Fuzzy Modeling for Micro EDM Parameters Optimization in Drilling of Biomedical Implants Ti-6Al-4V Alloy for Higher Machining Performance

Ahmed A.D. Sarhan, Lim Siew Fen, Mum Wai Yip, M. Sayuti

***Abstract*—**Ti6Al4V alloy is highly used in the automotive and aerospace industry due to its good machining characteristics. Micro EDM drilling is commonly used to drill micro hole on extremely hard material with very high depth to diameter ratio. In this study, the parameters of micro-electrical discharge machining (EDM) in drilling of Ti6Al4V alloy is optimized for higher machining accuracy with less hole-dilation and hole taper ratio. The micro-EDM machining parameters includes, peak current and pulse on time. Fuzzy analysis was developed to evaluate the machining accuracy. The analysis shows that hole-dilation and hole-taper ratio are increased with the increasing of peak current and pulse on time. However, the surface quality deteriorates as the peak current and pulse on time increase. The combination that gives the optimum result for hole dilation is medium peak current and short pulse on time. Meanwhile, the optimum result for hole taper ratio is low peak current and short pulse on time.

***Keywords*—**Micro EDM, Ti-6Al-4V alloy, fuzzy logic based analysis, optimization, machining accuracy.

I. Introduction

THE non-conventional micro EDM drilling process is widely used in machining extremely hard material [1]. Ti6Al4V has high tensile strength and high toughness at extreme temperature, light weight, good formability, high erosion resistance, high resistance to extreme temperature and so on [2]. The good characteristics of Ti6Al4V have made it the popular material in automotive industry, aerospace industry, and even the medical field due to its high biocompatibility [3]. Micro-EDM which is able to drill micro hole with high depth to diameter ratio is desirable in machining Ti6Al4V [4].

The objectives of this study were to investigate the influences of parameters of EDM on the hole dilation and hole taper ratio. Peak current and pulse on time were the parameters that manipulated in this experiment to determine the highest accuracy where the hole dilation and hole taper ratio were the smallest [5]. The quality of machined surface and tool electrode was investigated in this study. This study is useful in improving the surface quality and product quality of micro-EDM drilling process.

Mustafa Ay, Ulas Caydas, Ahmet Hascalik found that the increasing of peak current and pulse on time increase the hole dilation, hole taper ratio and gives bad surface characteristics [1]. In [5], they reported that as peak current and pulse on time increases, material removal rate (MRR) increases. Meanwhile, medium value of pulse off time and low value of pulse off time persuade the largest MRR [5].

Ahmed. A.D. Sarhan is with the Center of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (Corresponding author phone: +60379674593; fax: +60379675330; e-mail: ah_sarhan@um.edu.my).
Lim Siew Fen and M. Sayuti are with the Center of Advanced Manufacturing and Material Processing, Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, 50603, Malaysia (e-mail: s_fen512@hotmail.com, mdsayuti@um.edu.my).
Mum Wai Yip, is with Tunku Abdul Rahman University College, Jalan Genting Kelang, 53300 Setapak, Kuala Lumpur, Malaysia (e-mail: ayipmw@acd.tarc.edu.my).

II. Methodology

A. Experimental Setup

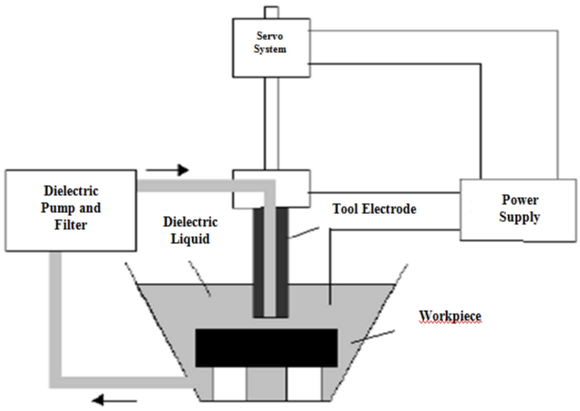

Fig. 1 Basic elements of EDM system

Fig. 1 shows the basic elements of EDM system. Power generator is on and the power is transmitted to the tool electrode through the tool holder. The workpiece is clamped to working table using magnetic conductive. X, Y, Z axis is adjusted to the desired distance. Dielectric fluid that used in this experiment is kerosene. The dielectric fluid is precisely filtered to avoid short circuit in the process and the dielectric nozzle is placed near to the working area to flush chips away from sparking area. The sparking gap between electrode and workpiece is automatically adjusted and retracted by servo motor in the process.

