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Influence of Parameters and Dielectric Fluids on Electric Discharge Machining of Titanium Alloy

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Abstract—*In this paper, influence of parameters such as discharge current, pulse on time, pulse off time and type of dielectric fluid on Electrical Discharge Machining (EDM) of Ti-6Al-4V has been studied. Experiments were carried out using Taguchi L27 (3^{13}) Orthogonal Layout. The process performance criteria such as material removal rate (MRR) and surface roughness (SR) are evaluated. Taguchi method was employed to optimize the process parameters such as discharge current, pulse on time and type of dielectric fluid on EDM performance of Ti-6Al-4V. Three types of dielectric fluids such as deionized water, drinking water and mixed water (25% deionized water and 75% drinking water) have been considered for machining of Titanium alloy. It has been observed from the Analysis, Drinking water as a dielectric fluid shows maximum metal removal rate and low surface roughness compared to other dielectric fluids. The lowest surface roughness value is about 2.53 µm and maximum material removal rate is 5.46 mm^3/min*

Keywords: *Electrical discharge machining (EDM); titanium alloy (Ti-6Al-4V); discharge current; pulse on time; pulse off time; Dielectric fluid*

1. INTRODUCTION

EDM is an important manufacturing process for machining hard metals and alloys [1]. This process is widely used for producing dies, moulds and finishing parts for aerospace, automotive and surgical components [2]. The process is capable of getting required dimensional accuracy and surface finish by controlling the process parameters [3]. EDM performance is generally evaluated on the basis of metal removal rate, tool wear rate and relative wear rate and surface roughness [2]. The important EDM machining parameters affecting to the performance measures of the process are discharge current, pulse on time, pulse off time, arc gap and duty cycle [4].

In EDM, high amount of heat is generated to melt the material and cooled by dielectric fluid. Thus continuous rapid heating and cooling of the material takes place. Some of molten metal resolidifies on the machined surface. This results in development of recast layer on the machined surface. Thermal stresses are produced during the impact of electric discharges on the surface. Tensile stresses are also developed within the work piece as the material removed by sparks is partly flushed away by the dielectric fluid. Due to heat generation during the process, if the dielectric fluid is hydrocarbon based, decomposes. Thus the carbon is produced which enters into the molten metal. This carbon contracts the molten metal more than the unmachined parent metal while cooling and develops stresses. Cracks are produced when these stresses are more than the ultimate tensile strength of the work piece material [5].

A considerable amount of work has been reported by the researchers on EDM of titanium alloy Ti-6Al-4V. **S.L. Chen et al (1999)** observed that the material removal rate is more and relative electrode wear rate is less when distilled water is used as a dielectric as compared to kerosene [6]. **S.K. Ho et al (2007)** found that the thickness of recast layer is increased when the powder metallurgy electrode and positive polarity is used [7]. **Ahmet Hascalik et al (2007)** compared performance of copper, graphite and aluminum electrodes. It was noticed that material removal rate is more in case of graphite electrode and surface roughness is less in aluminum electrode compared to other electrodes [8]. **Peter Fonda et al (2008)** observed that the optimal duty factor is 7% as far as productivity and quality of EDMed surface are concern [9]. **Sueleiman Abdulkareem et al (2009)** revealed that the copper electrode wear is reduced remarkably and surface finish is improved due to cryogenic cooling [10].

Ti-6Al-4V possesses high strength, low weight ratio, high corrosion resistance, resistance to high temperature and high toughness. This makes it successfully used for surgery, medicine, aerospace, automotive, chemical plant, pressure vessels and power generation. It is used to manufacture propeller shafts, rigging and other parts of boats. It also used to create artificial hips, pins for setting bones and other biological implants due to its excellent biocompatibility. Its application also includes aircraft turbine components, aircraft structural components, aerospace fasteners and high performance automotive parts [11-12].

Ti-6Al-4V is one of the materials difficult to machine due to its properties. It chemically reacts with almost all cutting tool materials. Its low thermal conductivity and low modulus of elasticity reduces the machinability [13]. Low cutting speeds, high feed rates, huge quantity of cutting fluids, sharp tools and rigid set up are essential for the conventional machining of Ti-6Al-4V. This makes its conventional machining uneconomical. EDM is one of the advance manufacturing process by which Ti-6Al-4V can be machined economically and efficiently [14]. However, it has been found that results are not available on optimization of EDM process parameters using Taguchi method of this material. Therefore, it is imperative to develop a suitable technology guideline for optimization of EDM parameters of Ti-6Al-4V using Taguchi method.

