OPTIMIZATION OF EDM PROCESS PARAMETERS AND GRAPHITE POWDER CONCENTRATION ON ELECTRICAL DISCHARGE MACHINING OF TI-6AL-4V ALLOY USING TAGUCHI METHOD

Bhiksha Gugulothu[1], D. Hanumantha Rao[2] and G. Krishna Mohana Rao[3]
[1]Research Scholar, Department of Mechanical Engineering, Jawaharlal Nehru Technological University, Kukatpally, Hyderabad-Telangana State
[2]Principal, Professor, Matrusri, Engineering College, Saidabad, Hyderabad, Telangana State
[3] Professor, Department of Mechanical Engineering, Jawaharlal Nehru Technological University, Kukatpally, Hyderabad-Telangana

Abstract

In the present investigation, the effect of graphite powder concentration into the dielectric fluid as drinking water on electric discharge machining of Ti-6Al-4V alloy is studied. Taguchi parameter design approach was used to get an optimal parametric setting of EDM process parameters namely, peak current, pulse on time, pulse off time and graphite powder concentration that give up optimal process performance characteristics such as material removal rate and surface roughness. Also individual effect of process Parameters on performance characteristics was studied. Experiments were conducted on experimental setup with modified dielectric fluid circulating system. To identify the significance of parameters on measured response, the analysis of variance (ANOVA) has been done. Further empirical models were developed by performing nonlinear regression analysis to predict the process performance characteristics. Confirmation tests were conducted at their respective optimum parametric settings to verify the predicted optimal values of performance characteristics.

Keywords: EDM, Taguchi method, Graphite powder, Material removal rate, Surface roughness

1. Introduction

Ti-6Al-4V alloy has high strength, low weight ratio, high corrosion resistance, and high temperature resistance. This makes it successfully used in various applications such as surgery, medicine, aerospace, automotive, chemical plant, pressure vessels and power generation [1-3]. Machining of these alloys would be a problem due to their low toughnessand low thermal conductivity and high chemical reactivity with the materialsto be machined therefore Conventional machining of Ti–6Al–4V, results in higher machining cost. EDM is one of the advance manufacturing process by which Ti-6Al-4V can be machined economically and efficiently [4].

Electrical Discharge Machining (EDM) is an important manufacturing process for machining hard metals and alloys, which is widely used for producing dies, moulds and finishing parts for aerospace, automotive and surgical components [5]. The process is capable of getting required dimensional accuracy and surface finish by controlling the process parameters. In EDM, the material is removed primarily through the conversion of electrical energy into thermal energy through a series of discrete electrical discharges occurring between tool and work piece when both are immersed inside a dielectric medium and are separated by a small gap. The material is removed from the work piece by localized melting and even vaporization of material by high temperature spark. This causes many defects such as micro cracks, porosity, residual stresses, and the white layer that is found on the machined surface due to rapid high temperature melting and subsequent rapid cooling during machining process. Further there is no physical contact between the tool and work piece which eliminates mechanical stresses, chatter and vibration problem during machining that enables EDM to machine brittle material [5]. In general, improved material removal rate (MRR) with decreased surface finish on the other hand improved surface finish with decreased MRR obtained during EDM. It is difficult to achieve both improved MRR and decreased surface roughness (SR) in EDM simultaneously. Many researchers attempted various techniques such as rotary EDM, vibratory assisted EDM and powder mixed EDM (PMEDM) to solve the above problems.

Chen et al. [6] attempted machining characteristics of Ti– 6Al–4V with kerosene and distilled water as the dielectrics. They found that MRR is greater and the Relative Electrode Wear Ratio (REWR) is lower, when machining in distilled water rather than in kerosene. A larger amount of debris and more micro cracks were also found when using distilled water as the dielectric. Lin et al. [7] exhibited an experimental investigation of the machining characteristics of titanium alloy (Ti–6Al-4 V) using a combination process of EDM with Ultrasonic Machining (USM). The EDM and USM machining mechanisms were integrated to improve the machining efficiency and accuracy. They concluded that combination of EDM/USM process can increase MRR, the thickness of the recast layer decreases and the discharge efficiency will be improved from the experimental results.

Hascalik et al [8] compared performance of copper, graphite and aluminum electrodes while EDM of Ti-6Al-4V. It has been found that SR is increased due to decomposition of recast layer on the surface, surface micro-cracks, debris and melted drops. Recast Layer Thickness(RLT) increases with increase in discharge current and pulse on duration. Surface cracks are not developed when aluminum and graphite electrodes are used for lower discharge current. In case of copper electrode, the tendency of developing surface cracks is observed for all the process parameters. MRR, SR and TWR are increased with increase in process parameters. MRR is higher in case of graphite electrode; it is medium in case of copper electrode and lower in case of aluminum. SR is lower in aluminum electrode compared to other electrodes.

Jabbaripour et al [9] investigated effects of process parameters on MRR and TWR and various aspects of surface integrity such as surface topography, crack formation and RLT. It has been observed that MRR increases as the pulse on time increases, but its effect is less as compared to current and voltage. The TWR also increases as the pulse on time increases but at higher pulse on time, TWR is not affected considerably. TWR decreases as the current is increased. Azad et al [10] optimized multiple performances of micro-EDM process parameters for a set of target performances when Ti6Al-4V is EDMed. They were observed that the most influential factors are voltage and current in the optimization of single quality characteristics. These factors are not influential in multiple quality characteristics. The predicted optimum condition has been verified experimentally.

