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Experimental Investigation on Micro EDM Process on Ti-6Al-4V Alloy and Optimization of Machining Parameters for Industrial Applications

K. Kalaiarasi
Department of ECE, University College of Engineering Villupuram
C. Senthilkumar
Department of Mechanical Engineering, University College of Engineering Panruti
M. Balamurugan
3Department of ECE, University College of Engineering Villupuram

Abstract: Micro electrical discharge machining occupies a vital role in modern manufacturing industries. This paper describes the effect of three different input parameters such as voltage, capacitance and electrode rotation speed of micro electrical discharge machining performances of surface roughness, overcut and circularity. The characteristics of machining are evaluated by the electrical and nonelectrical parameters in micro EDM process. The multi objective optimization techniques are used to determine the performance of optimal machining conditions. The ANOVA technique was calculated for machining performance and root mean square value was estimated. The optimal machining performance of surface roughness, overcut and circularity are calculated in the machining conditions of voltage 100 V, capacitance of 8µf and electrode rotation speed of 2500 rpm.

Key words: Ti-6Al-4V, Micro hole machining, optimization, Electrical discharge machining, Surface roughness.

INTRODUCTION

Several factors establish the performance of materials, which includes the different types of machining and parameters responsible for machining process and have influence over the life process of the specimens used [1]. The nontraditional machining process such as electrical discharge machining (EDM), Laser beam machining, electron beam machining change the behavior of micro structure and have major influence on mechanical surface by influencing cracks, formation of heat affected zone and propagation of diffused layer in parental material [2]. The numerous nontraditional machining process are available and among that electrical discharge machining is accomplished because of its adaptable capability to machine harder materials such as Ti-6Al-4V alloy [3]. The input process parameters such as voltage, time, and rotation speed of electrode in micro EDM process have a predominant role on Ti-6Al-4V alloy [4].

The different types of electrode such as copper, graphite, tungsten at different voltage have examined the performance of the machined surface [5]. The formation of cracks, debris and recast layer is observed on the machine surface [6]. The softened layer is viewed below the recast layer of Ti-6Al-4V alloy due to the low thermal conductivity property [7]. The dielectric medium such as kerosene, deionized water, hydrogen content have a major role in the EDM process of Titanium alloy where the surface roughness of the material increased with the increase of dielectric viscosity [8]. The increase of a voltage and capacitance value increase the cutting speed of the Titanium alloy [9]. Hence, it was assured that, higher discharge energy leads to double sparking which increases the cutting speed [10]. In addition, the formation of excess debris removal and formation of large craters on Titanium surface shows higher surface roughness [11]. Researchers have proved that Taguchi experimental design and ANOVA techniques is an efficient tool to find out the optimal combination of machining parameters for micro EDM process [12].

The input process parameters such as voltage (v), capacitance (µf) and electrode rotation speed have a higher response of the output process [13].

The controlled research has been performed in micro EDM process on Titanium alloy considering the output parameters such as Surface roughness, overcut and circularity. This paper describes the performance of micro EDM process on Titanium alloy. The input process parameters considered for this study were voltage, capacitance and electrode rotation speed at three levels. Nineteen different experimental combinations were selected at random with respect to full factorial design. Multi objective optimization techniques are used to evaluate the optimal combination of machining parameters for micro EDM process. The effect of surface roughness, overcut and circularity during the machining of micro EDM process are also presented. The experimental results are compared with multi objective optimization technique and percentage of accuracy was estimated.

2. Experimental work carried out

Titanium (Ti-6Al-4V) alloy of 0.4 mm thickness is chosen as the work piece material due to high temperature strength and excellent erosion resistance property. Table 1 show the chemical composition of Ti-6-Al-4V plate used. The Copper alloy of 0.5 mm diameter thickness was chosen as electrode and the machining trials were conducted to analyze the performance of surface roughness, overcut and circularity. Fig 1 show the SEM image of (Ti-6Al-4V) titanium alloy.

