Electro Discharge Machining of Ti-Alloy (Ti6Al4V) and 316L Stainless Steel and Optimization of Process Parameters by Grey Relational Analysis (GRA) Method

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Abstract Increasing demand on micro-product leads to the development of innovative manufacturing process in nonconventional machining process to these micro-scale applications. In the medical field a huge variety of products can be found in prosthesis, surgery devices and tissue engineering, which required the application of the EDM process to manufacture micro cavities. Now-a-days the materials like Ti-alloy (Ti6Al4V) and 316L Stainless Steel are widely used in biomedical fields, which are very difficult to machine. These materials are also used in additive manufacturing process. Here it presents an experimental study of electro-discharge machining (EDM) of titanium alloy (Ti6Al4V) and 316L Stainless Steel. The objective of this work is to study the effect and optimization of machining process parameters like pulse-on-time, discharge current and duty cycle on process performance parameters such as material removal rate (MRR), tool wear rate (TWR) and Radial over cut (ROC). A Taguchi L9 design of experiment (DOE) has been applied and three levels of process parameters have been taken. The optimization method Grey relational analysis (GRA) method was used to optimize the parameters. The Analysis of Variance (ANOVA) also indicated the percentage contribution of machining parameters that influence response performance parameters. By the GRA method it was found that for Ti-alloy the machining parameter duty cycle (DC) has maximum percentage contribution on the output responses followed by discharge current (I_p) and pulse on time (T_{ON}). Similarly for 316L Stainless Steel the

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machining parameter discharge current (I_p) has maximum percentage contribution on the output responses followed by pulse-on-time (T_{ON}) and duty cycle (DC).

Keywords EDM · Taguchi design · Multi-response optimization method · Grey relational analysis method · ANOVA

1 Introduction

Electro discharge machining (EDM) is a non-traditional machining process, which is very widely used in recent days. In EDM both the work piece and tool are immersed inside a dielectric medium. When a voltage is applied to the work piece and tool circuit, there is a generation of spark in between the electrodes (tool and work piece). Therefore, very high temperature is generated in the spark gap region. Due to the high temperature, the material removal occurs from the work piece by the process of melting and evaporation. In EDM both tool and work piece are electrically conducting [1, 2].

Titanium is a metal with high corrosion resistance, temperature resistance and high strength to weight ratio [3]. Similarly 316L Stainless Steel have also high corrosion resistance properties. Therefore, Titanium, Ti-alloys and 316L Stainless Steel are widely used in aerospace, automobile, biomedical, electronics and chemical industries. Titanium is very strong, light weight, highly durable and long lasting metal. Ti rods, plates and pins are easily works inside the humane body for many years. Due to the non-ferrous properties of titanium implants, it can be safely examined with MRIs and NMRIs [3]. Recently Titanium is widely used in biomedical and medical field because it is easily jointed with bone and body tissue. Irrespective of this, there are certain limitations for the use of Titanium because of its initial cost is high, its availability and manufacturability, but 316L Stainless Steel is less cost as compare to Titanium and it's alloys. These two materials are also required additive manufacturing for use in aerospace and automobile application. The machining of Titanium and it's alloys by traditional machining method is very difficult due to high temperature generation and high tool wear ratio. Also to produce complex shape and micro cavities on these materials for biomedical use is difficult by the conventional machining process. Therefore, non-traditional machining processes are applied in manufacturing industries for machining of titanium, it's alloys and 316L stainless steel [4, 3]. For non-traditional machining the tool also can be made by additive manufacturing process. Recently composite tool as well as composite work piece material were made by different methods like additive manufacturing, powder metallurgy method etc. and the EDM performance were studied by the composite materials [5–13]. Some thermalstructural model of EDM also performed [14]. Here in this paper we have studied Electro discharge machining (EDM) for machining of TI-alloy (Ti6Al4 V) and 316L Stainless Steel by taking cylindrical Copper tool and optimize the process parameters that gives the

Table 1 Chemical composition (weight %) of Ti-alloy

C	Fe	Al	O	N	V	H	Ti
0.018	0.22	6.08	0.18	0.05	4.02	0–0.15	Balance

Table 2 Chemical composition (weight %) of 316L stainless steel

C	Mn	P	S	Si	Cr	Ni	Mo	N	Fe
0.03	2.0	0.045	0.03	0.75	16–18	10–14	2–3	0.1	Balance

maximum benefit to the manufacturing industries. The chemical composition of Ti-alloy and 316L Stainless Steel were presented in Tables 1 and 2 respectively.