Tzeng and chen [11] investigated various powders like SiC, Cu, Cr and Al added into dielectric fluid effect on the surface quality of EDMed SKD-11.They observed that mixture of Al powder into the dielectric fluid significantly decreases the thickness of the recast layer and SR on the workpiece. Wong et al [12] studied the near mirror finish phenomenon in EDM on different powders mixed into the dielectric fluid of SKH-54. They applied three kinds of powders including graphite, silicon and molybdenum sulfide. There was found that by changing the type of powder, powder concentration, and powder size, different qualities are resulted in the same input machining parameters, this attributes that the selection of suitable powder in powder mixed EDM process is critical issue.

Kung et al. [13] studied the effect of four process parameters of powder concentration, particle size, current and pulse on time on the performance characteristics of material removal rate and tool wear ratio, during machining of tungsten carbide, applying aluminum powder. They examined that by increasing powder concentration, the MRR is increased and after a certain limit, the increase of concentration leads to reduction of MRR and also by increasing the particle concentration, tool wear ratio is decreased and after that by increasing the concentration, TWR is increased.

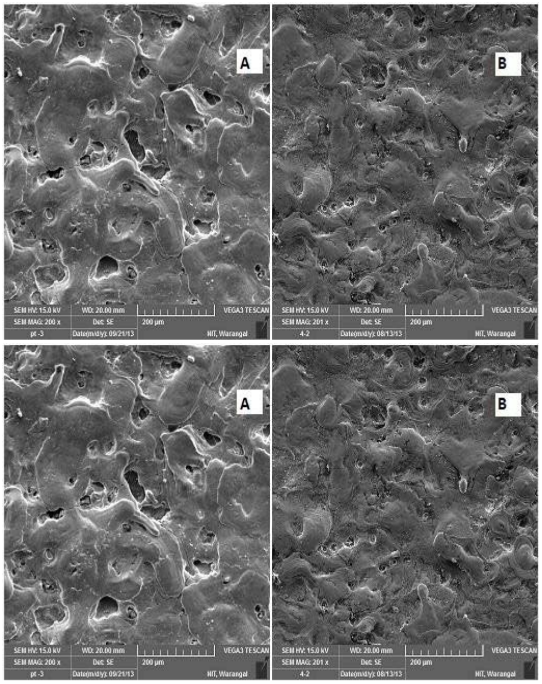
Jeswani [14] conducted experiments on graphite powder added to kerosene, results are indicated that increasing the material removal rate and reduced the tool wear rate. When graphite powder 4gm/lit mixture into dielectric fluid, his observed significantly reduction the breakdown voltage with higher discharge frequency.

Kibria et al [15] conducted experiments and compared the effect of various dielectrics such as kerosene, de-ionized water and mixing of B4C powder in kerosene and the de-ionized water during micro-hole machining of Ti-6Al4V using EDM. It has been noticed that MRR and TWR are more using de-ionized water than kerosene. When B4C powder mixed dielectrics are used, MRR increases with deionized water, but TWR decreases with kerosene. It has also been observed that the RLT is less in case of de-ionized water as compared to kerosene.

Murahri et al [16-19] conducted experiments on the addition of surfactant and surfactant with graphite and B_4C powder into the dielectric fluid and compare the results with without the addition of surfactant into the dielectric fluid while machining of Ti-6Al4V using modified EDM process. It has been observed that, surfactant with graphite powder addition into the dielectric fluid show better performance compared to that of B_4C powder addition.

Although the influence of various dielectrics on the stability of electrical discharge machining of titanium alloy has been studied extensively, including the material removal, surface roughness and recast layer thickness and the profile of the work piece and electrode to the best of our knowledge, there is little work reported in open literature regarding the use of drinking water as dielectric fluid for EDM of Titanium alloy.

In this paper, the feasibility of using drinking water to substitute for EDM oil as a variable dielectric is studied.



2 Experimental setup, procedure and equipment:

All the experiments are conducted on die sinking EDM machine of FORMATICS 50 model which is equipped with ELECTRONICA PRS 20 controller and modified working fluid circulating system has been designed for experimentation. In modified system, a separate tank mounted with micro pump is installed for better circulation of graphite powder in dielectric fluid. A motorized stirring system is incorporated to avoid settling of powder particles. Modified experimental set up is shown in Fig1. For conducting experiments, the work material Ti-6Al-4V alloy ingot is cut into the sample pieces with the dimensions of 80 X 30 X 6 mm by means of wire cut EDM process by setting very low peak current and pulse on time values. The hardness of the material is measured at different points and average hardness value was found to be 32-34 HRC. The chemical composition of the Ti-6Al-4V alloy is shown in Table1.The mechanical and physical properties of Ti-6Al-4V alloy are presented in Table2. The electrolyte copper rod of diameter ø14mm and length 70mm is selected as tool material to machine the Ti-6Al-4V alloy and the physical properties of electrolyte copper are presented in the Table 3. The drinking water as dielectric fluid used to conduct all the experiments is drinking water. Owing to higher thermal conductivity low electrical resistivity and high melting point, the graphite powder (particle size 20 to 30µm) is chosen to add into the dielectric fluid.

