	0.4879	0.5947
2	0.3911	0.6319	0.5313
3	0.9435	0.4407	0.4345
Delta	0.7176	0.1912	0.1601
Rank	1	2	3

Table 7: Response Table for Means of TWR

Level	I	T_{on}	T_{off}
1	18.6101	7.2911	5.9192
2	8.2289	5.0117	6.4524
3	0.554	15.0902	15.0213
Delta	18.0561	10.0785	9.1021
Rank	1	2	3

Table 8: Response Table for Signal to Noise Ratios of TWR Smaller the better

Here according to the ranks, the effects of various input factors on TWR in sequence are peak current, pulse on time and pulse of time. Table.9 presents the ANOVA for TWR at 95% confidence level. The data presented in the ANOVA reveals the significance of input parameters on TWR which is as follows. The peak current, and pulse on time are significant factors affecting the TWR since respective F values are higher than the F_{cr} .Where as pulse off time has not significant effect on TWR.

C. *Effect of process parameters on SR*

The average values of SR for each trial and their respective S/N ratio values are presented in Table.3 Figure.6 presents main effects plot for means of SR. Figure.7 shows main effects plot for S/N ratios of SR

Source	DOF	Seq.SS	Adj.SS	Adj.MS	F	P
Current	2	0.84737	0.84737	0.42368	88.71	0.011
Pulse on time	2	0.05952	0.05952	0.02976	6.23	0.138
Pulse off time	2	0.03903	0.03903	0.01952	4.09	0.197
Residual error	2	0.00955	0.00955	0.00478		
Total	8	0.95547				

Table 9: ANOVA for TWR (mm³/min), using Adjusted SS for Tests

S = 0.0691107 R-Sq = 99.00% R-Sq(adj) = 96.00%

Further it is observed from the Figures.6 and 7 that there is increase in surface roughness with increase in peak current. This can be attributed to the fact that increase in peak current causes increase in spark energy resulting in the formation of deeper and larger craters result in increase in surface roughness. It is also noticed that surface roughness increases with the increase in pulse on time. The spark energy and time of transferring energy in to the work piece increases with increase in pulse on time.

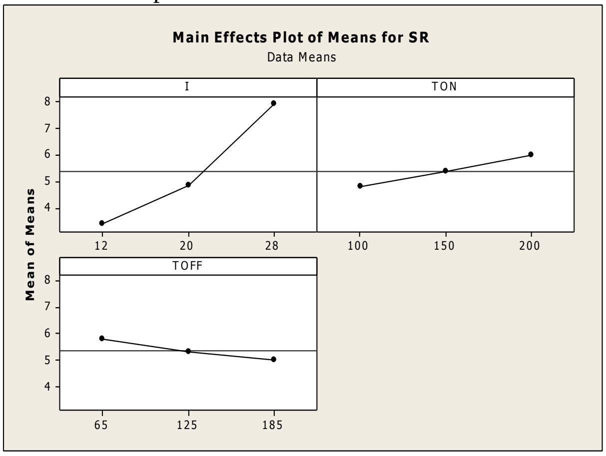

Fig. 6: Effect of process parameters on mean data of SR

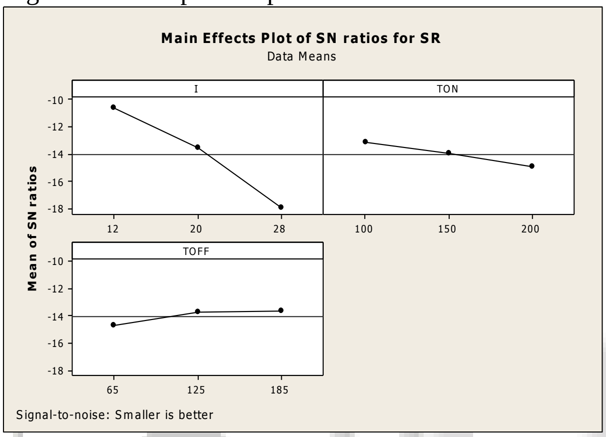

Fig. 7: Effect of process parameters on S/N ratio data of SR

This phenomenon leads to increase in formation of molten pool resulting in deeper and larger craters which again results in increase in SR (V.V.Reddy et al, 2014). However decrease in surface roughness value is observed with increasing in pulse off time. This may be due to proper removal of debris from the discharge channel. Since it is always desirable to minimize the SR smaller the better option is selected. From Figure4.6 noticed that minimum SR value is attained when peak current at 12A (level 1), pulse on time at 100µs (level 1) and pulse off time at 65µs (Level 1). Further optimum surface roughness value is calculated as 3.3505µm and corresponding S/N ratio is -10.5022. Table.10 shows response Table for means of SR. Table.11 presents response Table for S/N ratios for SR.

