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Optimization of EDM parameters on machining Ti-6Al-4V with a core electrode using grey relational analysis

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Abstract:

This paper represents the optimization of the electric discharge machining (EDM) of Titanium alloy (Ti-6Al-4V) with a core electrode using grey relational analysis. Experimental results confirm that the electrolytic copper electrode with central and eccentric through-holes has the optimum performance for machining from various aspects. Three observed values, material removal rate (MRR), electrode wear rate (EWR), and surface roughness (Ra,) verify this optimization of the machining technique. In addition, seven independent parameters are chosen as variables in evaluating the Taguchi method and are categorized into two groups: electrical parameters and non-electrical parameters. Moreover, analysis of the Taguchi method reveals that the electrical group has a more significant effect than the non-electrical group on the machining characteristics. Furthermore, either the pulse on duration or the peak current most prominently affects the MRR, SR or EWR amongst all of the parameters, whereas none of the non-electrical group has an equal affect. To overcome the limitations of Taguchi methodology which can only optimize only one output parameter at a time “The Grey Relational Analysis” has been done.

Key Words: Electro-discharge machining (EDM), Material removal rate (MRR); Electrode wear rate; Surface roughness; High speed machining.

1. Introduction:

The aerospace industry is the single largest market for titanium products primarily due to the exceptional strength- to- weight ratio, elevated temperature performance and corrosion resistance. Titanium applications are most significant in jet engine and airframe components that are subject to temperatures up to 600^0 C and for other critical structural parts [1]. Although high speed machining (HSM) can increase the productivity there are certain characteristics of titanium that poses limitations on its machinability. Some of these are given as follows:

1) Titanium alloy (Ti-6Al-4V) has low thermal conductivity, so heat does not dissipate easily from the tool-chip interface, the tool gets heated quickly due to the resulting high temperatures, and this leads to lower tool life.
2) Titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures. This causes welding and smearing along with rapid destruction of the cutting tool.
3) Titanium has a relatively low modulus of elasticity, thereby having more “springiness” than steel. Work has a tendency to move away from the cutting tool unless heavy cuts are maintained or proper backup is employed. Slender parts tend to deflect under tool pressures, causing chatter, tool rubbing and tolerance problems. Rigidity of the entire system is consequently very important, as is the use of sharp, properly shaped cutting tools.
4) Higher temperature produced in conventional machining of Ti–6A1–4V is due to their poor thermal diffusivity. Therefore, the cutting tool is subjected to rapid tool wear and responsible for deterioration of the surface condition [2].

Although the EDM process is not affected by material hardness and strength, it is a much slower process compared to other pre-processes. To increase its speed, a large electrical current discharge is normally used, but this will inevitably compromise the dimensional accuracy of the machined product. The EDM process can be very unstable due to arcing when too much debris clogs the gap. Therefore the question is how to develop an EDM process with the capability of high speed machining, high accuracy and precision without any major alterations to the EDM system Experts are in constant pursuit of improving the performance of EDM machining. In the past few years, the Taguchi method has played an important role in the optimization of process parameters. However, many of the studies focused on static or single-quality characteristics such as smaller-is-better, larger-is-better, and nominal-is- best, and classified attributes [3]. The application of this method using functional quality, or dynamic signal-to-noise S/N ratio, provides solutions to all three aspects of technologies, flexibility, and reproducibility. To meet the challenges of a rapidly changing world, the EDM technology must have the process capabilities of high speed, high accuracy and precision, versatility, and robustness. Hence, the purpose of this study is an attempt to apply a “robust technology development” approach of Taguchi methods for optimizing the EDM machining process so as to achieve the above goals. A non-traditional machining method, such as electrical discharge machining EDM has therefore been employed to machine titanium alloy Ti – 6Al – 4V, using electrolytic copper with multi hole tubular electrode.

In case of EDM, higher amount of thermal energy is released which influences the characteristics of the EDMed surface. The surface quality in EDM, is therefore, directly influenced by the discharge current and dielectric flushing in combination with tool electrode and work material. Further, good surface integrity is an essential requirement of the aerospace components those are thin, complex and demands higher dimensional stability. As these components are subjected to severe and hostile environment and operates under cyclic loading conditions, a good surface integrity is essential. Hence, optimized selection of process parameters related to work material, electrode and process conditions is necessary to achieve lower surface roughness and improved surface integrity in EDMed surfaces [4].

2. Literature Review:

The quality of a machined surface is becoming more and more important to satisfy the increasing demands of sophisticated component performance, longevity, and reliability. Structures for military and commercial aerospace, automotive, and other capital goods industries are being subjected to more severe conditions of stress, temperature, and hostile environments. In response to the above needs, there has been a continued increase in the development and use of heat resistant, corrosion resistant and high strength alloys in the wide variety of structural applications. Ti-6Al-4V is one of the alloys of titanium that is best suited for these types of applications [8].