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

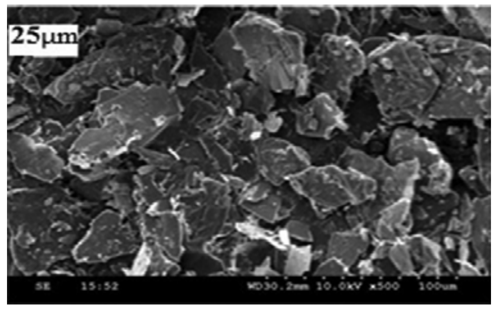
Fig.1 Modified experimental set up

Table 2 Mechanical and physical Properties of Ti-6Al-4V

Property	Quantity
Hardness (HRC)	36
Melting point (^{0}C)	1649
Density (g/cm^3)	4.5
Ultimate tensile strength (MPa)	897-1000
Thermal conductivity (W/m^{0}K)	7.2
Specific heat (J/kg^{0}K)	560
Mean coefficient of thermal expansion 100^{0}C/^{0}C	0-8.6x10^{-6}
Volume electrical resistivity (ohm-cm)	170
Elastic Modulus (GPa)	114

The ranges of each factor were taken based on the capability of the machine, and preliminary experiments were conducted on their performances effects. When straight polarity is used, the MRR is very low due to poor thermal conductivity and high electrical resistivity of workpiece (titanium alloy). This enhances the unstable erosion conditions like arcing, short circuit and so on. The preliminary experiment result shows that lower MRR is observed when straight polarity was used. Hence, this study is focusing on increasing the MRR of the work piece using reverse polarity [20-22].When the discharge current was kept above 10A, it was observed that the MRR was significant, and when more than 20A current was selected, it resulted in higher MRR necessitating the selection of values. The range selected for the pulse-on time and pulse-off time is based on the pilot experiments and the literature [23].The pilot experiments were carried out with the addition of graphite powder from 1 to 20g/L into the dielectric fluid. The graphite powder morphology can be observed as shown in Figure 2. The working range of process parameters in this study is presented in Table 3

Fig. 2 Morphology of graphite powder



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, L27 (3^{13}) OA is considered for the present study.The selected OA is presented in Table 4. Three trials of each experiment were conducted to average of these values to minimize the pure experimental error. Machining time has been chosen for conducting each experiment is 30 minutes, which is sufficient to produce tool shape on work material during EDM machining of Ti-6Al-4V alloy. Before machining, the work pieces and electrodes were cleaned and polished. The work piece was firmly clamped in the vice and immersed in the dielectric. The chosen input factors and corresponding levels for this study are presented in the Table5.

Table 3 Working range of the process Parameters and their levels

Parameters	**Units**	**Levels**		
Discharge current (A)	Amps	10	15	20
Pulse on time (B)	µs	25	45	65
Pulse off time (C)	µs	24	36	48
Graphite powder conc.(C)	g/l	4.5	9	13.5

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

Exp.No.	**Discharge current (B)**	**Pulse On Time (C)**	**Pulse Off Time (D)**	**Powder concentration (D)**
1	10	25	24	4.5
2	10	45	36	9
3	10	65	48	13.5
4	15	25	36	9
5	15	45	48	13.5
6	15	65	24	4.5
7	20	25	48	13.5
8	20	45	24	4.5
9	20	65	36	9
10	10	25	24	4.5
11	10	45	36	9
12	10	65	48	13.5
13	15	25	36	9
14	15	45	48	13.5
15	15	65	24	4.5
16	20	25	48	13.5
17	20	45	24	4.5
18	20	65	36	9
19	10	25	24	4.5
20	10	45	36	9
21	10	65	48	13.5
22	15	25	36	9
23	15	45	48	13.5
24	15	65	24	4.5
25	20	25	48	13.5
26	20	45	24	4.5
27	20	65	36	9

.

The Taguchi method uses S/N (Signal to Noise) ratio to measure the deviation of performance characteristics from the desired values. These are three categories of S/N ratios depending on the types of characteristics like higher is the best (HB), lower is the best (LB) and nominal is the best (NB). MINITAB16 software was used to analyze the experimental data. A digital weighing balance (citizen) having capacity up to 300 grams with a resolution of 0.1mg was used for weighing the work pieces before machining and after machining. Then the material removal rate (MRR) is calculated as

Follows.

$MRR\ (mm3/min) = \Delta W / \rho w \times t (1)$

Where ΔW is the weight difference of work piece

Before and after machining (g), $\rho w$is density of workmaterial (g/mm³) and t is machining time in minutes.

Surface roughness of the machined work pieces were measured using Talysurf surface roughness tester. The surface roughness is represented by the center line average method (Ra). Roughness measurements were carried out in the transverse direction on machined surface with cut-off length or sampling length of 0.8 mm and were repeated three times and average values are calculated.

3. Results and discussion

It is possible to sort out each process parameter on response at different levels since the experiments are designed in orthogonal nature. The raw data of various responses collected after conducting experiments for each trial were transferred in to their respective S/N ratio values using MINITAB 16 software

3.1. Effect of parameters on material removal rate (MRR)

The average values of MRR, SR for each trial (run) are presented in the Table 5.

Table 5 Average values of MRR, SR.