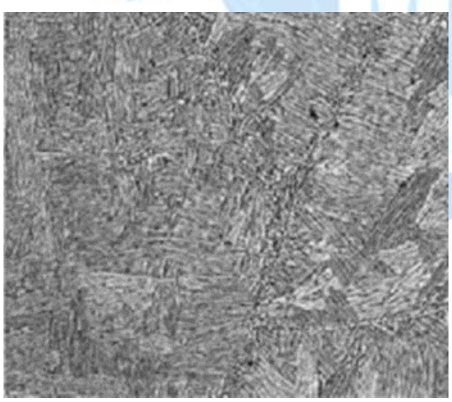

Fig 1. Titanium alloy

Table 1 chemical composition of Ti-6-Al-4V

Component	Al	V	Fe	O	C	N	H	Ti
Weight %	5.08	3.01	0.11	0.03	0.01	0.04	0.0034	Balance

The experiments were conducted by a precision machining tool with repeatability of 1 µm for all axes by Taguchi L27 orthogonal array (OA) with an RC circuit [14]. The quality of the outcome values are evaluated by (ANOVA) analysis of variance to determine the surface roughness, overcut and circularity. The optimal solution was found and the results were verified with confirmation experiments. In total, 19 experiments are performed in electrical discharge machining and the random method has been applied to cut in sequential selection. The experimental set up of micro EDM process is shown in Fig 2. A cylindrical zinc coated copper wire is chosen as the electrode tool material and workpiece material of Titanium alloy of 1 mm, length 50 mm and width 10 mm. The deionized water was used as a dielectric fluid.

Fig 2 Experimental setup of EDM process

Table 2 Input parameters and their level of micro EDM process

Process parameters	Symbol	Level 1	Level 2	Level 3
Voltage (V)	A	100	150	200
Capacitance (µf)	B	6	8	10
Electrode rotation (rpm)	C	500	1500	2500

Taguchi L27 orthogonal array (OA) based experiments have been applied with 3 levels as shown in Table 2. The experimental results of machining performance of micro EDM process are shown in Table 3. In the experiments the effect of surface roughness, overcut and circularity of micro EDM process on various input variables such as voltage, capacitance and electrode rotation speed were evaluated.

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Table 3 Experimental results for surface roughness, overcut and circularity

Voltage (v)	Capacitance (µf)	Electrode rotation speed (rpm)	SR (µm)	Circularity (µm)	Overcut (µm)
200	6	2500	0.204	38	42.167
150	8	2500	0.180	33.6	47.26
100	10	1500	0.312	22.73	53.00
200	10	2500	0.750	26.75	51.32
150	10	500	0.690	16.25	42.17
100	8	500	0.820	11.76	32.69
100	8	500	1.280	17.00	33.97
150	6	500	1.326	19.38	45.04
200	6	500	1.933	39.72	41.68
200	10	1500	0.217	34.26	43.17
150	8	1500	0.290	42.36	37.28
100	6	1500	0.358	24.11	43.29
150	6	1500	0.540	40.72	40.79
150	8	2500	0.378	48.58	37.69
200	10	2500	0.445	39.17	33.69
200	10	2500	0.119	32.78	32.98
100	6	500	1.132	31.76	42.37
100	8	500	1.172	42.16	34.96
200	10	1500	0.362	27.31	32.87

3. Measurement procedure

The surface roughness of machining surface can be measured by 3D profiler (Taylor Hobson tester) where the 3 trials were replicated and the average values of surface roughness were shown in Table 4.

Table 4 .Specification of Taylor Hobson surface roughness tester

Specification	Units
Measuring standard	ISO 4287:1997
Accuracy	± 15 %
Repeatability	< 12 %
Measuring area R_a	0.05 … 10 µm
Cut-off length	0.25 mm, 0.8 mm, 2.5 mm
Scanning path in total	6 mm
Probing speed	1 mm / s
Resolution	0.125 nm

Measuring standard ISO 4287:1997 is the universally accepted standard for measuring surface roughness texture profile. Contact type Taylor Hobson surface roughness tester is used for Ra measurement and its specification is shown in Table 4.

Fig 3.surface roughness measurement setup

Surface roughness has been measured in air conditioner room to avoid climatic change. Roughness tester and work piece material are placed in granite to calculate Ra as shown in Fig 3.