It has been accepted worldwide as a standard process in manufacture of forming tools to produce plastic moulds, die castings, forging dies etc. New developments in the field of material science have led to new engineering metallic materials, composite materials, and high tech ceramics, having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion [4].

Ti Grade 5 (Ti-6Al-4V) R56401 titanium alloy falls under the class of engineered material, which is developed specifically for severe environmental working condition. This alloy is extensively used in manufacturing of the aerospace components because of the combination of high strength-to-weight ratio, excellent fatigue properties, and fracture toughness and corrosion resistance [5].

WEDM is a special form of EDM in which the electrode is a continuously moving conductive wire. In this, the spark discharges are generated between the wire electrode and work piece with demonized water as a dielectric medium [6].

While in case of die sinking EDM dielectric fluid used is IOPL EDM oil. A typical die-sinking EDM is shown in Figure. 2.1. Material removal rate achieved by EDM is in the range from 800 to 3000 mm^3/min. The surface finish (Ra) obtained is in the range from 2.5 to 30 µm for rough machining whereas surface finish up to 0.2 µm can be achieved in finishing cuts [9].

3. Motivation and Objectives:

The goal of this research is to determine the possible effects of EDM Machining parameters on the Ti–6A1–4V, a titanium alloy, which is applied widely in the aerospace industries. With its high melting temperature and low thermal conductivity, it belongs to the group of difficult-to-cut materials, not suitable for traditional machining. A non-traditional machining method, such as electrical discharge machining (EDM) has therefore been employed to machine titanium alloy. Currently most of the researchers and engineers are interested in Ti–6A1–4V, to variety of design problems in industrial applications. Keeping the above in mind, it is proposed to investigate the effect of EDM parameters on machinability and also the surface integrity to achieve dimensionally stable and acceptable component. Therefore, overall objectives of the paper are as follows:

1. To examine the influence of process parameters such as current, duty cycle, tool type, tool working time, voltage, retraction distance R_D and flushing pressure using Taguchi experiments on dependant variables like material removal rate, electrode wear rate, and surface roughness (Ra).
2. To observe the quality of the drilled holes by visual inspection as over cut, recast layer.

4. Principles of EDM:

EDM is the process of electrically removing material from any conductive work piece. This is achieved by applying high frequency pulsed, A.C. or D.C. current through the electrode or wire, which melts and vaporizes the work piece. Positioned very precisely near the work piece, the electrode never touches the work piece but discharge its potential current through an insulating dielectric fluid (water or oil) across a very small gap. The spark is reported in the range of 8,000C to 12,000^{0}C and it vaporizes the work piece material.

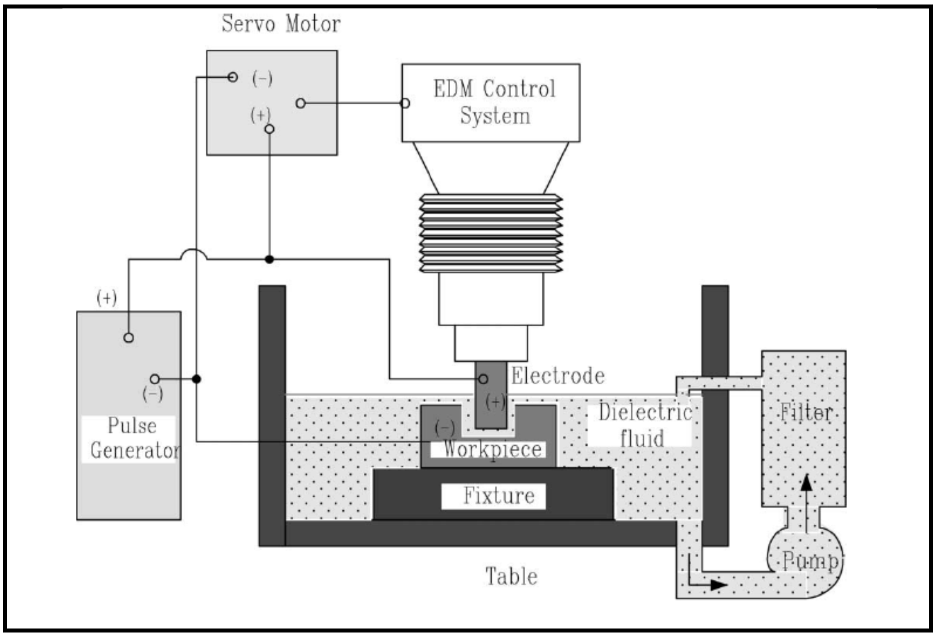

Figure 1 Typical Die-sinking EDM [31]