Ex.No	A	B	C	D	*Avg MRR	*Avg SR(microns)
1	10	25	24	4.5	2.5	2.14
2	10	25	36	9	2.212	2.126
3	10	25	48	13.5	2.277	3.641
4	10	45	24	9	3.057	2.001
5	10	45	36	13.5	3.681	4.211
6	10	45	48	4.5	2.410	4.67
7	10	65	24	13.5	3.983	3.650
8	10	65	36	4.5	4.063	4.288
9	10	65	48	9	1.949	5.27
10	15	25	24	4.5	3.944	2.308
11	15	25	36	9	3.327	2.787
12	15	25	48	13.5	2.217	3.502
13	15	45	24	9	3.557	2.703
14	15	45	36	13.5	4.276	3.657
15	15	45	48	4.5	4.089	4.33
16	15	65	24	13.5	5.111	4.25
17	15	65	36	4.5	6.788	4.495
18	15	65	48	9	3.223	5.56
19	20	25	24	4.5	5.029	3.505
20	20	25	36	9	4.147	3.221
21	20	25	48	13.5	3.401	3.654
22	20	45	24	9	6.721	4.27

23	20	45	36	13.5	7.746	4.01
24	20	45	48	4.5	8.55	4.589
25	20	65	24	13.5	7.606	5.46
26	20	65	36	4.5	9.414	5.533
27	20	65	48	9	8.059	6.41

