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Study of Hole Accuracy in Electro Discharge Machining of Ti6Al4V Alloy

Prithwiraj Roy, Arka Mondal*, Souren Mitra
Department of Production Engineering
Jadavpur University, Kolkata-700032, INDIA

Abstract

Ti6Al4V is an extensively used alloy in industries like aeronautics, automobile etc. Ti6Al4V is an alpha-beta titanium alloy with high strength to weight ratio and excellent corrosion resistant. Machining of this alloy is considered to be very difficult with conventional machining process due to its inherent physical properties, like high strength, low thermal conductivity etc. Therefore, electro discharge machining (EDM) has been considered as an alternative process to machine this material. EDM is a non-conventional machining process used to machine, difficult to machine conductive materials, where spark, generated in between tool and workpiece, erodes material from workpiece. The main challenge to this process is its machining rate and dimensional control. In the present research the same has been addressed by modifying the tool shape, making its face tapered. In this research full factorial design of experiments has been conducted to study the effect of process parameters, like peak current (I_p), pulse-on-time (T_{on}), duty cycle (T_{au}) and effect of tapered tool on responses, like diametric over-cut (DOC) and hole taper angle of machined hole. It is significant to see that using a tapered tool diametric over-cut has been decreased by 30%. It is also has been observed that use of tapered tool lead to enhanced dimensional accuracy at the lower part of the hole. As a result, the hole taper angle has been increased slightly using tapered tool.

Keywords: EDM, Ti6Al4V, Tapered tool, Diametric Over-Cut (DOC), Hole taper

1. INTRODUCTION

Ti6Al4V is an extensively used grade-V alpha-beta titanium alloy. The distinct features of this materials are like high strength to weight ratio, high corrosion resistivity. It has wide range of applications in aerospace industry, biomechanical engineering, marine engineering, in gas turbines and also in chemical industries. Because of its wide range of applications, need of machining Ti6Al4V has become very much important, but machinability of Ti6Al4V is considered to be very poor. High chemical affinity, low thermal conductivity and high strength have made it very difficult to machine using conventional machining processes. Therefore, the need of non-conventional machining process like EDM has become very significant to machine this material accurately.

In EDM, electrical energy is used to generate spark in between tool and workpiece, this spark generates thermal energy. Due to this, the temperature of the material rises more than 10^4 K which is much higher than the melting point temperature of the material and finally the material is eroded by melting and vaporization. As in EDM material is thermally eroded, mechanical properties of tool and workpiece material has no effect in machining, rather the thermal properties of the material has a significant effect here. Therefore, EDM is a viable and competitive option for precision machining of hard materials like titanium alloys. However during machining due to the improper flushing out of debris, its frequent adhesion between tool electrode and workpiece prevents the stability of the machining. Thus it hampers the accuracy of the machining. That’s why a proper control of this process is required to achieve desired accuracy.

In recent year various researches has been carried out to achieve desired machining characteristics in EDM. Various modification of EDM process aiming better material removal has also been found. G. D’Urso et al.[1] proposed helical grooves on tool surface to achieve better geometrical accuracy of machined hole and also investigated the influence of the electrode shape, electrode material, workpiece material and process parameters on the final output. Lin Gu et al.[2] suggested bundled electrode and multi hole inner flushing through electrode to achieve better machining characteristics. M.P.Jahan et al.[3] proposed low frequency workpiece vibration for better machining performance, dimensional accuracy and surface quality. They also mathematically modelled the vibration to achieve desired effect. Vijay Verma et al.[4] studied the different parametric influence on machining characteristics of Ti6Al4V alloy and also optimized the process parameters using full factorial design of experiments. Raju B. Bhosle et al. [5] also studied the effect of different process parameters on material removal and geometrical accuracy of machined hole on Inconel 600 alloy.