2 Experiment

For this experimental study the work can be done by Electric Discharge Machine, model ELECTRONICA-EMS-5535/PS 50 (die sinking type) with servo-head (constant gap) and positive polarity was taken to conduct the experiments. The specification of the machine was given in Table 3. EDM oil (water:kerosene = 60:40) as used as dielectric fluid. Cylinder-shaped Cu tools (diameter 8 mm) were used with EDM oil as dielectric medium [1]. The pulse discharge current was supplied in various steps with positive mode. The EDM machine and Tool and Workpiece during machining were given in Figs. 1 and 2 respectively.

2.1 Work Piece

Work pieces of rectangular block were taken and cut into suitable pieces. These pieces were grinded properly with the help of surface grinding machine and then polished using automatic polishing machine. The final dimensions of the work pieces are 102 mm × 52 mm × 8 mm. Copper tool (stepped cylindrical size of

Table 3 Machine specification

Description	Details
Machine	ELECTRONICA
Model	EMS 5535/PS 50
Supply voltage	75 V
Discharge current	30 A
Servo system	Electromechanical
Power consumption	2 kW
Specification	X = 300 × Y = 200 × Z = 250

Fig. 1 ELEKTRA EMS 5535

Fig. 2 Tool holder with work piece and tool

diameter 8 and 5 mm having total length of 35 mm) were taken separately for each experiment. The Figures Work pieces after machining were given in Fig. 3.

2.2 Responses and Design of Experiment

In this paper we discuss about the experimental work of EDM process which is consists of design of the L-9 orthogonal array according to Taguchi design [4, 15, 16]. Orthogonal array decrease the total number of experiments, in this experiment total 9 runs have taken. Input parameters current (I_p), Pulse on time (T_{on}), Duty

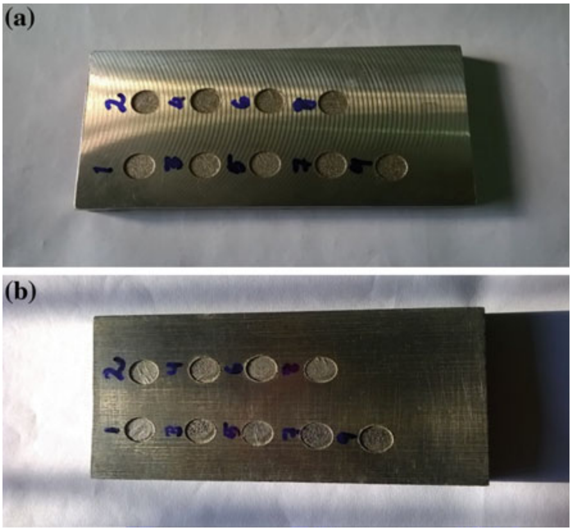

Fig. 3 Work piece material. **a** 316L stainless steel, **b** Ti-alloy (Ti6Al4V)

factor (Ʈ) or Duty cycle (DC), were taken and for different values of these the material removal rate (MRR), tool wear rate (TWR) and radial over cut (ROC) were calculated for respective 9 experiments [1, 17]. Cylindrical shaped copper tools were taken as electrodes which were diameter of 8 mm [1]. A rectangular block each of Ti-alloy (Ti6Al4 V) and 316L Stainless Steel were taken as work piece and using these copper electrodes holes were made on the work pieces [4, 3, 16]. Varying different input parameters a total 9 numbers of experiments were conducted for each work piece material. For each experiment MRR, TWR and ROC were calculated.

$$\mathrm{MRR} = \frac{W_{ji} - W_{jf}}{\rho t} \tag{1}$$

whereas

W_{ji} Initial weight of work piece before machining
W_{jf} Final weight of work piece after machining
t Machining time
ρ Density of material, For Ti-alloy $\rho = 4420\ \mathrm{kg/m^3}$, for 316L Stainless Steel $\rho = 8027\ \mathrm{kg/m^3}$

$$\mathrm{TWR} = \frac{W_{ti} - W_{tf}}{\rho t} \tag{2}$$

whereas

W_{ti} Initial weight of the tool before machining
W_{tf} Final weight of the tool after machining
t Machining time
ρ Density of tool