*average of three values

Fig3. The effect of process parameters on Mean of MRR

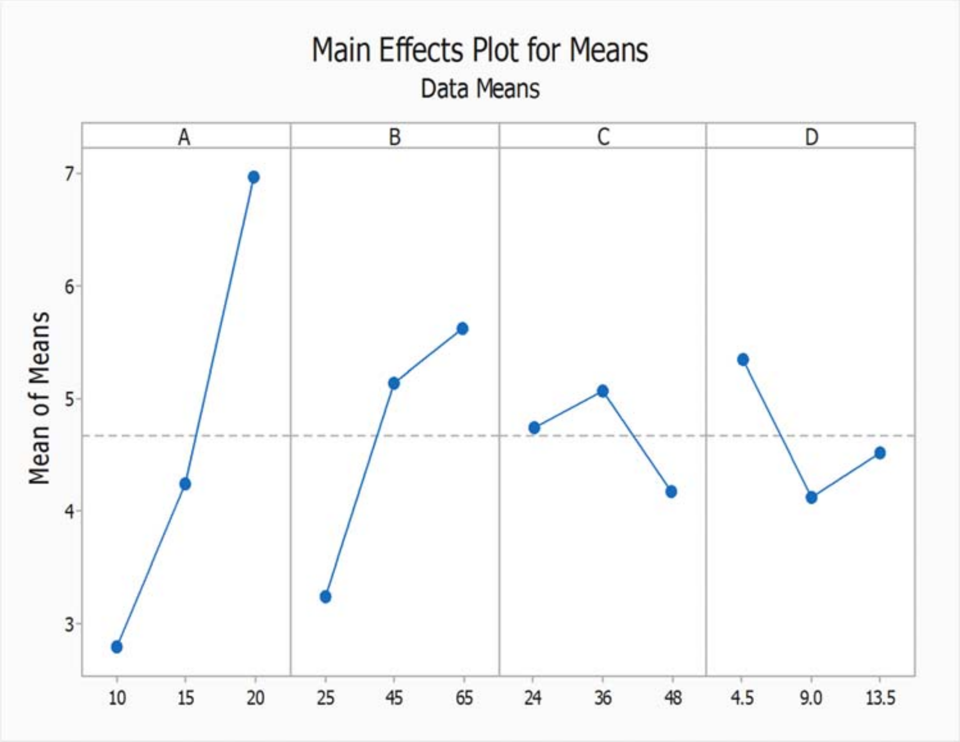


Fig 4. The effect of interaction process parameters on Mean of MRR

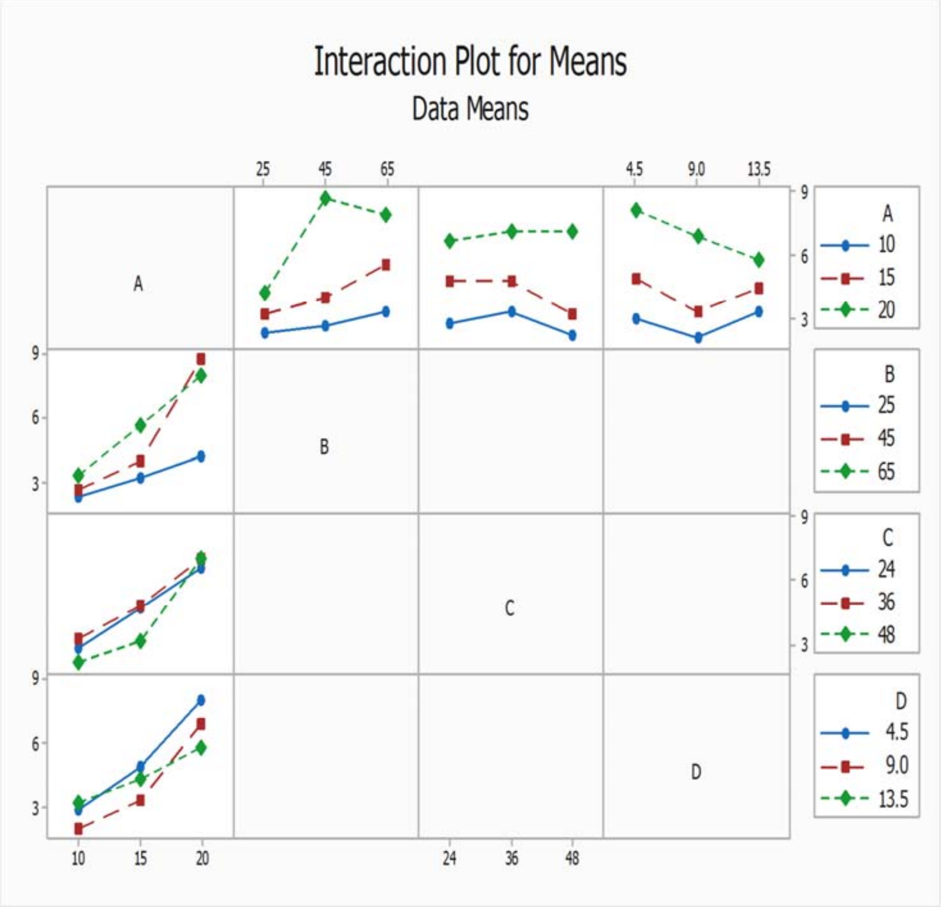


Table 6 Analysis of Variance (ANOVA) for raw data MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	276.095	276.095	138.048	147.91	0.000
B	2	89.435	89.435	44.718	47.91	0.000
C	2	26.554	26.554	13.277	14.23	0.005
D	2	28.505	28.505	14.252	15.27	0.004
A*B	4	27.961	27.961	6.990	7.49	0. 016
A*C	4	13.107	13.107	3.277	3.51	0. 083
A*D	4	25.558	25.558	6.390	6.85	0.020
Residual Error	6	5.600	5.600	0.933		
Total	26	492.816				

S = 0.9661 $R^2 = 98.9\%$ $R^2(adj) = 95.1\%$

The effect of process parameters and their interaction effect on the MRR is presented in Fig 3 and Fig 4 respectively. From the response graphs it has been observed that MRR increases significantly with increasing in peak current values from 10 to 20A. The peak current directly influences the discharge energy available in the inter electrode gap. The increase in peak current causes increasing in spark energy results higher current density, which rapidly over heats the work piece, thus increasing in MRR at higher peak current conditions [24]. At low current, the amount of energy utilized in melting and vaporizing the electrodes is not so intense due to generation of small quantity of heat at electrodes and major portion of it is absorbed by the surroundings. However with increase in peak current, a stronger spark with high thermal energy is produced, and a major portion of heat will be transferred to the electrodes. 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 [25].The trend in variation of MRR with increase in peak current is similar with the findings of H.K.Kansal et.al [26].

The pulse on time is the second significant factor as far as contribution and significance are concerned. It is clear from Fig 3. That, as the pulse on time increases from 25µs to 65µs, MRR increases to a smaller extent due to increase in energy supplied per cycle.

Generally, no material is removed from the work piece during the pulse off time as there is no discharge energy. MRR increases with increase in pulse off time from 24 µs to 36 µs and then decreases. The reason for this is that at low pulse off time, debris are suspended in the machining zone during machining due to incomplete flushing in short time and become barrier for effective sparking which results in unstable machining process. As the pulse off time increases, the dielectric gets sufficient time to flush away these debris which results in effective sparking and stability of the process and hence, MRR increases with pulse off time (36 µs) and further decreases due to amount of energy supplied to the process is decreases.

Further it is also noticed that increase in graphite powder concentration from 4.5(g/l) to 9(g/l), MRR decreases and marginally increases thereafter. This may be due to the fact that the excess powder accumulates in the gap and reduces the discharge transitivity and as a result the MRR is reduced [26]. From the Fig it is observed that input parameters namely peak current, pulse on time, pulse off time and graphite powder concentration appreciably affect the mean values of MRR. Fig3. suggests that when peak current is at 20A (level 3), pulse on time is at 65 s (level 3), pulse off time is at 36 s (level2) and powder concentration is at 4.5 g/lt (level 1) ,maximum MRR from the work surface can be obtained. Further ANOVA of the data presented in the Table8reveals the significance of input parameters on MRR which is as follows. The most significant, significant and less significant parameters are peak current, pulse on time and powder concentration respectively. Optimum value of MRR is calculated as 9.64 mm^3/min and corresponding S/N ratio is 20.0577 at its optimal parameter settings. Further empirical model has been developed using nonlinear regression analysis to predict the MRR values .The regression equation is

$$MRR = 3.76 - 0.892\,A + 0.0516\,B + 0.280\,C - 0.511\,D + 0.03052\,A^2 - 0.001239\,B^2 - 0.00526\,C^2 + 0.0400\,D^2 + 0.00791\,AB + 0.00494\,AC - 0.01929\,AD \quad (2)$$

3.2. Effect of parameters on surface roughness (SR)

The average values of SR for each trial and their respective S/N ratio values are presented in the Table6.Response (SR) curve for the individual effect of effect of peak current, pulse on time, pulse off time and graphite powder concentration on the average values of SR is shown in Fig5. The interaction effect of these parameters on the response is also shown in Fig 6. It is observed from the Fig 5 that increase in surface roughness value is noticed with increasing in peak current. This can be due to increase in peak current causes increase in spark energy resulting the formation of deeper and larger craters which results in increase in surface roughness. It is also observed that surface roughness increases with the increase in pulse on time

It is also noticed that initially surface roughness decreases with the increase in powder concentration from 4.5(g/l) to 9(g/l), and it increases further increasing the powder concentration. In powder mixed electrical discharge machining, the addition of electrically conductive powders into dielectric fluid causes decrease in its insulating strength leading to widening of the gap between electrodes to stabilize the discharge condition. The enlarged and widened discharged channel reduces the electrical density on the machining spot and thus generates shallow craters and lower surface roughness. On the other hand with increasing in thermal conductivity of dielectric due to the addition of powders, more heat is dissipated from electrodes gap through dielectric fluid, subsequently the level of heat energy available at work surface is decreased [28]. The small decrease in surface roughness value is observed with the increase in powder concentration from 4.5 g/lt to 9.0 g/lt and further increase in powder concentration from 9 g/lt to 13.5 g/lt. A very small decrease in SR value is noticed. It shows that the individual effect of powder concentration is not much significant on surface roughness; this may be due to the interactional effect of powder concentration with other parameters.