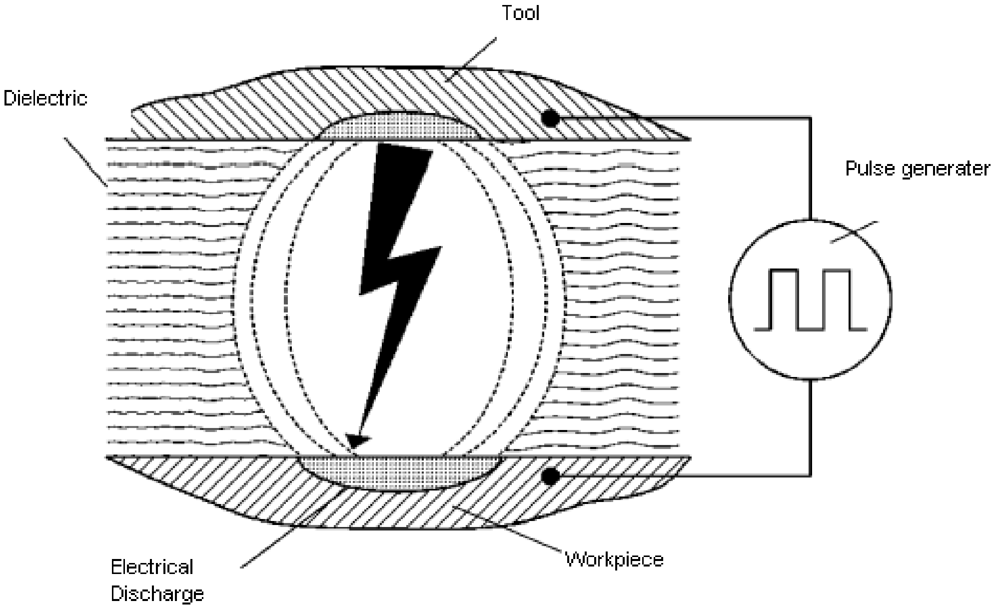

Figure 2 Working Principle of EDM [52]

Therefore, it is extensively applicable in tool and die manufacturing and for machining of precision parts made of materials such as high strength steel, tungsten carbides, hardened alloy steel, titanium alloy, ceramics and composite or other intricate parts. A thermo-electric theory is utilized in EDM based on three stages as described below [10, 31].

1) Ionization and arc formation at a localized area between electrodes, following the application of voltage exceeding the breakdown voltage.
2) The occurrence of the main discharge as an electron avalanche striking the anode; low electrical resistance in the discharge channel causes hydraulic restriction of the dielectric and the magnetic pinch effect which establish high current densities. The cathode is struck by ions and is heated less rapidly than the anode.
3) Local melting and evaporation occurs and material is removed from the site of discharge by explosion, which produced after the cessation of electrical discharge.

The current density decreased with increase in discharge duration and the discharge becomes an arc. De-ionization of the plasma channel occurs after the completion of the whole cycle and a new cycle starts at the site of the closest electrode distance.

5. Experimental procedure:

Titanium Alloy Ti – 6Al – 4V was drilled using electrolytic copper 99%, pure copper electrode of Ø20 mm. Negative polarities was maintained for the tool and positive polarity for the work piece. Weight of each electrode was measured with a single pan electrical weight balance (1mg). The work material was mounted on T-slot table and positioned at desired place and clamped with fixtures. The electrode was clamped in collate and X-Y coordinates were set to zero. The electrodes were gripped with the help of collate Ø 20 mm and fed downwards into the work piece under servo control. During all experiments, pump was kept continuously running for circulating dielectric fluid. A depth of 1 mm was set for the machining of all work specimens. Input parameters as selected were set on the machine for each experiment. After machining, the electrode was removed and weighed again. A surface roughness (Ra) in μm was measured using portable roughness tester. Each experiment was repeated once. Similar procedure was repeated for different electrode shapes and process parameters. Figure 3 shows the systematic procedure of the experiment.