Overcut is expressed as half of the difference of machined hole and copper tool size. It is observed that, machined hole periphery cannot be a perfect circle, hence the average radius of the micro hole machining was formed to calculate the overcut. The entry side of the micro hole radius was observed to be larger when compared with exit hole radius. Consequently, the overcut measurement was observed for the entry hole side. Circularity is defined as the distance between the minimum diameter of the circle and the maximum diameter of the circle. The error of circularity were found at the entrance of the machined hole as well as exit side of the machined hole which is calculated by the maximum value of the machined hole circularity.

4. Results and discussion

4.1 Effect of process parameters on surface roughness

The estimated surface roughness values are shown in Fig 4. The surface roughness value are calculated for various cutting conditions. It is noted that, for the different process parameters and their levels, the better surface finish is obtained for lower electrode rotation speed of 500 rpm, higher capacitance of 10µf and lower voltage value of 100 V. It is observed that higher feed rate leads to surface damage which results in poor surface finish.

The ANOVA technique was evaluated to estimate the effect of cutting process of surface roughness. The various process parameters and total number of experiments are determined for evaluation as shown in Table 5. ANOVA for surface roughness was evaluated with the model assumptions.

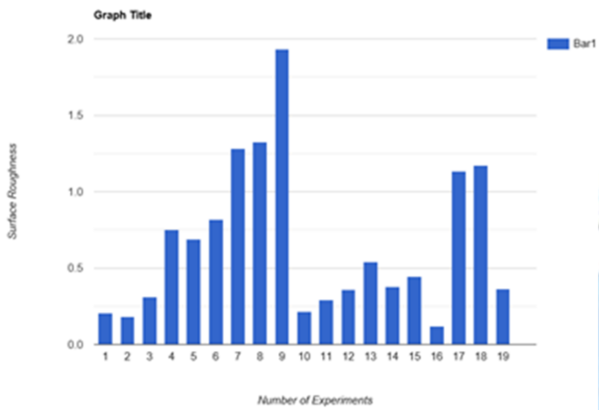

Fig 4. Experimental results on Surface roughness

The probability value of prob> F less than 0.05 shows that the voltage(A), capacitance(B), electrode rotation speed(C), interaction term of voltage and capacitance (AB), interaction term of voltage and electrode rotation speed(AC) and interaction term of capacitance and electrode rotation speed(BC) have significant effect on surface roughness. The value of P is greater than 0.1 shows that model is not significant and the predicted R squared value is 0.7045.

Table 5 ANOVA analysis for surface roughness (Ra)

Source	Degree of freedom	Sum of square	Mean square	F	P
A-voltage	1	0.03126	0.26237	3.06	0.106
B-capacitance	1	0.49934	0.01514	0.18	0.682
C-electrode rotation speed	1	1.44373	1.55157	18.07	0.001
AB	1	0.00004	0.25498	2.97	0.110
AC	1	0.00170	0.01976	0.23	0.640
BC	1	1.33595	1.33595	15.56	0.002
Error	12	1.03010			
Total	8	4.34212			

S=0.271015 R-sq=78.66% R-sq (adj)=70.45%

The degree of freedom is 1 and fishers (F) value and P value was calculated. The higher value 'F' have significant effect on response value. In order to determine the accuracy of null hypothesis, P value is < 0.05 which shows that 96% certainty is achieved. R squared value of ANOVA model for surface roughness is 70.45% that fits the good model data.

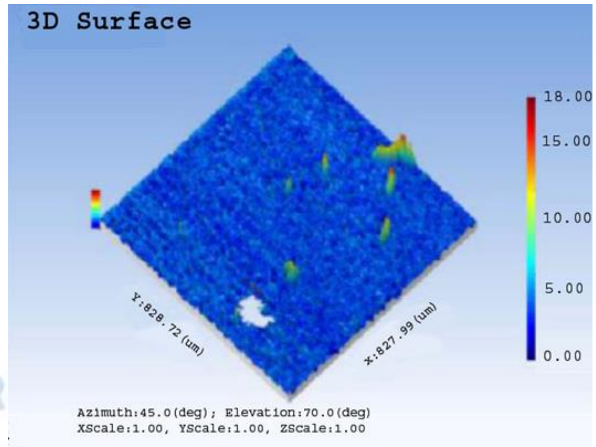

Fig 5.Surface Roughness

Fig 5 represents the 3D surface of surface roughness for optimum machining conditions varying voltage and capacitance and the Ra values reduced from 0.730 µm to 0.318 µm. From the Fig 6 it can be noted that when capacitance increases, surface roughness also increases accordingly. The observed result shows that, better surface finish of 0.318 µm is obtained when the capacitance value is 6 µf at lower level. The rough surface finish of 0.730 µm is observed at a higher capacitance value of 10 µf. It is due to capacitance has most significant role on discharge spark. The distribution of sparking uniformly spread over the Titanium surface. Hence, the shallow craters were appeared on the work piece surface which results in the improved surface finish.