In this present research a simple and cost-effective modification has been investigated by making the tool tapered. Full factorial method of design of experiments has been used in the study to plan the experimental trials. The effect of various process parameters like gap current, pulse-on-time, duty factor and also the effect of tapered tool has been studied on diametric overcut (DOC) and hole taper during machining of Ti6Al4V alloy material. Also Analysis of Variance (ANOVA) has been carried out to investigate the significance of different process parameters for diametric over-cut (DOC), hole taper angle.

2. EXPERIMENTAL DETAILS

Experimental details and methodology has been described below.

2.1. EDM Tests

The experiments are performed on ZNC ELECTRA machine with side jet flushing arrangement. Fig. 1 shows the photographic view of that ZNC ELECTRA EDM.
Experiments are carried out using Ferrolac 3M EDM oil as dielectric fluid.

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[*] Arka Mondal, arka630@gmail.com

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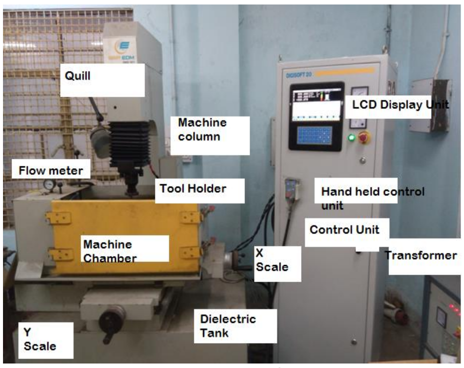

Fig. 1: Photographic view of ZNC ELECTRA

Material:

In this research, Ti6Al4V has been used as workpiece material. Chemical composition of the material is presented in Table 1. To conduct the experiments, the workpiece was sliced in wire-EDM. The workpiece used in this research work is of square shape (20mm x 20mm) with 1.2 mm of thickness.

Table 1: Chemical composition of Ti6Al4V alloy

Aluminum (Al)	6%	Carbon (C)	0.08%
Vanadium (V)	4%	Nitrogen (N)	0.05%
Iron (Fe)	0.4%	Hydrogen (H)	0.015%
Oxygen (O)	0.2%	Titanium (Ti)	Balance

Copper electrode of 3mm diameter has been used for experimental purpose. Two types of tool has been used here, one flat tool another tapered tool (Taper angle 73.74^0). Schematic diagram of the tools are shown in Fig. 2.

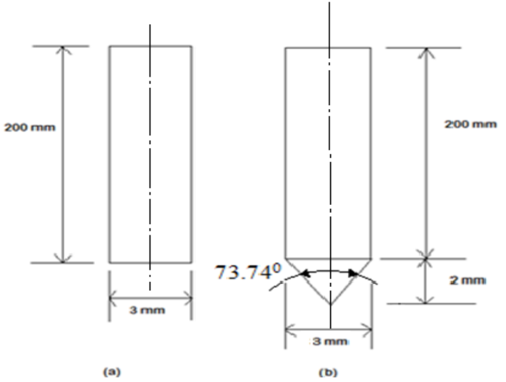

Fig. 2. Schematic diagram of tool (a) Flat tool (taper angle 180°) (b) Tapered tool (taper angle 73.74°)

Method*:*

The experiments have been conducted here in accordance with mixed level full factorial method of design of experiments. The parameters and levels of each parameters have been shown in Table 2.

Table 2. Machining parameters

Input Parameters	Level 1	Level 2	Level 3
Peak current (amp) (I)	4	6	7
Pulse on time(µs) (T_{on})	7.5	10	15
Duty factor (%) (T_{au})	40	50	
Tool taper angle(degree)	73.74 (tapered tool)	180 (flat tool)	

2.2. Process Characterization

For the evaluation of precision of the machined hole, two different responses have been considered. These are,