Table 4 Machining parameters and their level

Machining parameters	Symbol	Unit	Level 1	Level 2	Level 3
Pulse on time (A)	T_{on}	µs	100	150	200
Discharge current (B)	I_p	Ampere	40	45	50
Duty factor (C)	DC (Ʈ)	%	70	80	90

Table 5 Taguchi L9 experiment layout and output responses

Sl. No.	Input parameters			Responses (Ti-alloy)			Responses (316L S.S)		
	(mm^3/min)	(mm^3/min)	DC	MRR (mm^3/min)	TWR (mm^3/min)	ROC (mm)	MRR (mm^3/min)	TWR (mm^3/min)	ROC (mm)
1	1	1	1	0.4039	0.153	0.035	3.0913	0.328	0.030
2	1	2	2	0.5049	0.216	0.015	4.6312	0.595	0.025
3	1	3	3	0.3685	0.411	0.075	4.1946	0.670	0.015
4	2	1	2	0.3271	0.378	0.055	3.1699	0.817	0.025
5	2	2	3	0.3448	0.248	0.065	3.7468	0.582	0.050
6	2	3	1	0.3007	0.116	0.025	3.4896	0.210	0.070
7	3	1	3	0.2957	0.236	0.085	3.7558	0.583	0.025
8	3	2	1	0.2974	0.116	0.020	4.6424	0.280	0.045
9	3	3	2	0.3886	0.351	0.065	3.5594	0.438	0.080

For Copper $\rho = 8940$ kg/m^3

$$\mathrm{ROC} = \frac{D_f - D_i}{2} \tag{3}$$

where

D_f Final diameter of hole on the work piece,

D_i Initial diameter of tool.

In this process, the effects of different control parameters were studied. These machining parameters with their three levels are listed in Table 4. The Taguchi L9 experiment layout and output responses were given in Table 5.

Here the MRR, TWR and ROC were calculated using relations (1), (2) and (3).

3 Result and Discussion

3.1 Optimization Method

Ultimate aim of any manufacturer is to maximize the efficiency process by minimize the cost input which is maximizing the product quality and quantity. To achieve this goal optimization is the one of the most successful techniques applied for manufacturing processes. Optimization is the process of finding the best result with the given working parameters. It maximizes the desired benefits and minimizes the effort required.

Taguchi taken the response parameters (variables) by three different types, i.e., smaller is the better, larger is the better and nominal is the best [4, 16]. Considering that there are m experimental trials and for each trial, quality losses of a set of p response variables are calculated. Quality loss (L_{ij}) for jth response with respect to ith trial (i = 1, 2,…, m; j = 1, 2, …,p) for different types of response variables are given as follows [18]:

For smaller the better,

$$\mathrm{L}_{ij} = \left(\frac{1}{n} \sum_{k=1}^{n} y_{ijk}^{2} \right) \tag{4}$$

For larger the better,

$$\mathrm{L}_{ij} = \left(\frac{1}{n} \sum_{k=1}^{n} \frac{1}{y_{ijk}^{2}} \right) \tag{5}$$

For nominal the best,

$$\mathrm{L}_{ij} = \left(\frac{s_{ij}^{2}}{\bar{y}_{ij}^{2}} \right) \tag{6}$$

where, $\bar{y}_{ij} = \frac{1}{n}\sum_{k=1}^{n} y_{ijk}$, $s_{ij}^{2} = \frac{1}{n-1}\sum_{k=1}^{n} \left(y_{ijk} - \bar{y}_{ij}\right)^{2}$.

n is the numbers of repetitive experiments, y_{ijk} is the experimental value of jth response variable in ith trial at kth replication and L_{ij} is the calculated quality loss for jth response in ith trial.