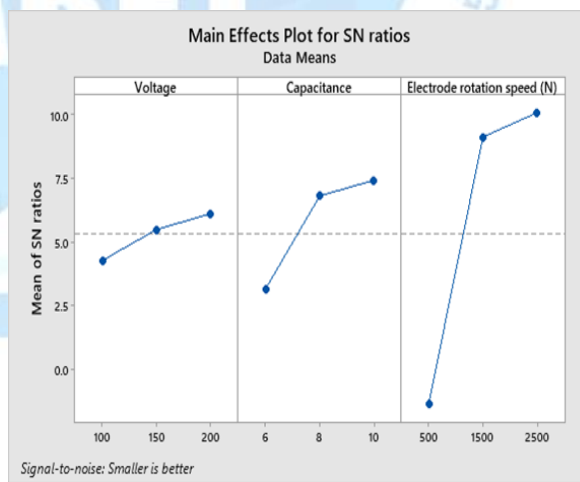

Fig 6 Effect of S/N ratio of Surface roughness

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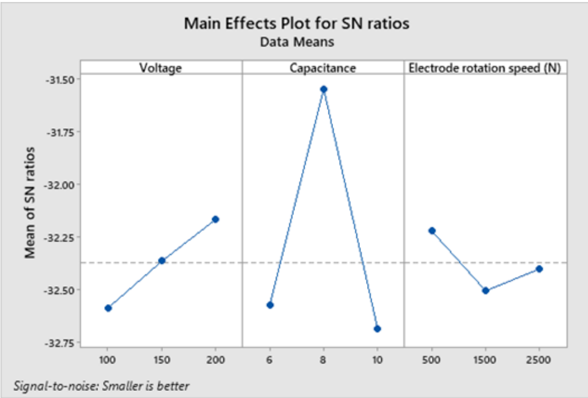

Fig 7. Effect of S/N ratio ofOvercut

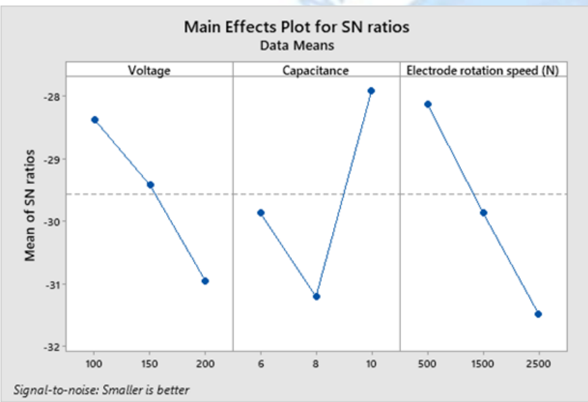

Fig 8 Effect of S/N ratio of Circularity

The response plots on surface roughness, overcut and circularity are shown in Fig 6-8. The optimization was performed by Taguchi technique and it is found that 8µf, 150Vthe better surface finish is achieved. The validation was estimated by optimum condition and the results shows the improved value of surface roughness of 0.318 µm than of initial machining process as shown in Fig 6. The circularity is good for 500 to 1500 rpm further it leads to decrease in performance by increasing the speed from 1500 rpm to 2500 rpm which is represented in Fig 8. The better overcut is achieved at 2500 rpm with feed rotation whereas surface finish and circularity of the cutting tool process increases with decrease in rotation speed. From the Fig 7, It is evident that, there is a random decrease in the overcut of the hole as the electrode rotation speed increases from 500 rpm to 2500 rpm. At the feed rate of 500 rpm, the penetration of hole is low because of longer machining time. The result shows that the exhibition of the work piece is larger and hence overcut is large.