The tool electrode used in this study is copper tube with ϕ 0.8mm diameter. The workpiece (Ti6Al4V) size is 6.3mm×70mm×110mm and the drilling depth is fixed at 6.3mm deep as shown in Fig. 2.

To calculate hole-dilation and hole-taper ratio, the diameter of tool electrode and both of the micro entrance and micro exit hole diameters are measured. Diameters of both the entrance and exit hole on workpiece are measured by scanning electron microscope (SEM). While, the quality of the electrode and holes surface are analyzed by SEM as well.

The hole taper ratio (%) is the ratio of entrance hole diameter and exit hole diameter as shown in (1):

$$H_t(deg) = Tan\ \alpha = \frac{d_{entrance} - d_{exit}}{2t} \quad (1)$$

where, $d_{entrance}$ = Hole entrance diameter; d_{exit} = Hole exit diameter; t = Thickness of material

The hole dilation (mm) is the difference between average diameter of drilled holes and the average diameter of original electrode as shown in (2):

$$H_d = \Delta c - D_e \quad (2)$$

$$\Delta c = \frac{D_1 + D_2 + \dots\dots + D_n}{n}$$

where; De is the original electrode diameter.

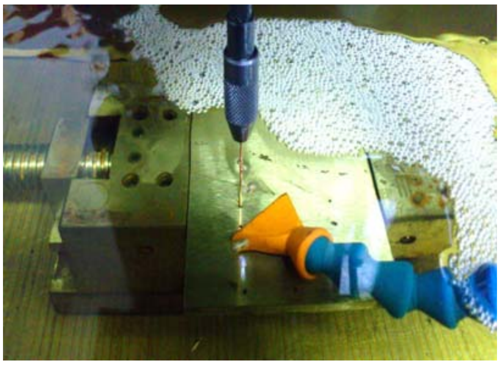

Fig. 2 Tool electrode and workpiece

B. Machining Control

The machining code C350, standard set of parameter is used to execute the experiment, shown in Tables I and II.

C. Design of Experiment

The micro-EDM machining parameters used in this research work are the peak current and pulse on time. The parameters and levels used are shown in Table III. While the experimental array of L_9 with 2 parameters 3 levels is shown in Table IV.

TABLE I
THE MACHINING CODE C350

Parameter	Machine code	Magnitude
Quiescent time	MA	01
Polarity	PL	+
No-load	V	01
Pulse control	PP	10
Capacitor	C	00
Servo speed	S	02
Pulse off time	OFF	07
Servo voltage	SV	5

TABLE II
STANDARD PARAMETER

Parameters	Peak current	Pulse on time
Machine code	IP	ON

TABLE III
PARAMETERS AND LEVELS

Parameters	Levels		
	1	2	3
A - Peak current, (A)	0.3	0.6	0.9
B - Pulse on time, (μs)	6	12	30

TABLE IV
L_9 EXPERIMENTAL ARRAY

No. of Experiments	Parameter combinations	
	A	B
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

D. Fuzzy Logic Analysis

Fuzzy logic analysis is used to find the optimum result through the combination of parameters. It includes the max-min fuzzy inference and it is applied to deal with multiple responses using the fuzziness of human concepts. This is worked by using linguistic variables which are associated with different levels of linguistic values to map with uncertainty or so-called fuzziness. There are three major parts of a fuzzy logic controller; such are fuzzifier, inference engine, and defuzzifier.

The fuzzizier first obtains the fuzziness of each input parameter through the membership functions, which map an input parameter from the input domain to a fuzzy value between 0 and 1. The inference engine then uses fuzzy rules (if-then inference rules) to perform fuzzy inference to synthesize output fuzzy value. The defuzzifier is then converts the fuzzy value into a fuzzy reasoning grade. The inference engine triggers the If-Then inference rules,

Rule 1: if x1 is A1 and x2 is B1 and x3 is C1 then y is D1
Rule 2: if x1 is A2 and x2 is B2 and x3 is C2 then y is D2

Ai, Bi, Ci and Di are fuzzy subsets defined by the corresponding membership functions where y is the multi-response output. Based on the values obtained from experiment, various degrees of membership of the fuzzy sets are calculated. Finally, the defuzzifier mapped output fuzzy values back to the output domain to generate the output parameters. The membership function is plotted according to the range of the parameters.