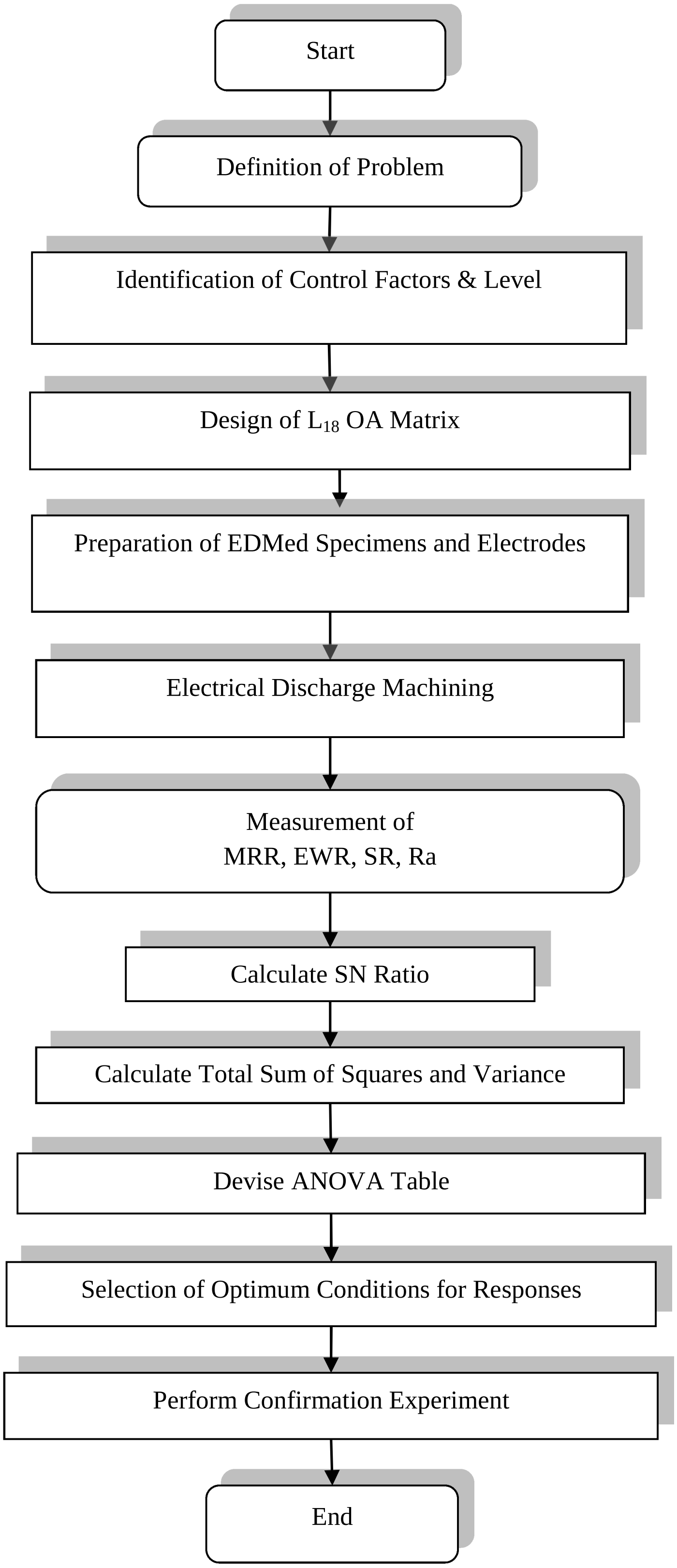
Start
Definition of Problem
Identification of Control Factors & Level
Design of L18 OA Matrix
Preparation of EDMed Specimens and Electrodes
Electrical Discharge Machining
Measurement of
MRR, EWR, SR, Ra
Calculate SN Ratio
Calculate Total Sum of Squares and Variance
Devise ANOVA Table
Selection of Optimum Conditions for Responses
Perform Confirmation Experiment
End

Figure 3 Experimental Procedure

6. Results and Discussions:

6.1 Optimization of Process Parameters Using Gray Relational Analysis:

Taguchi approach is not designed to optimize multiple response characteristics. It is used for optimizing single response characteristic. The lower-the-better characteristic for one factor may affect the performance other factors since other factors may demand higher-the better characteristics. In present study, the use of orthogonal array with the Grey relational analysis (GRA) optimization methodology for multi-response optimization is discussed. The grey-Taguchi method has been applied to optimize multiple performance responses of end milling process (Kopac and Krajnik, 2007), electro discharge machining process (Lin and Lin, 2005) and arc welding process (Tarng*et al.* 2001). Through grey relational analysis, a grey relational grade is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade [51].

6.2 Experimental Design:

Table No. 1 below shows the machining parameters and their respective levels based on our experimental set up used for Taguchi (L_{18}) approach. Eight (8) factors are selected with a combination of four (4) electrical parameters and four (4) non electrical parameters. Current I, amp, Electrode Type, Voltage V volts and Pulse on Time τ_{on} µs. % Duty Cycle, $T_{L,}$ Working Time T_W s, Retraction distance R_D mm, Flushing Pressure kgf /cm^2 are non electrical parameters. Based on Taguchi's method DOE, an L_{18} (2^1 X 3^7) orthogonal arrays table with 18 rows L_{18} (corresponding to the number of experiments) is selected for experimentations. Experimental layout of L_{18} orthogonal array is shown in table Tale 1.