4.2 Effect of process parameters on overcut

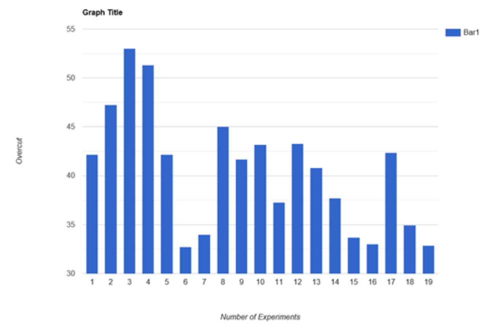

Fig 9 Experimental results on overcut

The overcut value are calculated for different experimental condition as shown in fig 9. It is observed that, overcut dependent on voltage and electrode rotation speed. The electrode rotation speed increases hence the overcut value also increases accordingly.

Table 6 ANOVA analysis for Overcut

Source	Degree of freedom	Sum of square	Mean square	F	P
A-voltage	1	24.69	47.61	1.06	0.323
B-capacitance	1	0.39	14.19	0.32	0.584
C-electrode rotation speed	1	26.87	0.00	0.00	1.000
AB	1	36.83	30.99	0.69	0.422
AC	1	38.89	34.70	0.78	0.396
BC	1	14.04	14.04	0.31	0.586
Error	12	8.472			
Total	8	237.02			

S=9.26961 R-sq=88.14% R-sq (adj)=80.10%

The ANOVA was tabulated in Table 6 and the model F value of 1.06 shows that the developed model fits within the domain of consideration and prob>F less than 0.05 shows that the values are significance. Hence, A, B, C, AB, AC and BC are a significant factor to be considered. The R2 value of 80.10% is obtained shows that the process parameter have good level with the data value. From ANOVA Table 6 it is observed that electrode rotation speed is the most significant factor that have influence over the dimensional accuracy of overcut. Based on the contribution of capacitance value it can be found that it has a remarkable impact in reducing the overcut.

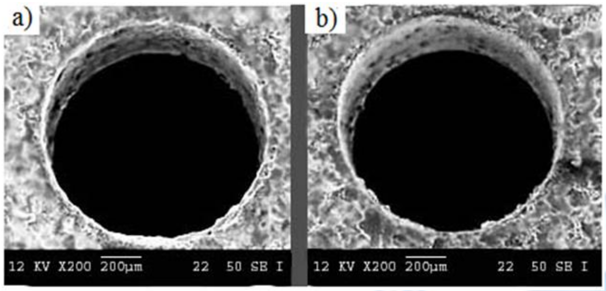

Fig 10 (a) Maximum overcut of 51.32µm and (b) Minimum overcut of 32.69 µm.

Fig 10 (a) and (b) shows the SEM images for the maximum and minimum overcut. In the electrode rotation speed of 1500 rpm the overcut error increases. At the electrode rotation speed of 500 rpm the penetration of workpiece tool is larger which leads to increase in overcut size of 51.32 µm. In the combination of capacitance value of 8µf, minimum overcut of 32.69 µ is achieved. Hence the electrode rotation speed and capacitance plays a predominant role in overcut.

4.3 Effect of process parameters on circularity

The obtained data value of circularity for number of experiments are shown in Fig 11. The capacitances have significantly influences the circularity when analyzed with open circuit voltage of 200 V. With the capacitance value of 6 µf and 8 µf the value of circularity increases linearly to a better value greater than 45.05 and a further increase of capacitance of 10 µf drastically reduce the value of circularity. Also, with the combined effect of the level of 150 V and 8 µf gives the best values of circularity.

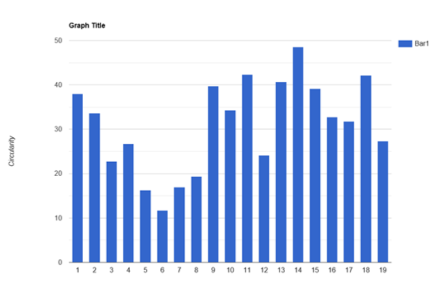

Fig 11 Experimental results on circularity

Table 7 ANOVA analysis for circularity

Source	Degree of freedom	Sum of square	Mean square	F	P
A-voltage	1	114.2	38.1	0.38	0.550
B-capacitance	1	99.8	3.2	0.03	0.862
C-electrode rotation speed	1	260.7	8.5	0.08	0.776
AB	1	11.9	9.5	0.09	0.764
AC	1	30.2	27.3	0.27	0.613
BC	1	8.5	8.5	0.08	0.776
Error	12	7.02			
Total	8	372.09			