Fig. 3 shows the membership function of peak current as an example of the input parameter. Meanwhile, Figs. 4 and 5 show the membership function of holes dilation and holes tapper ratio as output parameters.

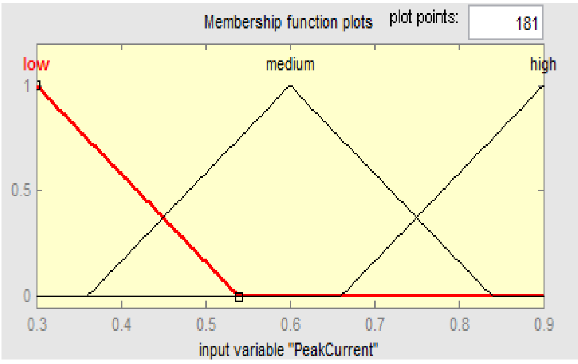

Fig. 3 Membership function of peak current as an input parameter

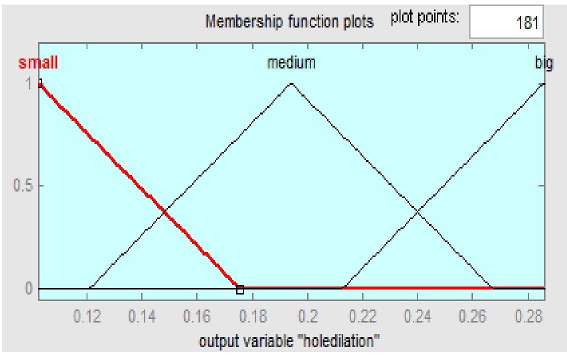

Fig. 4 Membership function of holes dilation

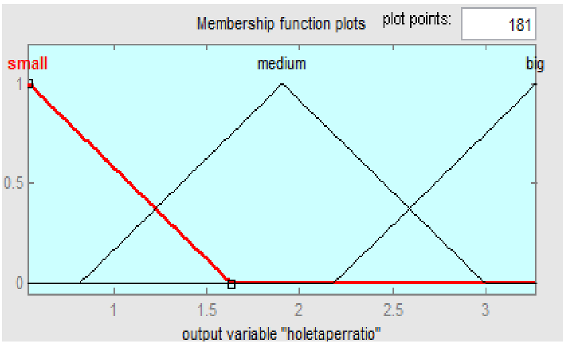

Fig. 5 Membership function of holes tapper ratio

III. Results, Analysis and Discussion

A. SEM Micrograph Results

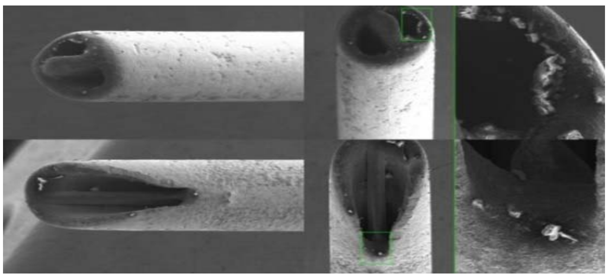

Fig. 6 SEM micrograph of the surface of copper tool electrode at 0.6A and 6µs (a & b) and 0.9A and 12µs (b & c)

Figs. 6 (a) & (b) depict the surface condition of tool electrode at 0.6A and 6µs (Exp. No. 4). These parameters combination determined the best result where the tool wear is minimum. In addition, the condition on the lateral surface appears to be smooth and contains less craters. Meanwhile, Figs. 6 (c) & (d) show surface condition of tool electrode at 0.9A and 12µs (Exp. No. 8). These parameters combination gives the biggest holes dilation and biggest holes taper ratio. Beside, the electrode wear is more serious compare to the other case shown in Figs. 6 (a) & (b) (exp. no. 4). As can be seen in Figs. 6 (c) & (d) the lateral surface is rough and coarse and the tip of the electrode is observed to be tapered off. These are mainly caused by the high peak current value. Figs. 7 (a) & (b) show the entrance and exit side images of micro-holes. As can be seen in Fig. 7, the micro-EDM process produces debris, pockmarks and melted drops of work piece material other than tool wear.