Table 1 Machine Control Factors and Their Respective Levels

Control Factors	Machining Parameter	Level 1	Level 2	Level 3	Units
A	% Duty Cycle T_L	10	12	-----	--
B	Current I, amp	24	30	42	Amps
C	Working Time, $T_{W,}$ s	5	10	15	Seconds
D	Electrode	C	CH_2	CH_4	
E	Voltage V, volts	50	75	100	Volts
F	Retraction distance R_D mm	1	1.5	2	Millimetres
G	Pulse on Time τ_{on} µs	20	75	400	µ sec.
H	Flushing Pressure kgf /cm^2	0.3	0.7	1	kgf /cm^2

Table 2 Experimental layout using an L_{18} orthogonal array

Ex. No	A% Duty Cycle	B Current I Amp	C Working Time, s, Tw	D Electrode Type	E Gap Voltage V	F Retraction Distance R_D mm	G Pulse on time µs, τ_{on}	H Flushing Pressure Kgf/cm^2	A	B	C	D	E	F	G	H
1	10	24	5	C	50	1	20	0.3	1	1	1	1	1	1	1	1
2	10	24	10	C_{H2}	75	1.5	75	0.7	1	1	2	2	2	2	2	2
3	10	24	15	C_{H4}	100	2	400	1	1	1	3	3	3	3	3	3
4	10	30	10	C_{H4}	75	1.5	400	1	1	2	1	3	2	2	3	3
5	10	30	15	C	100	2	75	0.3	1	2	2	1	3	3	2	1
6	10	30	5	C_{H2}	50	1	20	0.7	1	2	3	2	1	1	1	2
7	10	42	5	C_{H2}	50	2	75	1	1	3	1	2	1	3	2	3
8	10	42	10	C_{H4}	75	1	20	0.3	1	3	2	3	2	1	1	1
9	10	42	15	C	100	1.5	400	0.7	1	3	3	1	3	2	3	2
10	12	24	15	C_{H2}	100	1.5	20	0.3	2	1	1	2	3	2	1	1
11	12	24	5	C_{H4}	50	2	75	0.7	2	1	2	3	1	3	2	2
12	12	24	10	C	75	1	400	1	2	1	3	1	2	1	3	3
13	12	30	15	C_{H4}	100	1	20	0.7	2	2	1	3	3	1	1	2
14	12	30	5	C	50	1.5	75	1	2	2	2	1	1	2	2	3
15	12	30	10	C_{H2}	75	2	400	0.3	2	2	3	2	2	3	3	1
16	12	42	10	C	75	2	20	0.7	2	3	1	1	2	3	1	2
17	12	42	15	C_{H2}	100	1	400	1	2	3	2	2	3	1	3	3
18	12	42	5	C_{H4}	50	1.5	75	0.3	2	3	3	3	1	2	2	1

Three criteria of machining performance characteristics namely material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (SR) were used in present study. The weighing of the work piece mass loss minus the initial work piece mass before machining with the machining time taken will represent the MRR of the work piece. MRR can be expressed as the work piece removal weight (WRW) under a period of machining time in minute (T) as illustrated in Equation 1.

MRR (g/min) = MRR/T ………………………………………… (1)

The weighing of the pipe tool electrode mass loss represents the electrode wear ratio (EWR). The electrode wear ratio (EWR) is defined by the ratio of the electrode wear weight (EWW) to the work piece removal weight (WRW) and usually expressed as a percentage as shown in Equation 2.

EWR (%) = (MRR/EWR) x 100 …………………………………….. (2)

The surface roughness (SR) of the machined work piece is measure using Mitutoyo surface roughness measuring machine. Due to the variability of surface finish data, multiple measurements were taken of each surface evaluated so that averages could be calculated.

6.3 Criteria for Optimization of Multiple Performances:

The optimization of the process includes the following steps:

1) Normalizing the experimental results.
2) Calculating the Grey relational coefficients (GRC).
3) Averaging the GRC to calculate the Grey relational grade (GRG).
4) Analyzing the experimental results using the grey relational grade
5) Selecting the optimal levels of process parameters
6) Verifying the optimal parameters setting through the confirmation experiment

Table 3 Experimental results for material removal rate, electrode wear ratio and surface roughness