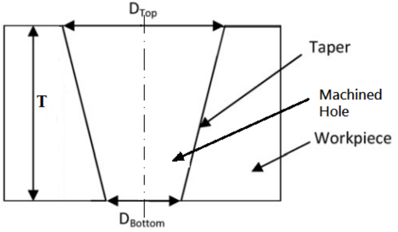

Fig. 3. Schematic diagram of machined hole

Diametric Over-cut (DOC): The diameter of the machined hole is greater than the diameter of the tool. Difference between this effective top diameter of machined hole (D_{Top}) and tool diameter (D_{Tool}) is termed as DOC.

$$DOC= D_{Top} - D_{Tool}$$

Hole Taper Angle: Hole taper angle is the second machined hole precision indicator evaluated in this research. This gives information about the tapering of hole due to electo discharge machining. Hole taper angle has been calculated as,

$$\text{Hole Taper Angle} = \tan^{-1} [(D_{Top} - D_{Bottom})/2T]$$

3. RESULTS & DISCUSSIONS

In this experimental plan two responses, diametric over-cut (DOC) and hole taper, have been taken. The experimental value of DOC and hole taper are obtained through experiments according to the experimental plan based on DOE, as shown in Table 3.

Table 3.Experimental results for DOC & Taper angle

Std. Ord.	I (amp)	Ton (µs)	T_{au} (%)	Tool taper angle (^{0})	DOC (µm)	Hole taper angle (^{0})
1	4	7.5	40	73.74	94	2.1870
2	4	7.5	40	180	95.4	1.0970
3	4	7.5	50	73.74	89.5	1.3770
4	4	7.5	50	180	96.6	0.7625
5	4	10	40	73.74	62.6	0.6810
6	4	10	40	180	106.9	0.4650
7	4	10	50	73.74	57.35	2.2670
8	4	10	50	180	68.5	1.8700
9	4	15	40	73.74	89.9	2.6360
10	4	15	40	180	145.1	2.0930
11	4	15	50	73.74	80.6	2.8270
12	4	15	50	180	97.7	1.4120
13	6	7.5	40	73.74	60.1	1.4480
14	6	7.5	40	180	99.85	0.5200
15	6	7.5	50	73.74	97.5	0.6125
16	6	7.5	50	180	93.4	0.4870
17	6	10	40	73.74	82.2	0.7310
18	6	10	40	180	114.2	0.9911
19	6	10	50	73.74	76.7	3.1880
20	6	10	50	180	124.3	1.8480
21	6	15	40	73.74	84.5	1.9440
22	6	15	40	180	135.3	2.2960
23	6	15	50	73.74	96.9	2.6500

24	6	15	50	180	154.3	1.9110
25	7	7.5	40	73.74	65.4	1.0713
26	7	7.5	40	180	93.1	1.4584
27	7	7.5	50	73.74	100	1.2260
28	7	7.5	50	180	101.8	1.1079
29	7	10	40	73.74	69.8	0.9716
30	7	10	40	180	104.2	1.1280
31	7	10	50	73.74	68.2	3.0338
32	7	10	50	180	100.4	2.2840
33	7	15	40	73.74	63.6	1.7920
34	7	15	40	180	143.5	3.1527
35	7	15	50	73.74	96.5	2.2840
36	7	15	50	180	130.2	2.2590

3.1. Analysis of DOC:

The analysis of variance (ANOVA) has been carried out to determine influence of different parameters and also influence of their interaction effect on DOC. Table 4 shows the ANOVA (analysis of variance) tale for DOC.

Table 4. ANOVA for DOC

Source	DF	Adj SS	Adj MS	F Value	P Value
Peak current	2	773.0	386.50	4.23	0.034
Pulse on time	2	3781.9	1890.95	20.68	0.000
Duty factor	1	12	12.02	0.13	0.722
Tool taper angle	1	9006	9006.01	98.48	0.000
Peak current *pulse on time	4	1036.3	259.07	2.83	0.060
Peak current *duty factor	2	1532.3	766.15	8.38	0.003
Peak current *tool taper angle	2	366.3	183.16	2.00	0.167
Pulse on time *duty factor	2	574.8	287.42	3.14	0.071
Pulse on time*tool taper angle	2	2042.5	1021.24	11.17	0.001
Duty factor*tool taper angle	1	724.5	724.51	7.92	0.012
Error	16	1463.2	91.45		
Total	35	21312.8			
R-sq – 93.13%		R-sq(adj) - 84.98%			

(DF-degrees of freedom, SS-sum of squares, MS-mean square)

From Table 4 it is observed that tool taper angle has the maximum effect on DOC. P value for duty factor, as shown in Table 4, is .722 which is much higher than 0.05. As the P value for duty factor is that much high, the effect of duty factor on DOC is insignificant.