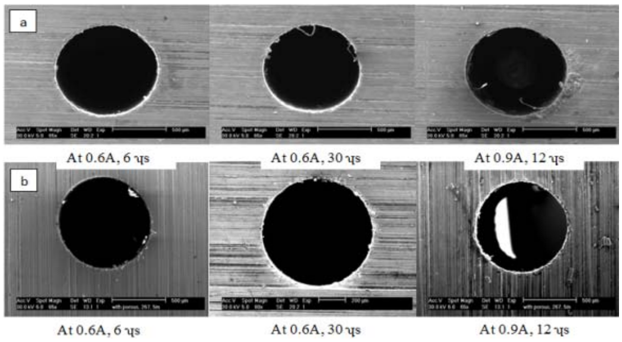

Fig. 7 Entrance (a) and exit (b) side images of micro-holes

Furthermore, the images of the holes show that the surface quality of hole is deteriorates with the increasing of peak current and pulse on time. However, the peak current looks has greater effects on surface characteristics than pulse on time. It may be attributed to that as peak current increases, the heat input increases. More heat is absorbed into workpiece causes lager recast layer and big heat affected zone. In addition, more material is melted and suspended within the spark gap. Therefore, the periphery of the hole appears to have some residue of molten material remained on it. The exit holes are more to oval shape due to the weary of the tip of the tool. The tip of the tool is no more in perfect round shape which results in exit holes that appear to be in oval shape.

B. Hole Dilation results

Table V and Fig. 8 show the hole dilation results and the 3D surface profile of holes dilation. As can be seen in Fig. 8, the lowest holes dilation is produced at 0.6A and 6µs peak current and pulse on time. Beside that the holes dilation is high at higher peak current and longer pulse on time in the combination of parameter set which is represented by the yellow area in the 3D surface profile. Electric sparks occurs at the tip as well as the lateral surface of electrode. The side spark erosion will eventually leads to a micro-holes diameter that is larger than the tool diameter. Therefore, the holes dilation is higher during high peak current. The plasma channel is extended by long pulse on time. Prolonged pulse on time exposes the affecting area of workpiece to electric spark bombardment more which turns out increases the hole dilation.

TABLE V
HOLE DILATION RESULTS

No. of Experiments	Parameter combinations		Hole dilation (mm)
	A	B	
1	1	1	0.1363
2	1	2	0.1778
3	1	3	0.232
4	2	1	0.1023
5	2	2	0.1363
6	2	3	0.1958
7	3	1	0.2045
8	3	2	0.13
9	3	3	0.2208

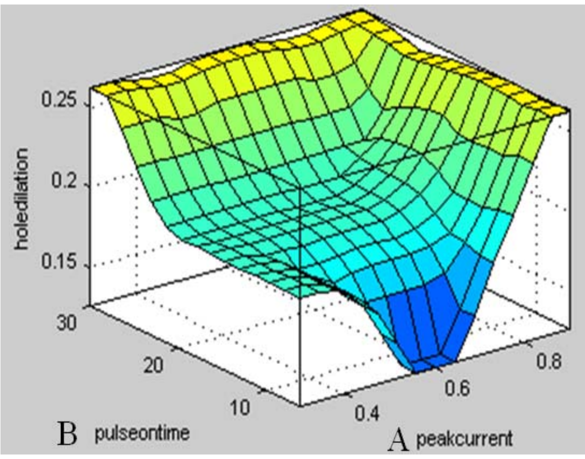

Fig. 8 (3D) surface profile of holes dilation

C. Hole Taper Ratio Results

Table VI and Fig. 9 show the hole taper ratio results and the 3D surface profile of holes taper ratio. The yellow area of the profile is representing the big hole taper ratio during high peak current and long pulse on time. As peak current increases, the violent sparks causes the material of workpiece and electrode to melt. The sparking condition and sparking area that keep changing when electrode protrudes into the workpiece lead to taper off of electrode. Electric sparks occurs more readily at the tip of the electrode compared to the lateral surface of the electrode. Since high peak current causes the electrode to taper off more, the micro hole on workpieceis also tapered off in great scale which in turns causes big hole taper ratio. During long pulse on time, single pulse energy increases. The amount of energy exposes to both the workpiece and electrode increases and more material is melted. The tool wear deteriorates in axial and radial direction. However, the tool wear happens more readily at the tip of the electrode and causes the micro hole to be non-parallel where the entrance diameter is bigg er than the exit diameter. The blue area shows the optimum result where hole taper ratio is the smallest at lower peak current and shorter pulse on time.