In EDM, for optimum machining performance measures, it is an important task to select proper combination of machining parameters [15]. Generally, the machining parameters are selected on the basis of operator's experience or data provided by the EDM manufactures. When such information is used during EDM, the machining performance is not consistent. Data provided by the manufacturers regarding the parameter settings is useful only for most commonly used materials. Such data is not available for special materials like titanium alloy, ceramics and composites. For these materials, experimental optimization of performance measures is essential. Optimization of EDM process parameters becomes difficult due to more number of machining variables. Slight changes in a single parameter significantly affect the process. Thus it is essential to understand the influence of various factors on EDM process. Analytical and statistical methods are used to select best combination of process parameters for an optimum machining performance.

The present work describes the optimization of the EDM performance measures using Taguchi method. In this method it is required to consider all aspects of the design that affect the deviation of functional characteristics of the product from target values. It is also essential to consider methods to reduce undesirable and uncontrollable factors that can cause functional deviations [16]. It is possible to evaluate the effects of individual parameter independent of other parameters and interactions on the identified quality characteristics by using this method [17-18]. Taguchi method is one of the popular methods used for optimization as it requires minimum experimental cost and decreases the effect of the source of variation effectively [19].

2. SCHEME OF INVESTIGATION

In order to maximize the desirable performance measures and minimize undesirable performance measures, the investigation was done in the following sequence:

- Selection of work piece material and electrode material.
- Identify the important EDM process parameters.
- Determine the working range of the identified process parameters.
- Select the orthogonal array (OA) (design of matrix).
- Conduct the experiments as per the selected OA.
- Record the performance measures (i.e. MRR, SR.
- Find the optimum condition for performance measures and identify the significant factors.
- Conduct the confirmation test.

2.1 Selection of the work piece material and electrode material

The work piece material employed in this study was Ti-6Al-4V. Copper was selected as an electrode material as it is commonly used due to its high thermal conductivity and electrical conductivity. The chemical composition and properties of Ti-6Al-4V are shown in Table 1 and Table 2, respectively.

Table 1: Chemical Composition of Ti-6Al-4V

Element	C	Al	V	N	O	Fe	H	Ti
%	Max. 0.08	5.5-6.5	3.5-4.5	0.05	0.13	0.25	0.01	Balance

Table 2: Properties of Ti-6Al-4V

Property	Quantity
Hardness (HRC)	36
Melting point (0C)	1649
Density (g/cm3)	4.5
Ultimate tensile strength (MPa)	897-1000
Thermal conductivity (W/m0K)	7.2
Specific heat (J/kg0K)	560
Mean coefficient of thermal expansion 0-1000C/0C	8.6x10-6
Volume electrical resistivity (ohm-cm)	170
Elastic Modulus (GPa)	114

2.2 Identify the important EDM process parameters

On the basis of the literature and previous work done, it was concluded that the most important EDM process parameters which has greater influence on the MRR and SR are Dielectric fluid, discharge current, pulse on time and pulse off time.

2.3 Determination of the working range of the process parameters

A large number of trials were conducted by varying one of the process parameters and keeping the other parameters constant. The working range of discharge current, pulse on time and pulse off time was explored by inspecting the blind hole produced in the work piece by the electrode. The working range of the process parameters selected under the present study is indicated in Table 3.

Table 3: Working range of the process parameters and their levels

Parameters	Levels		
Dielectric fluid(A)	Deionised water	Drinking water	Mixed (25% deionised water+ 75% drinking water)
Discharge current (B)	10	15	20
Pulse on time(C)	25	45	65
Pulse off time(D)	24	36	48

2.4 Selection of OA

In this study, the number of process parameters considered were four, and the level of each parameter was three. The degrees of freedom of all four parameters were two (i.e. number of levels-1) and the interaction between A and B, A and C and A and D are considered. The degree of freedom of all the interactions is 6. The total degree of freedom of the entire factor (i.e. 4×2 = 8) and the interactions (i.e 3X 2=6) is 14. The selected Orthogonal Arrays (OA) degrees of freedom (DOF) (i.e. number of experiments – 1= 27 – 1 = 26) must be greater than the total DOF of all the factors and the interactions (14). Hence, **L_{27} (3^{13})** OA is considered for the present study. Two trials of each experiment were conducted to average of these values to minimize the pure experimental error. The selected OA is presented in Table 4.