Ex. No.	MRR, g / min		EWR, g/ min		% Electrode Wear rate		SR µm		Average		
	Rep. I	Rep II	Rep. I	Rep II	Rep. I	Rep. II	Rep. I	Rep. II	MRR	EWR	SR µm
1	0.0036	0.0037	0.0035	0.0032	97.2222	86.4865	5.408	7.6	0.0037	91.854	6.504
2	0.0085	0.0073	0.0022	0.0011	25.8824	15.0685	7.6	7.84	0.0079	20.475	7.720
3	0.0096	0.0109	0.0005	0.0038	5.2083	34.8624	5.846	10.31	0.0103	20.035	8.078
4	0.0088	0.0127	0.0008	0.0011	9.0909	8.6614	9.03	9.68	0.0108	8.876	9.355
5	0.0077	0.0096	0.0019	0.0019	24.6753	19.7917	7.864	8.07	0.0087	22.233	7.967
6	0.005	0.005	0.0023	0.0019	46.0000	38.0000	5.5	5.18	0.0050	42.000	5.340
7	0.0109	0.0146	0.0039	0.0031	35.7798	21.2329	7.91	7.825	0.0128	28.506	7.868
8	0.0034	0.0033	0.0007	0.0012	20.5882	36.3636	4.274	4.28	0.0034	28.476	4.277
9	0.0133	0.0145	0.0016	0.0041	12.0301	28.2759	18.12	18.90	0.0139	20.153	18.510
10	0.0053	0.005	0.0011	0.0014	20.7547	28.0000	3.25	3.28	0.0052	24.377	3.265
11	0.0074	0.0079	0.0014	0.0015	18.9189	18.9873	6.06	6.01	0.0077	18.953	6.035
12	0.0127	0.0132	0.0008	0.0012	6.2992	9.0909	8.9	8.9	0.0130	7.695	8.900
13	0.0046	0.0042	0.0007	0.0007	15.2174	16.6667	5.9	5.61	0.0044	15.942	5.755
14	0.0079	0.0084	0.0045	0.0047	56.9620	55.9524	6.22	7.05	0.0082	56.457	6.635
15	0.0107	0.0105	0.0018	0.0011	16.8224	10.4762	9.94	9.26	0.0106	13.649	9.600
16	0.0043	0.0041	0.0043	0.0031	100.000	75.6098	5.95	5.97	0.0042	87.805	5.960

17	0.0150	0.0145	0.0021	0.001	14.0000	6.8966	10.03	9.66	0.0148	10.448	9.845
18	0.016	0.0165	0.0046	0.0053	28.7500	32.1212	5.61	5.36	0.0163	30.436	5.485

6.4 Grey Relational Analysis:

The first step of GRA is the linear normalization of DOE data according to the type response. Material removal rate (MRR) is the bigger-the-better performance criteria. Meanwhile, electrode wear ratio (EWR) and surface roughness (SR) are the lower-the better performance response. The raw experimental results are shown in Table 3. The normalized experimental results for MRR which observes the bigger-the-better performance criteria, χ_{ij} can be calculated as shown in Equation 3.

$$\chi_{ij} = \frac{y_{ij} - \min_i y_{ij}}{\max_i y_{ij} - \min_i y_{ij}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where y_{ij} is the i th experimental results in the j th experiment. Meanwhile, in case of EWR and SR which observe the lower-the-better performance criteria, the normalized experimental results, χ_{ij} can be calculated as shown in Equation 4.

$$\delta_{Ij} = \frac{\min_i \min_j |x_i^o - x_{Ij}| + \xi \max_i \max_j |x_i^o - x_{Ij}|}{|x_i^o - x_{Ij}| + \xi \max_i \max_j |x_i^o - x_{Ij}|} \quad \ldots\ldots (4)$$

Larger normalized results correspond to the better performance and the best normalized result should be equal to 1 (Deng, 1989). The normalized values are ranged between zero and one. The larger values yield better performance and the ideal value should be equal to one. The normalized results for each machining response are shown in Table 3. Next, the Grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be calculated as shown in Equation 5

$$\gamma_j = \frac{1}{m} \sum_{i=1}^{m} \xi_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where χ^0 is the ideal normalized result for the i^{th} performance characteristics. ζ is the distinguishing coefficient which is set between zero and one; in our case it was set to $\zeta = 0.9$. The grey relational grades are calculated by averaging GRCs for each performance characteristic. The GRG values are tabulated in the last column of Table 4. The higher the GRG represents that the experimental result is closer to the ideally normalized value (Deng, 1989). In the present work, experiment '8' has the best multi response characteristics amongst the 18 experiments conducted. The mean GRG for each level of the machining parameters can be calculated by averaging the GRG based on OA as shown in Figure 1.

The optimal process parameter level yields the highest particular GRG in Figure 1. The optimal machining parameter setting is $A_1B_3C_2D_3E_2F_1G_1$ H_1 or maintaining % duty cycle at 10, Current 42 Amp, Tool working time 10sec,electrode having 4 mm flushing hole, voltage 75 volts, minimum retraction distance i.e. 1mm, pulse on duration at level 1 (20μs) and flushing pressure minimum 0.3kgf / cm^2.