Fig5. The effect of process parameters on Mean of SR

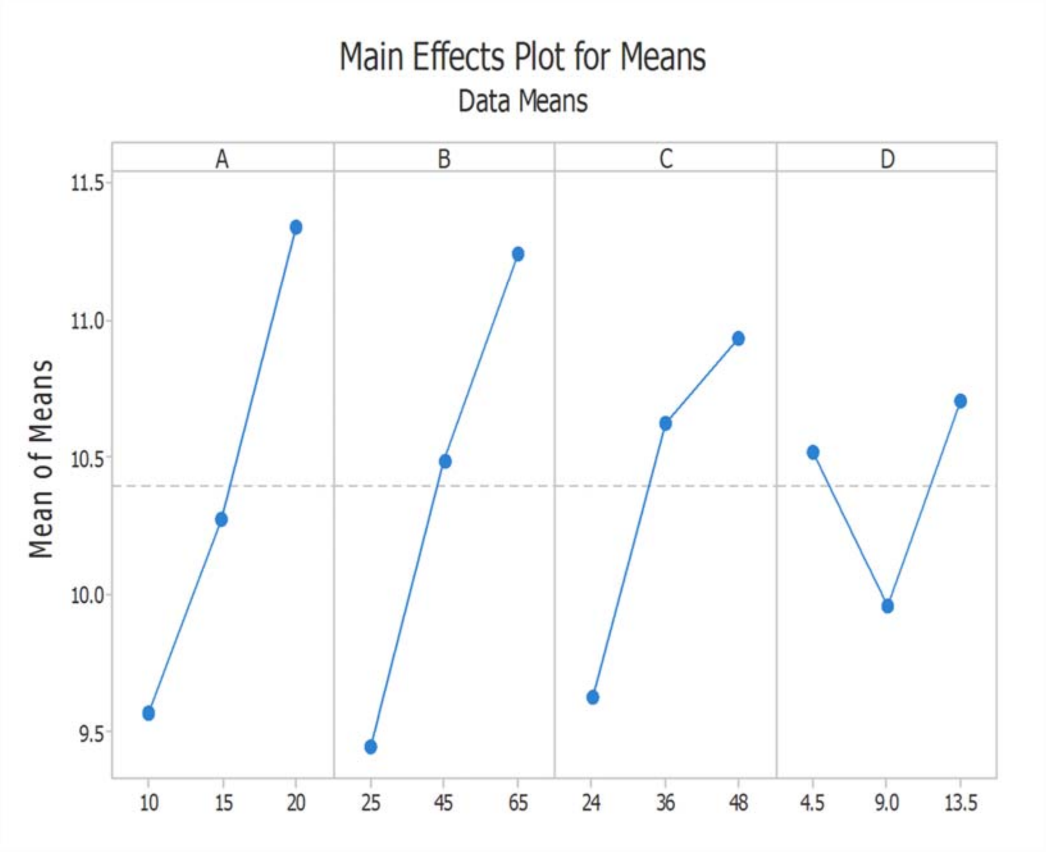


Fig 6. The effect of interaction process parameters on Mean of MRR

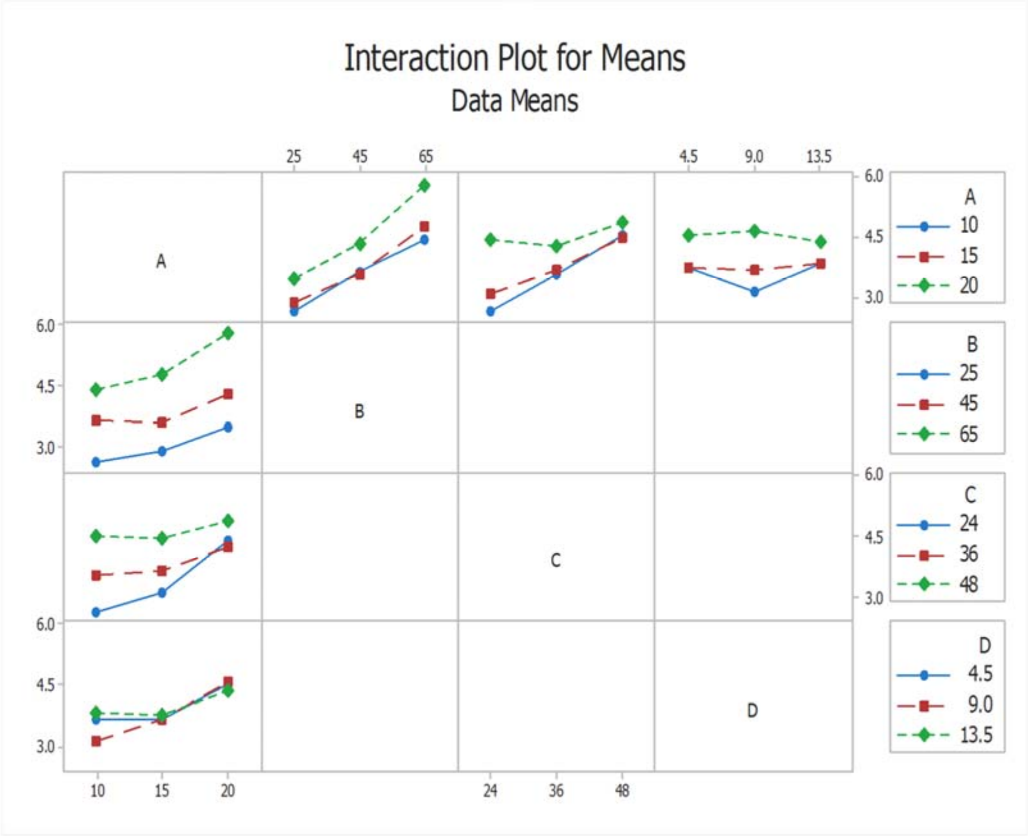


Table 7 Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	27.223	27.2228	13.6114	28.57	0.001
B	2	92.903	92.9033	46.457	97.49	0.000
C	2	42.737	42.7369	21.3685	44.85	0.000
D	2	5.082	5.0822	2.5411	5.33	0.0047
A*B	4	0.446	0.4459	0.1115	0.23	0. 909
A*C	4	14.629	14.6290	3.6572	7.68	0. 015
A*D	4	7.152	7.1518	1.7879	3.75	0.0073
Residual Error	6	2.859	2.8588	0.4765		
Total	26	193.031				

S = 0.6903 R-Sq = 98.5% R-Sq(adj) = 93.6%

From Fig3,it is noticed that input parameters namely peak current surfactant concentration and graphite powder concentration appreciably affect the mean values of SR.

Fig2. Suggests that when peak current is at 10A (level 1), pulse on time is at 25 s (level 1), pulse off time is at 24 s (level1) and powder concentration is at 9 g/lt

(Level 2) ,minimum SR from the work surface can be obtained. Further ANOVA of the data presented in the Table reveals the significance of input parameters on SR which is as follows. It is observed from the Table 8that the peak current has most significant effect on surface roughness whereas other two parameters surfactant concentration and powder concentration don’t have that much effect on surface roughness. This may be due to the interactional effect between the two parameters. Further the empirical model has been developed using nonlinear regression analysis to predict the SR values.The regression equation is

$$SR = SR2 = 0.91 - 0.084\,A - 0.0079\,B + 0.0531\,C - 0.105\,D + 0.01215\,A^2 + 0.000405\,B^2 + 0.001256\,C^2 + 0.00877\,D^2 + 0.00143\,AB - 0.00607\,AC - 0.00336\,AD \quad (3)$$

The regression coefficients are presented in the Table12.The predicted values of SR using regression equation *(3)* and corresponding residuals are presented in the Table13.The values of R² (94.65%) and R²adj (90.72%) of the model are in the acceptable range of variability in predicting SR values.

4. Confirmation experiments:

To verify the predicted values of responses such as MRR, SR at their optimal parametric settings, three confirmation experiments were conducted at their optimal parametric settings and each experiment is repeated three times to take the average value .The data from the confirmation experiments and their comparisons with respective predicted values and the deviation of predicted results from experimental results are calculated as % error with equation *(6)* and are presented in Table20.