The Signal-to-Noise ratio value $\left(\eta_{ij}\right)$ (Table 7) is obtained by putting the value of L_{ij} for the jth response in the ith trial in the equation:

$$\eta_{ij} = -10 \log 10\, \mathrm{L}_{ij} \tag{7}$$

The quality loss (L_{ij}) (Table 6) is normalized to decrease the variability among different responses. The normalized quality loss (S_{ij}) is given as:

$$S_{ij} = L_{ij} / \overline{L}_{i} \tag{8}$$

where $\overline{L}_{\mathrm{i}} = \frac{1}{m}\sum_{i=1}^{m} L_{ij}$ is the average quality loss for the jth response.

Sometimes, Signal-to-noise ratio is normalized instead of quality loss and is scaled between 0 and 1.

Table 6 Quality loss

Sl. No.	Quality loss (L_{ij}), Ti-alloy			Quality loss (L_{ij}), stainless steel		
	MRR	TWR	ROC	MRR	TWR	ROC
1	6.130	0.023	0.001,225	0.105	0.108	0.000900
2	3.923	0.047	0.000225	0.047	0.354	0.000625
3	7.364	0.169	0.005625	0.057	0.449	0.000225
4	9.346	0.143	0.003025	0.100	0.667	0.000625
5	8.411	0.062	0.004225	0.071	0.339	0.002500
6	11.059	0.013	0.000625	0.082	0.044	0.004900
7	11.436	0.056	0.007225	0.071	0.340	0.000625
8	11.306	0.013	0.000400	0.046	0.078	0.002025
9	6.622	0.123	0.004225	0.079	0.192	0.006400

Table 7 Calculation of S/N ratio

Sl. No.	S/N ratio (η_{ij}), Ti-alloy			S/N ratio (η_{ij}), stainless steel		
	MRR	TWR	ROC	MRR	TWR	ROC
1	−7.875	16.383	29.119	9.788	9.666	30.458
2	−5.936	13.279	36.478	13.279	4.510	32.041
3	−8.671	7.721	22.499	12.441	3.478	36.478
4	−9.706	8.447	25.193	10.000	1.759	32.041
5	−9.248	12.076	23.742	11.487	4.698	26.021
6	−10.437	18.861	32.041	10.862	13.565	23.098
7	−10.583	12.518	21.412	11.487	4.685	32.041
8	−10.533	18.861	33.979	13.372	11.079	26.936
9	−8.210	9.101	23.742	11.024	7.167	21.938

$$Y_{ij} = \frac{(\eta_{ij} - \eta_j^{\min})}{(\eta_j^{\max} - \eta_j^{\min})} \quad (9)$$

where Y_{ij} = scaled signal-to-noise ratio value (Table 8) for the jth response in the ith trial, $\eta_j^{\min} = \min\{\eta_{1j}, \eta_{2j}, \ldots \eta_{mj}\}$. and $\eta_j^{\max} = \max\{\eta_{1j}, \eta_{2j} \ldots \eta_{mj}\}$

3.2 Grey Relational Analysis (GRA) Method

In this method, Grey Relational Grade (GRG) value is taken as the process performance index (PPI) [19]. The steps for obtaining PPI are as follows [19, 18]:

Step 1: Calculation of the Signal-to-Noise ratio (η_{ij}) values for each response for each trial using Eq. (7).

Table 8 Scaled S/N ratio

Sl. No.	Scaled S/N ratio (Y_{ij}), Ti-alloy			Scaled S/N ratio (Y_{ij}), stainless steel		
	MRR	TWR	ROC	MRR	TWR	ROC
1	0.583	0.778	0.512	0.000	0.670	0.586
2	1.000	0.499	1.000	0.974	0.233	0.695
3	0.411	0.000	0.072	0.740	0.146	1.000
4	0.189	0.065	0.251	0.059	0.000	0.695
5	0.287	0.391	0.155	0.474	0.249	0.281
6	0.031	1.000	0.705	0.300	1.000	0.080
7	0.000	0.431	0.000	0.474	0.248	0.695
8	0.011	1.000	0.834	1.000	0.789	0.344
9	0.511	0.124	0.155	0.345	0.458	0.000

Step 2: Obtaining the scaled Signal-to-Noise ratio (Y_{ij}) (Table 8) values for each response for each trial using Eq. (9).