S=6.10627 R-sq=92.1% R-sq (adj)=91.13%

According to ANOVA shown in Table 7, the most significant parameters with respect to circularity are voltage (A), capacitance (B) and electrode rotation speed (C), interaction of voltage and capacitance (AB), voltage and electrode rotation speed (AC), capacitance and electrode rotation speed (BC). The F value was obtained and P> 0.05 shows the significant effect on process parameter. It is observed that circularity depends on voltage and capacitance variables for the given electrode rotation speed. From ANOVA Table7, it is observed that the electrode rotation speed highly impact the quality of the hole in terms of circularity. As capacitance and voltage increases hence circularity increases. R squared value of the circularity is 0.9113 and it is reasonable with adjusted R squared value of 0.9211. Hence, it is found to be quite fit of model data.

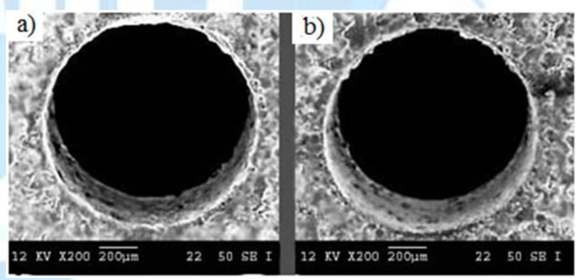

Fig 12 (a) Maximum circularity of 42.36µm (b) Minimum circularity of 11.76µm

Fig 12 (a) and (b) shows the SEM images for the maximum and minimum circularity. It shows that circularity error increases with increase in electrode rotation speed of 2500 rpm. Better circularity can be obtained at high electrode rotation speed of 2500 rpm when contrasted with low rotation speed of 500 rpm. In general, the higher rotational speed leads to rise of

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the air pressure that boosts up circularity of the Titanium alloy.

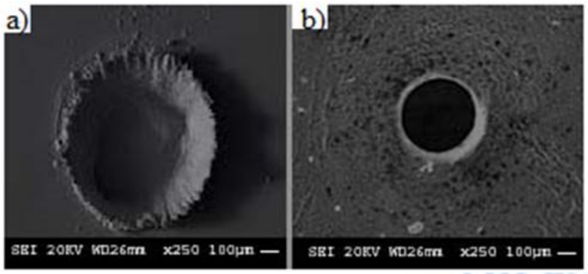

Fig 13 SEM image of the Titanium alloy (a) single electrical discharge machining (b) surface morphology

The photographs of Fig 13 shows the SEM image of the machined portion. Smaller level of cracks are seen in the structure. Fig 13 (a) shows the molten surface layer on single discharge of machining. The removal process of molten surface varied according to gaseous state. The morphology of the surface varies by applied discharge energy during machining process. The discharge energy is very low, the smooth machined surface is observed. However, at high discharge energy, solidification layer is found on the machined surface. The fig 13 (b) shows the accurate shape of the micro channel due to low discharge energy.

Table 8 Set of optimal solutions for micro EDM process

No	Voltage (v)	Capacitance (μf)	Electrode rotation speed (rpm)	Surface roughness	Circularity	Overcut	Desirability
1	200	6	2500	0.170	42.11	41.16	0.658
2	200	6	1500	0.112	32.26	43.17	0.617
3	200	6	500	0.630	37.12	51.00	0.590
4	100	8	2500	0.530	39.72	51.11	0.598
5	100	10	2500	0.710	47.50	41.17	0.575
6	100	10	2500	1.180	31.77	31.76	0.558
7	150	10	500	1.227	32.17	32.10	0.557
8	150	8	500	1.033	41.11	43.14	0.542
9	150	6	1500	0.117	21.37	40.17	0.582
10	200	6	2500	0.190	21.17	42.10	0.511
11	200	8	500	0.258	15.15	36.17	0.503
12	100	8	500	0.440	11.16	41.16	0.418
13	100	8	2500	0.267	31.10	40.16	0.431
14	150	10	2500	0.221	39	33.17	0.301
15	150	10	1500	1.102	40.10	31.97	0.295