$$\%error = \frac{experimentalvalue - predictedvalue}{experimentalvalue} \times 100$$

(5)

Table8 Confirmation tests for MRR, SR

S.No.	Optimum parameters				Response	Optimum condition	Predicted value	Experimental value *	% error
	A	B	C	D					
1	20	65	48	4.5	Max.MRR (mm³/min)	$A_3B_3C_2D_1$	9.64352	10.567	9.56
2	10	25	24	9	Min. SR (µm)	$A_1B_1C_1D_2$	1.2545	2.231	7.5

- Average of three values

5. Conclusions

1. Based on the experimental results in the present work, the following conclusions are drawn:
2. Machining characteristics namely MRR, SR increase with increase of peak current.
3. MRR decreases less significantly with increase of powder concentration.

Whereas SR decreases with increasing powder concentration and attains maximum value when powder concentration is 9 g/lt and then decreases with further increasing in powder concentration to 13.5 g/lt.

4. Based on the results of ANOVA analysis, peak current is most significant parameter affecting MRR and SR. However powder concentration has less significant effect on all response characteristics namely MRR and SR.
5. Further optimal parametric settings were found for all performance characteristics. Corresponding optimum response values are calculated and also confirmation experiments were conducted at respective optimal parametric settings to verify predicted optimum values. The corresponding %error values of MRR and SR were estimated and the values are in the range of 9.56% to 7.5%.

6. Empirical models were developed by performing nonlinear regression analysis to predict all response characteristics such as MRR, SR.

References

[1] ASM International, Introduction to Titanium and Titanium alloys, Properties and selection: Nonferrous alloys and Special purpose Materials, Vol.2., ASM Handbook, 1993, in English

[2] E.O. Ezugwu, Z.M. Wang, Titanium alloys and their machinability- a review. Journal of Materials Processing Technology, 68, 1997, p 262-274, in English

[3] C.H.C. Haron, A. Jawaid, The effect of machining on surface integrity of titanium alloy Ti-6Al-4V, Journal of Materials Processing Technology, 166, 2005, p 188-192, in English

[4] B.H. Yan, H.C. Tsai, F.Y. Huang, The effect in EDM of a dielectric of a urea solution in water on modifying the surface of titanium, International Journal of Machine Tools Manufacture, 45, 2005, p 194-200, in English

[5] R. Casanueva, M. Ochoa, F.J. Azcondo and S. Bracho, ―Current mode controlled LCC resonant converter for electrical discharge machining applications‖, Proceedings of ISIE-2000, Mexico.