Step 3: Computation of the grey relational coefficients.
Grey relational coefficient (γ_{ij}) for the jth response in the ith trial is calculated as follows:

$$\gamma_{ij} = \left(\Delta_{j\min} + \xi\Delta_{j\max}\right)/\left(\Delta_{ij} + \xi\Delta_{j\max}\right) \tag{10}$$

where $\Delta_{ij} = \left|1 - \ Y_{ij}\right|,\ \Delta_{j\min} = \min\left\{\Delta_{1j},\ \Delta_{2j},\ldots,\ \Delta_{mj}\right\},$

$$\Delta_{j\max} = \max\left\{\Delta_{1j}, \Delta_{2j},\ldots,\ \Delta_{mj}\right\}$$

and ξ = distinguishing coefficient ($\xi \in [0,1]$).
The distinguishing coefficient (ξ) is used to increase or decrease the range of grey relational coefficient and is mostly taken as 0.5 [18].

Step 4: Calculating the grey relational grade (GRG_i) corresponding to ith trial as follows:

$$\mathrm{GRG_i} = \sum_{j=1}^{P} W_j\,\gamma_{ij} \tag{11}$$

where W_j is the weight for jth response and $\sum_{j=1}^{P} W_j = 1$.

3.3 Calculation of Quality Loss, S/N Ratio and Scaled S/N Ratio

The expressions for quality loss, S/N ratio and Scaled S/N ratio have been discussed in the Sect. 3.1 and calculated values are shown in Tables 6, 7 and 8 respectively.

3.4 Determination of Process Performance Index (PPI) Values and Analysis of Variance (ANOVA)

3.4.1 Grey Relational Analysis (GRA) Method

Here in the GRA method, Grey relational grade (GRG) value is taken as the process performance index value.

The GRG value calculated are shown in Table 9. The higher value of GRG gives the optimum level of input machining parameters.

3.4.2 Analysis of Variance (ANOVA)

The percentage contribution of each input parameters on the output responses can be calculated by performing ANOVA. From the ANOVA table (Tables 12 and 13) effect of the input parameters on the output responses can be calculated and the more significant parameter was obtained.

From the level average values (Tables 10 and 11) and level average values graphs (Fig. 4) for both work pieces and for all the four methods, following results

Table 9 Grey relational coefficient and grey relational grade

Sl. No.	Grey relational coefficient (γ_{ij}) Ti-alloy			Grey relational coefficient (γ_{ij}) 316L SS			GRG_i (Ti-alloy)	GRG_i (316L SS)
	MRR	TWR	ROC	MRR	TWR	ROC		
1	0.545	0.693	0.506	0.333	0.602	0.547	0.581	0.494
2	1.000	0.500	1.000	0.951	0.395	0.621	0.833	0.656
3	0.459	0.333	0.350	0.658	0.369	1.000	0.381	0.676
4	0.381	0.348	0.400	0.347	0.333	0.621	0.376	0.434
5	0.412	0.451	0.372	0.487	0.400	0.410	0.412	0.432
6	0.340	1.000	0.629	0.417	1.000	0.352	0.656	0.590
7	0.333	0.468	0.333	0.487	0.399	0.621	0.378	0.502
8	0.336	1.000	0.751	1.000	0.703	0.433	0.696	0.712
9	0.506	0.363	0.372	0.433	0.480	0.333	0.414	0.415

Mean GRG_i(Ti-alloy) = 0.525, Mean GRG_i(316L SS) = 0.546

Table 10 Level average of GRG values (Ti-alloy)

Machining parameters	Level-1	Level-2	Level-3	Δ	Rank	Optimal level
T_{on} (A)	0.598	0.481	0.496	0.117	3	L-1
I_p (B)	0.445	0.647	0.484	0202	2	L-2
DC (C)	0.644	0.541	0.390	0.254	1	L-1

Table 11 Level average of GRG values (316L SS)

Machining parameters	Level-1	Level-2	Level-3	Δ	Rank	Optimal level
T_{on} (A)	0.609	0.485	0.543	0.124	2	L-1
I_p (B)	0.476	0.600	0.560	0.124	1	L-2
DC (C)	0.599	0.502	0.537	0.093	3	L-1