TABLE VI
HOLES TAPER RATIO RESULTS

No. of Experiments	Parameter combinations		Hole taper ratio %
	A	B	
1	1	1	0.543
2	1	2	2.092
3	1	3	2.778
4	2	1	0.989
5	2	2	0.838
6	2	3	1.643
7	3	1	1.519
8	3	2	1.519
9	3	3	2.14

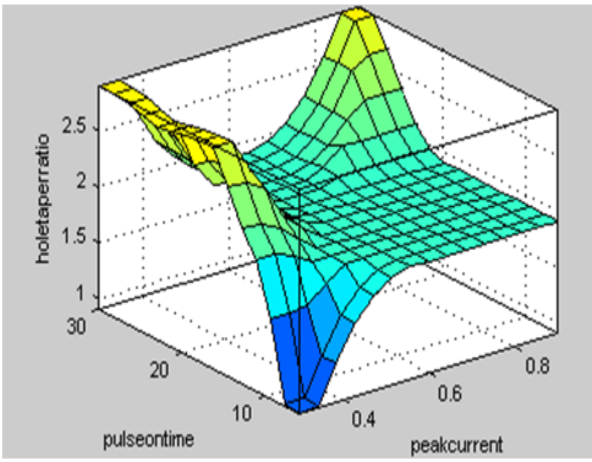

Fig. 9 (3D) surface profile of holes taper ratio

IV. CONCLUSIONS

The study has identified the best combination that gives the optimum result. Medium peak current and short pulse on time gives small hole dilation. Meanwhile low peak current and short pulse on time gives small hole taper ratio. The influences of parameters on machining characteristics were observed too. The higher the peak current and the longer the pulse on time, the bigger the hole dilation and hole taper ratio. Besides that, high peak current and long pulse on time gives bad surface quality for micro hole and cause more tool wear.

ACKNOWLEDGMENT

The authors acknowledge the financial support under the FRGS grant, project no. FP008-2014A from the Ministry of Higher Education, Malaysia.

REFERENCES

[1] Mustafa Ay & Ulas Caydas & Ahmed Hascahk (2012).Optimization of micro-EDM drilling of inconal 718 superalloy. Int J Adv. Manuf. Technol.
[2] C. Diver, J. Atkinson, H.J. Helml, L. Li (2004). Micro-EDM drilling of tapered holes for industrial application. Journal of Materials Processing Technology 149, 296-303.
[3] M. M. Rahman & Md. Ashikur Rahman Khan & K. Kadirgama M. M. Noor & Rosli A. Bakar (2010). Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity. World Academy of Science, Engineering and Technology 71.

[4] Ali Ozgedik & Can Cogun (2006). An experimental investigation of tool wear in electric discharge machining. Int J Adv. Manuf. Technol. 27, 488–500.

[5] M. M. Rahman& Md. Ashikur Rahman Khan & K. Kadirgama M. M. Noor & Rosli A. Bakar (2010). Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity. Int J of Mechanical and Materials Engineering 1:3.

Ahmed. A.D. Sarhan is graduated with a PhD from the Precision Engineering Department, Kyoto University, Japan. During his work in Japan for around 6 years, he gained experience in the field of intelligent manufacturing processes. He worked with the Intelligent Numerical Control (INC) Research Consortium with multiple industrial and academic partners. The industrial partners include OKK Corp, Sumitomo Electric Industries Ltd., Heidenhein Corporation, Mitsubishi Electric Corp., Mori Seiki Co. Ltd., Yasuda Kogyo Co. Ltd., and Yamazaki Mazak Corp. The academic partners were the University of Shiga Prefecture, Niigata University and Kyoto University. He developed an intelligent spindle for CNC machine tools with displacement and thermal sensors to simultaneously monitor the spindle characteristics and machining process in order to protect the spindle from damage at higher spindle speeds.

In 2007, Dr. Sarhan joined University of Malaya, Kuala Lumpur, Malaysia. Throughout his engineering career, he have completed several major research projects funded by the public and private sectors and has also undertaken various consulting assignments in the field of machining (higher accuracy and higher productivity machining technologies) and cutting tool technology (metal cutting operations using multiple sensors, data acquisition, and signal processing technology). He published more than (110) technical papers in reputable journals and conferences, granted 17 patents and won several gold, silver and bronze medals in local and international exhibitions. Currently, Dr. Sarhan undertaking 5 projects in commercialization. In addition, He is a reviewer for many Master and PhD theses, some reputable engineering journals and refereed international conferences.