[6] Chen, S.L., Yan, B.H. and Huang F.Y., ‗Influence of kerosene and distilled water as dielectric on the electric discharge machining characteristics of Ti-6Al-4V‘, Journal of Materials Processing Technology, 87, 107-111, 1999.

[7] Lin, Yan Cherng, Yan, BiingHwa, ―Chang, and Song, Machining characteristics of titanium alloy (Ti 6Al 4V) using a combination process of EDM with USM‖, Journal of Materials Processing Technology, 104, 171-177, 2000.

[8] Hascalik, Ahmet, Caydas, and Ulas, ―A comparative study of surface integrity of Ti-6Al-4V alloy machined by EDM and AECG‖, Journal of Material Processing Technology ,190, 171-180, 2007.

[9] B. Jabbaripour, M. H. Sadeghi, Sh. Faridvand, and M. R. Shabgard, ―Investigating effects of EDM parameters on Surface integrity, MRR and TWR in Machining of Ti-6Al-4V‖, Machining Science and Technology, 16:419-444, 2012.

[10] M. S. Azad and A. B. Puri, ―Simultaneous optimization of Multiple performance characteristics in Micro-EDM drilling of Titanium alloy‖, International Journal of Advanced Manufacturing Technology, 61: 1231-1239, 2012.

[11] Tzeng YF and Chen FC, ―Investigation into some surface characteristics of electrical discharge machined SKD-11 using powder-suspension dielectric oil‖, Journal of Materials Processing Technology, 170, 385– 91, 2005.

[12] Wong Y, Lim LC, Rahuman I and Tee WM, ―Near-mirror finish phenomenon in EDM using powder mixed dielectric‖, Journal of Materials Processing Technology, 79, 30–40,1998.

[13] Kung K, Horng J and Chiang K, Material removal rate and electrode wear ratio study on the powder mixed electrical discharge machining of cobalt-bonded tungsten carbide‖, International

Journal of Advanced Manufacturing Technology, 40, 95–104, 2007.

[14] M. L. Jeswani, ―Effect of the addition of graphite powder to kerosene used as the dielectric fluid in electrical discharge machining‖, Wear, 70, 133 – 139, 1981.

[15] Kibria G., Sarkar B. R., Pradhan B. B. and Bhattacharyya, B. ―Comparative study of different dielectrics for micro-EDM performance during microhole machining of Ti-6Al-4V alloy‖, International Journal of Advance Manufacturing Technology, DOI 10.1007/s00170-009-2298y, 2009.

[16] MurahariKolli and Adepu Kumar, Influence of Span 20 Surfactant and Graphite Powder Added in Dielectric Fluid on EDM of Titanium alloy, Bonifring Journal, 2014, Vol. 4 (2), 63-67

[17] MurahariKolli and Adepu KumarParametric Optimization of Boron Carbide Powder Added Electrical Discharge Machining of Titanium Alloy, *Applied Mechanics and material*, 2014**,** Vol. 592-594, PP.578- 586.

[18] MurahariKolli and Adepu Kumar, Surfactant and Graphite Powder Assisted Electrical Discharge Machining of Titanium Alloy, *ProcIMechE part B: Journal of Engineering Manufacture*, 1-17, 2015, DOI: 10.1177/0954405415579019.

[19] MurahariKolli and Adepu Kumar, Optimization of Surfactant mixed EDM parameters on Ti–6Al–4V Alloy using GRA-Taguchi Method, *Journal of Material in Technologie*, DOI: mit.imt.si/Revija/ mit 249-2016, Impact Factor:0.555

[20] Chen SL, Yan BH and Huang FY. Influence of kerosene and distilled water as dielectrics on the electric discharge machining characteristics of Ti-6Al-4V. J Mater Process Tech 1999; 87: 107–111.

[21] Rajurkar KP and Lin Gu. Review of electrical dischargemachining of Titanium alloy. In: Proceedings of the seventh international conference on precision, meso, micro and nano engineering at COE, Pune, Maharashtra, India, 10–11 December 2011, pp.10–18. Pune, Maharashtra: COPEN 7, College of Engineering, Pune.

[22] Lin YC, Yan BH and Chang YS. Machining characteristics of titanium alloy (Ti-6Al-4V) using a combination process of EDM with USM. J Mater Process Tech 2000; 104: 171–177.

[23] Nikalje AM, Deep Gupta R and Kumar A. Analysis ofrecast layer and surface machined by electrical discharge machining. In: International conference on recent advances in mechanical engineering, Dr. M.G.R. Educational and Research Institute University, Chennai, India, 19–20 April 2012, pp.19–20

[24] K.D.Chattopadhyay, S.Verma, P.S.Satsangi, P.C.Sharma, (2009) Development of empirical model for different process parameters during rotary electrical discharge machining of copper-steel (EN-8) system, J. of Materials Processing Technology, 209: 1454-1465.

[25] BehzadJabbaripour, Mohammad Hossein Sadeghi, Mohammad Reza Shabgard, Hossein Faraji, (2013) Investigating surface roughness, material removal rate and corrosion resistance in PMEDM of γ-TiAl intermetallic, Journal of Manufacturing Processes 15: 56-68.

[26] H.K.Kansal, Sehijpal Singh, P.Kumar, (2006) Performance parameters optimization of powder mixed electrical discharges machining (PMEDM) by Taguchi method, West Indian J. of Engineering 29: 81-94.

[27] BehzadJabbaripour, Mohammad Hossein Sadeghi, Mohammad Reza Shabgard, Hossein Faraji, (2013) Investigating surface roughness, material removal rate and corrosion resistance in PMEDM of γ-TiAl