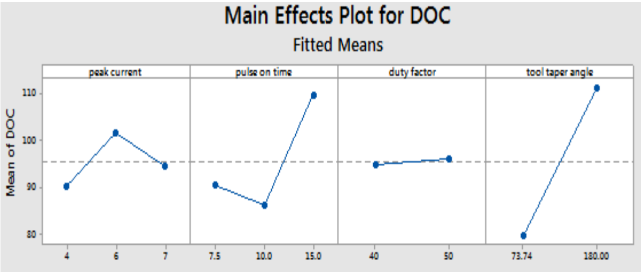

Fig. 4. Main Effects Plot for DOC

The main effects of DOC have been shown in Fig. 4. From main effect it has been observed that as peak current increases from 4 amp to 6 amp, DOC increases .When current increases, discharge energy increases too. By enhancement of discharge energy, more thermal energy has been transferred to the machining zone. This phenomenon leads to melting and vaporizing of more material. Therefore, the diameter and depth of crater increases and more overcut has been occurred at higher current value. Also larger size debris have been formed due to higher discharge at higher current value and these are difficult to flush away from machining zone. These debris in the machining zone causes secondary discharge at the side walls of machined hole. These secondary discharges affects the hole accuracy and increases the DOC. On the other hand, as the peak current increases from 6amp to 7 amp, DOC decreases. High increase in peak current causes comparatively higher tool wear rate. Due to high tool wear, dimension of the tool decreases. As a result diameter of the machined hole also decreases. Because of that at high peak current range, the DOC decreases.

As pulse-on time (T_{on}) increases from 7.5 µs to 10 µs the DOC decreases, because due to higher T_{on} tool wear rate increases. As the tool wear rate increases, dimension of the tool decreases, as a result diameter of the machined hole decreases too and DOC decreases. On the other hand, as T_{on} increases from10µs to 15µs, a high rise in DOC has been observed. Discharge energy increases as T_{on} increases. As a result larger crater forms. Although tool wear rate is increasing, but effect of larger crater size is much higher here. Because of this, the high rise in DOC has been observed.

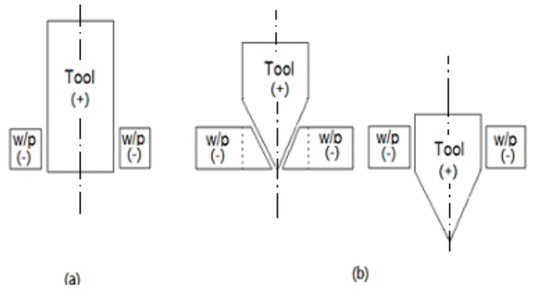

Fig. 5. Material removal using (a) flat tool (b) using tapered tool

It is significant to observe that tapering of EDM tool has decreased the DOC almost by 30%. In case of flat tool the tool is continuously interacting with the final machined surface as shown in Fig. 5.(a). On the other hand, in case of tapered tool, tapered portion of the tool drills a smaller conical hole first, then the tool finishes hole. So, the tool interacts with the final machined surface for a lesser period of time as shown in Fig. 5.(b). As the tool is interacting with the final machined surface for a lesser period of time, the accuracy of the final machined surface is increasing and DOC is decreasing as shown in fig.4. Also as the tapered tool drills the conical hole in the workpiece first, the flushing of debris from the machined surface gets easier which also causes the improved DOC.