Table 4: Experimental layout using an L_{27} (3^{13}) OA

Exp. No.	Dielectric fluid(A)	Discharge current (B)	Pulse On Time (C)	Pulse Off Time (D)
1	Deionized	10	25	24
2	Deionized	10	45	36
3	Deionized	10	65	48
4	Deionized	15	25	36
5	Deionized	15	45	48
6	Deionized	15	65	24
7	Deionized	20	25	48
8	Deionized	20	45	24
9	Deionized	20	65	36
10	Drinking	10	25	24
11	Drinking	10	45	36
12	Drinking	10	65	48
13	Drinking	15	25	36
14	Drinking	15	45	48
15	Drinking	15	65	24
16	Drinking	20	25	48
17	Drinking	20	45	24
18	Drinking	20	65	36
19	Mixed	10	25	24
20	Mixed	10	45	36
21	Mixed	10	65	48
22	Mixed	15	25	36
23	Mixed	15	45	48
24	Mixed	15	65	24
25	Mixed	20	25	48
26	Mixed	20	45	24
27	Mixed	20	65	36

2.5 Conduct the experiments as per the selected OA

The work piece material of 60 mm in diameter and 6 mm thick and the electrode of 12 mm diameter were used. The experiments were conducted as per the layout shown in Table 4. A Formatics EDM 50 die sinking machine with Electronica PSR-20 controller was employed for conducting the EDM experiments. Each experiment was conducted for thirty minutes duration. Prior to machining, the work pieces and electrode were cleaned and polished. The work piece was firmly clamped in the vice and immersed in different dielectric fluids. The negative polarity was used during the experiments. The schematic diagram of die sinking EDM machine and experimental set up is shown in Fig. 1 and Fig. 2, respectively.

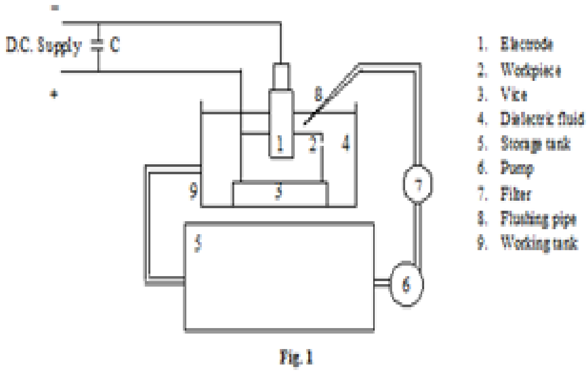

Fig. 1: Schematic diagram of EDM machine

Fig. 2: Experimental set up

2.6 Record the performance measures (i.e. MRR and SR)

The machining performance measures were evaluated by MRR, SR.

The MRR is the work piece weight loss (WWL) under a period of machining time in minutes

$$MRR\ (mm^3/min) = \frac{WWL\ (g) \times 1000}{\rho\ (g/cm^3)\ \times machining\ time(min)}$$

ρ = Density of work piece material

The SR is referred to the roughness or smoothness of a given surface. In this study, it was measured in terms of R_a (Roughness average), which is an arithmetic average of peaks and valleys of a work piece surface measured from the centerline of evaluation length. It was measured by Zeiss (Make:Surcom 130A) surface roughness tester. The machining performance measures i.e. MRR and SR were evaluated for all the conditions and presented in Table 5.

Table 5: Average results of MRR and SR

Exp. No.	Dielectric (A)	Discharge current (B)	Pulse ON Time(C)	Pulse OFF Time(D)	Average MRR(mm3/min)	Average SR (Ra) (µm)
1	Deionized	10	25	24	2.09175	2.25
2	Deionized	10	45	36	2.19472	2.49
3	Deionized	10	65	48	2.46345	3.00
4	Deionized	15	25	36	2.5608	2.51
5	Deionized	15	45	48	4.05	3.48
6	Deionized	15	65	24	3.2522	3.22
7	Deionized	20	25	48	3.4784	3.47
8	Deionized	20	45	24	4.43515	2.78
9	Deionized	20	65	36	4.776	3.63
10	Drinking	10	25	24	1.966	2.68
11	Drinking	10	45	36	2.2922	2.95
12	Drinking	10	65	48	2.41405	2.94
13	Drinking	15	25	36	3.21775	2.61
14	Drinking	15	45	48	4.11685	2.72
15	Drinking	15	65	24	3.3091	3.06
16	Drinking	20	25	48	3.89725	2.93
17	Drinking	20	45	24	4.4074	3.10
18	Drinking	20	65	36	4.5758	3.22
19	Mixed	10	25	24	2.26895	2.91
20	Mixed	10	45	36	2.4754	3.03
21	Mixed	10	65	48	2.7267	3.18
22	Mixed	15	25	36	3.5737	2.76
23	Mixed	15	45	48	4.18	2.89
24	Mixed	15	65	24	3.44735	3.40
25	Mixed	20	25	48	4.02855	3.12
26	Mixed	20	45	24	4.61275	3.48
27	Mixed	20	65	36	4.81545	3.49