Table 9 Optimum machining conditions

Response	Goal	Desirability	Optimum combination			Predicted value	Actual value
			A (v)	B (μf)	C (rpm)		
SR	Minimum	0.658	100	6	2500	0.170	0.180
Overcut	Minimum	0.658	100	6	2500	41.16	41.68
circularity	Maximum	0.658	100	6	2500	42.11	42.16

4.4 Multi objective optimization of response parameters by desirability approach

Multi response optimization was obtained for optimal machining conditions of micro EDM process by desirability approach. The goal is to minimize the surface roughness, overcut and maximize the circularity. A set of 15 optimal solutions is established for the distinct parameters of surface roughness, overcut and circularity using design expert statistical software. The high value of desirability shows the optimum machining condition for the different parameters as shown in Table 8.

Experimental results have been compared with predicted value. Both the results are estimated for optimum process variables and their corresponding average value of surface roughness, overcut and circularity are shown in Table 9. It is found that, the multi objective predicted value and experimental result shows optimized value and their results are within the acceptable limits of 98% confidence intervals.

4.5 Regression modeling

Regression modeling has been used to present the inter relationship between dependent and independent variables. Response variables such as surface roughness, overcut and circularity depends on voltage, capacitance and electrode rotation speed. The analytical model has been established and regression equation as follows.

Model equation of SR

SR =1.68 - 0.0045 Voltage + 0.248 Capacitance - 0.002154 Electrode rotation speed (N)
+0.000062 Voltage*Voltage - 0.0213 Capacitance*Capacitance
+ 0.000000 Electrode rotation speed (N)*Electrode rotation speed (N)

- 0.001064 Voltage*Capacitance - 0.000003 Voltage*Electrode rotation speed (N)
+ 0.000136 Capacitance*Electrode rotation speed (N)(1)

Model equation of circularity
Circularity=-118 + 0.236 Voltage + 33.0 Capacitance + 0.0088 Electrode rotation speed (N)
- 0.00005 Voltage*Voltage - 2.23 Capacitance*Capacitance
- 0.000005 Electrode rotation speed (N)*Electrode rotation speed (N)
- 0.0129 Voltage*Capacitance - 0.000006 Voltage*Electrode rotation speed (N)
+ 0.00152 Capacitance*Electrode rotation speed (N)(2)

Model equation of overcut
Overcut=124.9 + 0.419 Voltage - 30.0 Capacitance + 0.0034 Electrode rotation speed (N)
- 0.00065 Voltage*Voltage + 2.114 Capacitance*Capacitance
+ 0.000002 Electrode rotation speed (N)*Electrode rotation speed (N)
- 0.0277 Voltage*Capacitance - 0.000066 Voltage*Electrode rotation speed (N)
+ 0.00061 Capacitance*Electrode rotation speed (N)(3)

5. Conclusion

This paper describes multi objective optimization process of micro EDM process of Titanium alloy. The statistical analysis of ANOVA shows that the major influencing parameters observed in this study improved machining performance of micro EDM process.

- The ANOVA technique is used to estimate the machining parameters of voltage, capacitance and electrode rotation speed which influence the machining performance of micro EDM process. ANOVA test result shows that machining parameters of voltage (A), capacitance (B), electrode rotation speed (C), interaction of voltage and capacitance (AB), voltage and electrode rotation speed (AC), capacitance and electrode rotation speed (BC) have significant effect of surface roughness , overcut and circularity.

- The mathematical modeling of regression analysis was evaluated for predicting optimal condition of surface roughness, overcut and circularity.

- The multi objective optimization technique of all three responses of surface roughness, overcut and circularity are evaluated. The optimal machining condition of Titanium alloy can be achieved is at voltage of 100 V, capacitance of 8 µf and electrode rotation speed of 2500 rpm. This combination of parameter results in minimum surface roughness of 0.180 µm, overcut of 41.68 µm and circularity of 42.16 µm is achieved.

- All the process parameters plays a significant role amongst which capacitance and electrode rotation speed were the most influencing parameters for the reduction of surface roughness and overcut.