Table 4 Data pre-processing of the experimental result for each performance characteristic

Sr. No	Normalized Values			Gray Relational Coefficient		
	MRR, g / min	% Electrode Wear rate	SR µm	MRR, g / min	% Electrode Wear rate	SR µm
Ideal	1	1	1			
1	0.97674	91.854	0.78754	0.97481	47.368	0.80902
2	0.64729	20.475	0.70777	0.71844	85.563	0.75489
3	0.46512	20.035	0.68429	0.62723	85.99	0.74031
4	0.42636	8.876	0.60052	0.61073	98.465	0.69259
5	0.58915	22.233	0.69157	0.68658	83.897	0.74477
6	0.87209	42.000	0.86389	0.87557	68.827	0.86863
7	0.27132	28.506	0.69810	0.55259	78.446	0.74881
8	**1.00000**	28.476	**0.93362**	**1.00000**	78.471	**0.93131**
9	0.18217	20.153	0.00000	0.52392	85.876	0.47368
10	0.86047	24.377	1.00000	0.86577	81.951	1.00000
11	0.66667	18.953	0.81830	0.72973	87.06	0.83202
12	0.25581	7.695	0.63037	0.54738	100	0.70887
13	0.91860	15.942	0.83667	0.91706	90.181	0.84640
14	0.62791	56.457	0.77894	0.70750	60.835	0.80281
15	0.43798	13.649	0.58445	0.61559	92.712	0.68413
16	0.93411	87.805	0.82322	0.93178	48.599	0.83583
17	0.11628	10.448	0.56838	0.50456	96.493	0.67587
18	0.00000	30.436	0.85438	0.47368	76.909	0.86073

Table 5 Grey relational grades for each experiment

Ex. No.	Grey relational grade
1	0.75250363
2	0.776319417

3	0.742479715
4	0.762654802
5	0.756770222
6	0.810824295
7	0.695289347
8	0.905338852
9	0.618785698
10	0.895092531
11	0.810784421
12	0.752083863
13	0.888422658
14	0.706221129
15	0.742277846
16	0.751199791
17	0.715119652
18	0.701170036

Table 5 shows the grey relational grade for each experiment using the L_{18} orthogonal array. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. Experiment 8 has the best multiple performance characteristics among 18 experiments because it has the highest grey relational grade shown in Table 5. In other words, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. Since the experimental design is orthogonal, it is then possible to separate out the effect of each machining parameter on the grey relational grade at different levels. For example, the mean of the grey relational grade for the % duty cycle at levels 1 and 2 can be calculated by averaging the grey relational grade for the experiments 1 to 9 and 10 to 18, respectively. The mean of the grey relational grade for each level of the other machining parameters can be computed in the similar manner. The mean of the grey relational grade for each level of the machining parameters is summarized and shown in Table 6. In addition, the total mean of the grey relational grade for the 18 experiments is also calculated and listed in Table 6. Figure 4 shows the grey relational grade graph and the dash line indicated in Figure 4 is the value of the total mean of grey relational grade. Basically, the larger the grey relational grade, the better is the multiple performance characteristics. However, the relative importance among the machining parameters for the multiple performance characteristics still needs to be known so that the optimal combinations of the machining parameter levels can be determined more accurately.