2.7 Find the optimum condition for performance measures and identify the significant factors.

In Taguchi method, the effects of process parameters on performance measures are evaluated under optimal condition. It is used to determine appropriate combination of process parameters to maximize MRR and minimize SR. The experimental results of MRR and SR were further transformed into a signal-to-noise ratio (S/N) ratio. The characteristic that higher value represents better machining performance, such as MRR, is called ‘higher the better’. The characteristics that lower the value represents better machining performance, such as SR is called ‘lower the better.’ Therefore, “higher the better” for the MRR, and “lower the better” for SR were 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

$$\eta = -10\log(M.S.D) \qquad (1)$$

Where M.S.D. is the mean-square deviation for the output characteristic.

To obtain optimal EDM performance, higher the better quality characteristic for material removal rate from work piece must be taken. The mean-square deviation (M.S.D.) for higher the better quality characteristic can be expressed as

$$M.S.D. = \frac{1}{m}\sum_{i=1}^{m}\frac{1}{MRR_i^{\ 2}} \qquad (2)$$

Where *m* is the number of tests and MRR $_i$ is the value of MRR and *i* ^{the} test.

On the other hand, lower the better quality characteristics for SR should be taken for obtaining optimal EDM performance. The M.S.D. for lower the better quality characteristic can be expressed as:

$$M.S.D. = \frac{1}{m}\sum_{i=1}^{m} SR_i^2 \qquad (3)$$

Where SR_i^2 is the value of SR for the *i* th test

The average experimental results of MRR, SR and their corresponding S/N ratios using equations (1) to (3).

The optimization of process parameters using Taguchi method permits evaluation of the effects of individual parameters independent of the other parameters [20]. The analysis of variance (ANOVA) is used to determine which design parameters significantly affect the performance measures. In ANOVA, first total sum of squared deviations SS_T from total mean S/N ratio η_m can be calculated as

$$SS_T = \sum_{i=1}^{n}(\eta_i - \eta_m)^2 \qquad (4)$$

Where *n* is the number of experiments in the orthogonal array and η_i is mean S/N ratio for *i* ^{the} experiment.

ANOVA was applied to find out the significance of main factors and the *F*-test was used to determine the process parameter significantly effect on the responses (MRR and SR). Usually, the change of the EDM process parameter has significant effect on the response when *F* ratio is large. The results of ANOVA for MRR and SR are presented in Table 6 and Table 7 respectively.

Table 6: ANOVA analysis for material removal rate (MRR)

Factor	Sum square	Degrees of freedom	Mean sum of square	Per.contribution (%)
(A)	10.78	2	5.39	5.58
(B)	153.72	2	76.86	79.69
(AXB)	0.67	4	0.16	0.34
C	19.33	2	9.66	10.02
AXC	2.45	4	0.61	1.27
D	1.45	2	0.72	0.75
AXD	1.02	4	0.25	0.53
Error	3.44	6	0.57	1.78
St	192.88	26		100

Table 7: ANOVA analysis for surface roughness (SR)

Parameter	Sum square	Degrees of freedom	Mean sum of square	Per.contribution
(A)	4.510561504	2	2.25	12.22
(B)	8.579256394	2	4.28	23.25
(AXB)	3.730956924	4	0.93	10.11
C	12.35823198	2	6.17	33.49
AXC	0.048866944	4	0.012	0.13
D	2.352982883	2	1.176	6.37
AXD	1.635441424	4	0.408	4.43
Error	3.678515757	6	0.613	9.97
St	36.89481381	26		100

ANOVA also provides an indication of which process parameter combination is predicted and the optimum results. These optimum results and validation of the optimum results are presented in Table 8.

2.8 Conduct the confirmation test

Optimum levels of design parameters were used for prediction and confirmation of the performance measures improvement. The estimated S/N ratio, $\hat{\eta}$ using the optimal level of the design parameters can be calculated as:

$$\hat{\eta} = \eta_m + \sum_{i=1}^{o}\left(\hat{\eta}_i - \eta_m\right) \qquad (5)$$

Where η_m is the total mean S/N ratio, $\hat{\eta}_i$ is the mean S/N ratio at the optimal level, and so is the number of main design parameters that affect the quality characteristic.

For validations of the optimum results, experiments were conducted as per the optimum conditions for MRR and SR and the results are presented in Table 8.

Table 8: Validation of optimum results It is observed that, experimental values are closer to the optimum values.