3.2. Analysis of Hole Taper Angle:

The analysis of variance (ANOVA) also has been carried out for hole taper angle. Table 5 shows the ANOVA table for hole taper angle.

Table 5. ANOVA table for hole taper angle

Source	DF	Adj SS	Adj MS	F Value	P Value
Peak current	2	0.4266	0.21329	1.58	0.236
Pulse on time	2	8.0927	4.04636	30.02	0.000
Duty factor	1	1.2632	1.26323	9.37	0.007
Tool taper angle	1	0.9295	0.92949	6.90	0.018
Peak current *pulse on time	4	0.9923	0.24807	1.84	0.170
Peak current *duty factor	2	0.1002	0.05010	0.37	0.695
Peak current * tool taper angle	2	1.2084	0.60422	4.48	0.028
Pulse on time *duty factor	2	6.7279	3.36397	24.95	0.000
Pulse on time *tool taper angle	2	0.1073	0.05363	0.40	0.678
Duty factor* tool taper angle	1	0.7695	0.76948	5.71	0.030
Error	16	2.1569	0.13480		
Total	35	22.7744			
R-sq – 90.53%		R-sq(adj) - 79.28%			

ANOVA table clearly shows that pulse-on-time has the most significant effect on hole taper angle. Apart from that, the interaction between pulse-on-time and duty factor has also significant effect on hole taper angle. P value for peak current here is very high. Therefore, the effect of peak current is insignificant here.

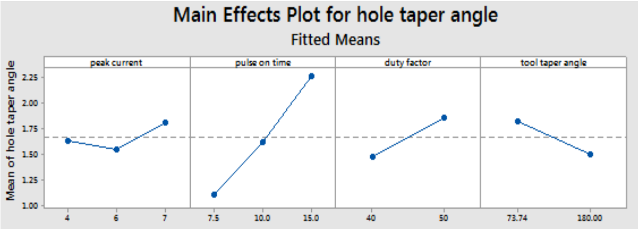

Fig. 6. Main Effects Plot for hole taper angle

It has been observed from Fig. 6 that increase in pulse on time, increases hole taper angle very sharply. Tool wear increases with increase in pulse on time. As a result the diameter of the tool decreases with time, i.e., diameter of the tool decreases as the tool reaches the bottom surface of the workpiece. Diameter of the machined hole also decreases with decrease in tool diameter along the thickness of workpiece, as a result increase in hole taper angle is observed.

Similarly, hole taper angle has also been increased with duty factor. Frequency of spark increases as the duty factor increases. High frequency of spark causes high tool wear rate and this finally causes the high rise in hole taper angle.

Also it is significant to observe that use of tapered tool has caused rise in hole taper angle. As shown in Fig. 5 the tapered tool firstly drills a conical hole, then it finishes the hole. To finish the conical hole, higher amount of material is to be removed from lower surface of the workpiece than the upper surface. As a result, the feed rate of the tool gradually decreases as it moves from upper to lower surface of the material during finishing of the hole. Because of that the upper portion of the finished hole surface is exposed to side spark relatively for a longer period of time than the lower part of the finished hole surface. As a result the accuracy of the lower part of the hole is higher than the upper part of the hole. This means a slight high difference of diameter between upper and lower surface of the hole which finally causes larger hole taper angle due to the use of tapered tool.

4. CONCLUSION

In the present work, a detailed experimental work on Ti6Al4V has been carried out to investigate the effect of different process parameters on diametric over-cut and hole taper angle. Tapered tool has been introduced to improve the accuracy of machining. The following conclusions have been drawn from the present work

- Diametric over-cut (DOC) of the machined hole has been increased with increasing current and pulse-on-time.
- DOC has been decreased almost 30% by using tapered tool.
- Hole taper angle has been increased as pulse-on-time and duty factor increased.
- Hole taper angle has been increased using tapered tool as the accuracy of the machined hole at the lower part of the workpiece has been increased.

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