Level	I	T_{on}	T_{off}
1	3.403	4.787	5.809
2	4.823	5.373	5.307
3	7.915	5.982	5.025
Delta	4.512	1.196	0.784
Rank	1	2	3

Table 10: Response Table for Means of SR

Level	I	T_{on}	T_{off}
1	-10.64	-13.15	-14.73
2	-13.55	-14.01	-13.74
3	-17.94	-14.97	-13.65
Delta	7.3	1.82	1.07
Rank	1	2	3

Table 11: Response Table for Signal to Noise Ratios of SR Smaller the better

Here according to ranks, the effects of various input factors on SR in sequence of its effect are pulse on time peak current, and pulse off time. Table.12 represents the ANOVA for SR at 95% confidence level.

Source	DOF	Seq. ss	Adj. SS	Adj.MS	F	P
Current	2	31.9322	31.9322	15.9661	238.01	0.004
Pulse on time	2	2.1456	2.1456	1.0728	15.99	0.059
Pulse off time	2	0.9471	0.9471	0.4735	7.06	0.124
Residual error	2	0.1342	0.1342	0.0671		
Total	8	35.159				

Table 12: ANOVA for SR, using Adjusted SS for Tests
S = 0.259001 R-Sq = 99.62% R-Sq(adj) = 98.47%

The data presented in the ANOVA reveals the significance of input parameters on SR which is as follows. The pulse on time, peak current, and pulse off time are significant factors affecting the SR since respective F values are higher than theF_{cr}. The optimal conditions for three parameters are: Optimum condition for MRR is (A3B1C3) = 2.30248 mm³/min

Optimum condition for TWR is (A1B3C3) = 0.0149 mm³/min

Optimum condition for SR is (A1B1C1) = 3.3505 µm

D. Confirming Results

The confirmation tests for the optimal parameters with its levels were conducted to evaluate quality characteristics for EDM of titanium alloy. The predicted values were obtained by.

Predicted Response = Average of A3 + AverageofB2 + Average of C1 –2xMeanofresponse (Yij) (7)

After finding the predicted values confirmation experiments were conducted at optimal parametric setting. Further predicted values were compared with experimental results and the deviation is calculated as percentage of error corresponding to each performance characteristic and it can be calculated with the following equation.

$$\%error = \frac{experimentalvalue - predictedvalue}{experimentalvalue} \times 100 \quad (8)$$

Level	Optimal process parameters		% of error
	Predicted	Experiment	
MRR (mm^3/min)	11.7404	7.2439	-0.5199
TWR (mm^3/min)	-6.0638	36.5377	1.1659
SR (µm)	45.7374	10.5022	3.3554

Table 13: Percentage of error values between experimental predicted

The response values obtained from the experiments are MRR=11.740426mm³/min, TWR=6.06387mm³/min and SR=45.7374 µm are shown in table.13.The values shows the good agreement between the predicted.

V. CONCLUSIONS

The general conclusions of the entire work are given below:

1) Titanium super alloy can easily be machined on EDM with reasonable speed and surface finish. It is difficult to machine Titanium super alloy on conventional machining because of shorter tool life and severe surface abuse due to its high hardness and strength.
2) All the chosen responses namely MRR, TWR, and SR are increased with increase in peak current and pulse on time. However MRR and SR decrease with increase in pulse off time. Whereas non-significant increase in TWR was noticed with increase in pulse off time.
3) Further the dominant process parameters for optimum response are: I is at 28 A, T_{on} is at 100µs and T_{off} is at 185 µs yield maximum MRR (2.30248mm³/min). I is at 12A, T_{on} is at 200µs and T_{off} is at 185µs is at minimum TWR (0.0149 mm³/min). I is at 12A, T_{on} is at 100µs and T_{off} is at 65µs is at minimum SR (3.3505 µm). Confirmation experiments are conducted at respective optimal parametric settings to verify predicted optimum values.
4) Peak current pulse on time and pulse off time are significant parameters affecting MRR, TWR and SR. While pulse off time has no significant affect on TWR.

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