Parameter	Optimum condition	Predicted Optimum value	Experimental values
MRR (mm3/min)	A2B3C3D3	5.46	5.90
SR (µm)	A2B1C1D1	2.53	2.98

3. RESULTS AND DISCUSSIONS

3.1 Analysis of Variance (ANOVA)

The ANOVA is performed to find the effect of process parameters on various performance measures. F-values are used to determine the relative significance of various process parameters. From the ANOVA analysis shown in Table 6 and Table 7, it is observed that the dielectric fluid (A), pulse on time (C) is the most significant factor affecting to MRR and SR... It is observed from the ANOVA tables that discharge current (A) and pulse off time (B) have a high percentage of contribution on various performance measures as compared to pulse off time (C).

3.2 Effect of machining parameters on MRR

Fig. 6 shows ANOVA results for MRR. It is observed that as the dielectric fluid from deionized water to drinking water the MRR increases and after that it is decreases in mixed condition (25% deionized water + 75% drinking water)

It is observed that as the discharge current increases from 10A to 20A, the MRR increases significantly. The amount of heat energy supplied to remove the material is controlled by the discharge current. So as the discharge current increases, this energy also increases. Thus the MRR is lower at 10A and increases with increase in discharge current to 20A. The contribution of discharge current is 79% and it is the first significant factor. The pulse on time controls the duration of time for which the current is allowed to flow per cycle. The material removed is directly proportional to the amount of energy supplied during this period. Thus it is the most significant factor as far as contribution and significance is concerned. As the pulse on time increases from 25µs to 65µs, the MRR also increases almost nonlinearly. Its contribution is 10%. Pulse off time is the least significant factor and shows minimum contribution. This is due to the fact that no material is removed from the work piece as there is no discharge current supplied. Its contribution towards MRR is 0.7%. It is observed that as the pulse off time increases from 24µs to 48µs, the MRR is improved by very small amount. At minimum pulse off time 24 µs, the dielectric fluid gets less time to deionize and flush away the debris. As the pulse off time increases to 48 µs, the dielectric fluid gets sufficient time to de-ionize and to flush away the debris. Thus stability of the machining process enhanced and hence MRR is improved.

3.3 Effect of machining parameters on SR

Fig. 7 presents ANOVA for SR. It is observed that as the dielectric fluid from deionized water to drinking water the SR decreases and after that it is increases in mixed condition (25% deionized water + 75% drinking water) .It shows that as the discharge current increases from 10A to 20A, the SR slightly decreases nonlinearly. The amount of heat energy supplied to remove the material is controlled by the discharge current. So as the discharge current increases, the bombarding impulsive force of electrons also increases. In case of negative polarity, the bombardment of electrons takes place from work piece to electrode. This resulted in deposition of material on the machines surface causing reduction of surface roughness. The SR is higher at 10A as the amount of material deposited is less. When the discharge current at 20A, the larger impulsive force produces deeper and greater craters are deposited with more amount of material. Hence the surface roughness is lower. The contribution of dielectric fluid on the SR is 12% and it is the third largest. The contribution of discharge current is 23% and its significance is the second largest. The pulse on time controls the duration of time for which the current is allowed to flow per cycle. The material removed from the electrode is directly proportional to the amount of energy supplied during this period due to negative polarity. Thus it is the most significant factor. As the pulse on time increases from 25μs to 65μs, the SR also decreases almost linearly. Its contribution is 33%. Pulse off time is the least significant factor and shows minimum contribution as far as SR is concerned. This is due to the fact that no material is removed from the work piece as there is no discharge current supplied. Its contribution towards SR is 6%. It is observed that as the pulse off time increases from 24μs to 48μs, the SR is improved by very small amount. At minimum pulse off time 24μs, the dielectric fluid gets less time to de-ionize and flush away the debris. As the pulse off time further increases to 48μs, the dielectric fluid gets sufficient time to de-ionize and to flush away the debris. Thus stability of the machining process enhanced and hence SR is improved.

4. CONCLUSIONS

In this study, the influence of dielectric fluid i.e deionized water, drinking water and mixed (25% deionized water + 75% drinking water), the process parameters and optimization of titanium alloy (Ti-6Al-4V) in the die sinking EDM was studied by using Taguchi method. From the results it was found that drinking water, discharge current, pulse on time and pulse off time have been found to play significant role in EDM operations. Also, it was found that the optimal levels of the factors for MRR and SR are differing from each other. From ANOVA, pulse on time is more significant than discharge current for SR whereas discharge current is more significant than pulse on time for MRR. On the other hand interaction between dielectric fluid and discharge current is also significant in case of SR.

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