References

[1] M. Nurhaniza, M. K. A. M. Ariffin, F. Mustapha, and B. T. H. T. Baharudin. Analyzing the Effect of Machining Parameters Setting to the Surface Roughness during End Milling of CFRP-Aluminium Composite Laminates. International Journal of Manufacturing Engineering ,2016, https://doi.org/10.1155/2016/4680380.

[2] Sanjeev Kumar, Rupinder Singh, T.P.Singh, B.L.Sethi. Surface modification by electrical discharge machining: A review, Journal of Materials Processing Technology, 209 (8), 2009, Pp. 3675-3687. https://doi.org/10.1016/j.jmatprotec.2008.09.032.

[3] Shajan Kuriakose, M.S.Shunmugam. Characteristics of wire-electro discharge machined Ti6Al4V surface. Materials Letters, 58 (17–18), 2004, Pp. 2231-2237. https://doi.org/10.1016/j.matlet.2004.01.037.

[4] J. Y. Kao, C. C. Tsao, S. S. Wang & C. Y. Hsu. Optimization of the EDM parameters on machining Ti–6Al–4V with multiple quality characteristics, The International Journal of Advanced Manufacturing Technology volume 47, pages395–402(2010). https://doi.org/10.1007/s00170-009-2208-3.

[5] Munmun Bhaumik and Kalipada Maity. Effect of different tool materials during EDM performance of titanium grade 6 alloy, Engineering Science and Technology, an International Journal, 21(3), 2018, Pp. 507-516. https://doi.org/10.1016/j.jestch.2018.04.018.

[6] T. Roy, P.S. Sarkar & R. Balasubramaniam. Non-destructive surface characterization of reverse micro-EDM-induced arrayed µ-features with varying aspect ratio. The International Journal of Advanced Manufacturing Technology volume 107, pages2609–2622(2020). https://doi.org/10.1007/s00170-020-05217-w

[7] A. Pramanik, A.K. Basak and C. Prakash. Understanding the wire electrical discharge machining of Ti6Al4V alloy.Heliyon, 2019, 5(4). doi: 10.1016/j.heliyon.2019.e01473.

[8] Xiangzhi Wang, Zhidong Liu, Rongyuan Xue, Zongjun Tian&Yinhui Huang. The International Journal of Advanced Manufacturing

Technologyvolume 72, pages979–987(2014). https://doi.org/10.1007/s00170-014-5716-8.

[9] Muhammad P. Jahan & Farshid Alavi. A Study on the Surface Composition and Migration of Materials and Their Effect on Surface Microhardness during Micro-EDM of Ti-6Al-4V. Journal of Materials Engineering and Performance volume 28, pages3517–3530(2019). https://doi.org/10.1007/s11665-019-04120-0

[10] Somvir Singh Nain,Dixit Gargand SanjeevKumar. Modeling and optimization of process variables of wire-cut electric discharge machining of super alloy Udimet-L605. Engineering Science and Technology, an International Journal, 20 (1), 2017, Pp. 247-264. https://doi.org/10.1016/j.jestch.2016.09.023.

[11] M. Vignesh&R. Ramanujam. Machining of Ti–6Al–4V using diffusion annealed zinc-coated brass wire in WEDHT. Journal of the Brazilian Society of Mechanical Sciences and Engineeringvolume 41. https://doi.org/10.1007/s40430-019-1860-2.

[12] PR. Periyanan1, U. Natarajan, A. Elango. Optimization of parameters on material removal rate in micro-WEDG process, International Journal of Engineering, Science and Technology Vol. 3, No. 9, 2011, pp. 66-76. DOI: http://dx.doi.org/10.4314/ijest.v3i9.5.

[13] Farshid Alavi&Muhammad P. Jahan. Optimization of process parameters in micro EDM of Ti-6Al-4V based on full factorial design. The International Journal of Advanced Manufacturing Technologyvolume 92, pages167–187(2017). https://doi.org/10.1007/s00170-017-0103-x.

[14] Nitesh Krishnan J ,Deepak J and Hariharan P. Multi-response optimization of electro chemical micro machining on maskedSS304. Eng.Res.Express2(2020)015041. https://doi.org/10.1088/2631-8695/ab5eb9