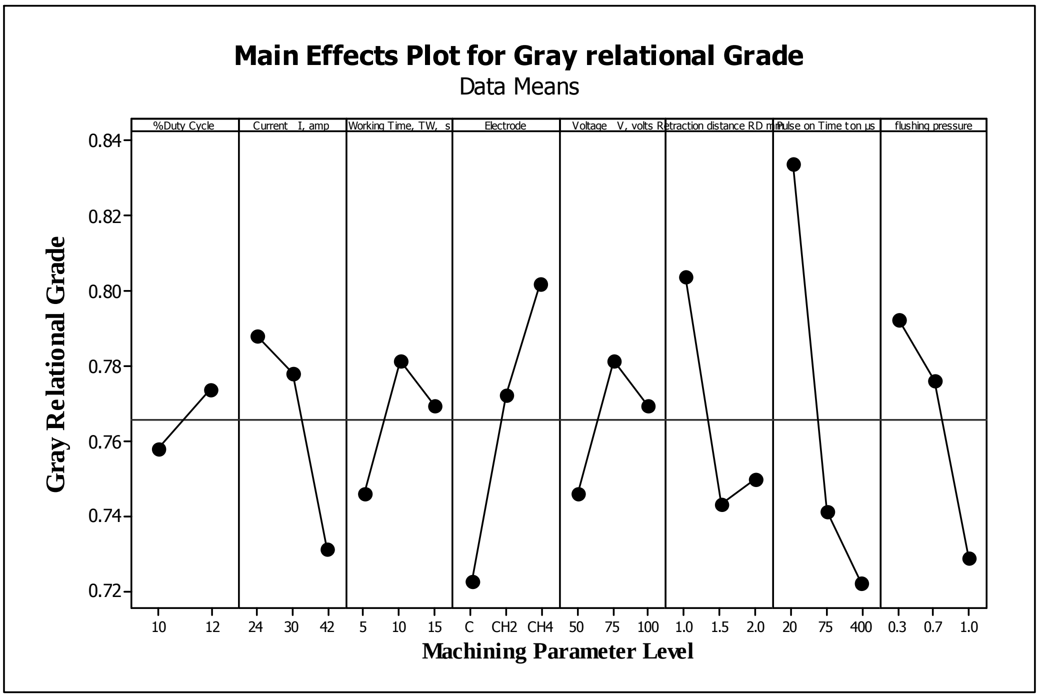

Figure 4 Grey Relational Grade Graph

Table 6 Response table for the grey relational grade

Symbol	Machine Parameter	Grey Relational Grade			Max - Min	Total
		Lavel-1	Lavel-2	Lavel-3		
A	% Duty Cycle T_L	0.757885	0.773597	----	0.015712	1.531
B	Current I, amp	0.788211	0.777862	0.731151	0.05706	1.519
C	Working Time, $T_{W,}$ s	0.746132	0.781646	0.769445	0.035514	1.528
D	Electrode	0.772927	0.772487	0.801808	0.029321	1.574
E	Voltage V, volts	0.746132	0.781646	0.769445	0.035514	1.528
F	Retraction distance R_D mm	0.804049	0.743374	0.7498	0.060675	1.547
G	Pulse on Time τ_{on} µs	0.833897	0.741092	0.722234	0.111663	1.556
H	Flushing Pressure kgf/cm^2	0.792192	0.776056	0.728975	0.063217	1.521
Total Mean Value of the Grey Relational Grade=**0.7657**						

6.5 Confirmation test:

The confirmation tests were conducted using the optimum combinations of machining factors. These confirmation tests were used to predict and verify the improvement in the quality characteristics for machining of titanium alloys Ti-6Al-4Vwith respect to the chosen initial parameters setting.

Table 7 Result of the confirmation experiment

Table 7 Results of Machining Performance Using the Initial and Optimal Machining Parameter

	Initial machining Parameters	Optimal cutting parameters	
		Predicted	Experimental
Setting level	$A_2B_3C_3D_2E_3F_2G_3H_3$	A_2 B_1 C_1D_2 E_3 $F_2G_1H_2$	$A_1B_3C_2D_3E_2F_1G_1$ H_1
MRR (g/min)	0.785 g /min	0.865 g /min	1.00 g /min
SR (µm)	0.861µm	1.00	0.78471µm
EWR (%)	33.885	81.951	28.476
GRG	0.7997	0.89509	0.9053

7 Conclusions:

In this work, Taguchi experiments were carried out to assess the effect of various EDM process parameters on surface integrity of Titanium alloy Ti-6Al-4V. To evaluate the desired objectives material removal rate and Surface Integrity of the EDMed holes was evaluated statistically. Following conclusions can be deduced from the experimental study.

- It is found that while all the factors have significant effect to varying degrees on the EDM performance, Pulse on time, (τ_{on}) is the most significant factor affecting material removal rate, dimensional accuracy and surface integrity of drilled hole. Among the process parameters, it is the types of tool which has the most dominating effect followed by pulse on time surface roughness and electrode.
- It was observed that maximum MRR can be obtained by adjusting the parameters to the level A2B3C3D2E3F2G3H3 the MRR obtained is 0.216 g/min.
- The confirmation experiment shows that the optimum conditions of process parameters obtained agreed well with the predicted results. Type of Electrode and flushing pressure are found to have significant influence on the surface roughness. While, the diameter and depth of crater size increased with an increase in current, the surface irregularity increases with an increase in the flushing pressure. This may be due to higher discharge energy involved that increases secondary sparking resulting in rough surface.
- It is evident that there is no crack formation occurred in any of the work material. From the practical point of view, this is an extremely desirable characteristic in case of cyclic loading conditions. However, in case of electrode severe cracks were observed at the higher machining conditions.

- From Minitab 16 it is observed that, it is possible to set-up the actual value of control parameters. So it is possible to select the required parameter for optimum output.

Taguchi's Signal – to – Noise ratio and Grey Relational Analysis were applied in this work to improve the multi-response characteristics such as MRR (Material Removal Rate), TWR (Tool Wear Rate) and Surface Roughness of Titanium alloy Ti-6Al-4Vduring EDM process.

The conclusions of this work are summarized as follows:

The optimal parameters combination was determined as A_1 B_3 $C_2D_3E_2F_1G_1$ H_1 i.e. % duty cycle at 10, Current 42 Amp, Tool working time 10sec, electrode having 2 mm flushing hole, voltage 50 volts, minimum retraction distance i.e. 1mm, pulse on duration at level 1 (20µs) and flushing pressure minimum 0.3kgf / cm^2.

1. The predicted results were checked with experimental results and a good agreement was found.
2. This work demonstrates the method of using Taguchi methods for optimizing the EDM parameters for multiple response characteristics.

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