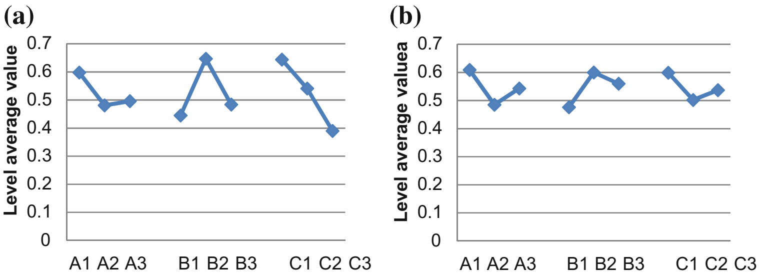

Fig. 4 Graph of level average of GRA values. **a** GRA values of Ti-alloy, **b** GRA values of 316L SS

have obtained. In GRA method, greater value of level average means better quality. So, optimal condition using GRA method for Ti-alloy and 316L SS are A1, B2, C1 and A1, B2, C1 respectively.

The contribution of each input parameters i.e. Pulse-on-time (A), Discharge current (B) and Duty cycle (C), on the performance parameters i.e. material removal rate (MRR), tool wear rate (TWR) and radial over cut (ROC) has been calculated by using Analysis of Variance (ANOVA).

In GRA method, (from Table 12 and also from Fig. 5a), for Ti-alloy it is found that duty cycle (C) has the highest contribution of 41.84 % followed by discharge current (B) and pulse-on-time (A) having contribution of 29.44 and 10.38 %

Table 12 ANOVA table for GRG values (Ti-alloy)

Machining parameters	SS	DF	MS	F	% contribution
T_{on}	0.0243	2	0.01215	0.5664	10.38
I_p	0.0689	2	0.03445	1.6061	29.44
DC	0.0979	2	0.04895	2.2821	41.84
Error	0.0429	2	0.02145	–	18.34
Total	0.2340	8	0.117	–	100

Table 13 ANOVA table for GRG values (316L SS)

Machining parameters	SS	DF	MS	F	% contribution
T_{on}	0.0231	2	0.01155	0.5179	21.83
I_p	0.0236	2	0.0118	0.5291	22.31
DC	0.0145	2	0.00725	0.3251	13.71
Error	0.0446	2	0.0223	–	42.15
Total	0.1058	8	0.0529	–	100

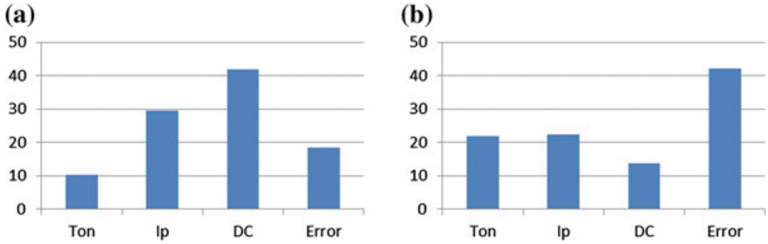

Fig. 5 Percentage contribution of input parameters for GRA method. **a** Ti-alloy, **b** 316L stainless steel

respectively. Similarly, (from Table 13 and also from Fig. 5b), for 316L Stainless Steel it is obtained that discharge current (B) has the highest contribution of 22.31 % followed by pulse-on-time (A) and duty cycle (C) having contribution of 21.83 and 13.71 % respectively.

4 Conclusion

The present study describes a solution towards improvement of quality and productivity of complex parts produced, which is allied with the accurate application of the specified performance.

The model proposed here not only explains the complex build mechanism but also present in detail the processing parameter effect on performance measure. The comparisons of EDM performances with Ti-alloy and 316L Stainless Steel as work piece materials and copper as tool have been taken. The development of multi response optimization techniques are used to optimize process parameters for better performance. The optimization of the process parameters for MRR, TWR, and Radial Overcut has been performed individually for both Ti-alloy and 316L Stainless Steel.

Using the above method in EDM process, it is found that duty cycle having maximum significant effect on the output parameters in case of Ti-alloy work piece. For 316L Stainless Steel, discharge current became more influential factor affecting response parameters.

Owing greater value of level average towards better quality in GRA method, optimal condition for Ti-alloy has been derived as A-1, B-2, C-1 and optimal GRG value is 0.644. Similarly for 316L Stainless Steel the same is A-1, B-2, C-1 with GRG value is 0.600.

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