A STATISTICAL COMPARISON OF SCREENING WIRE-EDM PARAMETERS FOR MACHINING TITANIUM ALLOY

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ABSTRACT: Wire electrical discharge machining (WEDM) is one of non-traditional processes known as a solution for machining difficult-to-machine material. In this study, the existing parameters provided by WEDM machine (Mitsubishi RA90) were tested and compared for machining Ti6Al4V purposely for parameter screening further optimization. A statistical approach namely one way analysis of variance (ANOVA) with Tukey's multiple comparison was used for effective comparison focusing on surface roughness, kerf width and material removal rate. The descriptive statistic yielded that Power Supply 1 (HP) of Mitsubishi RA90 produced higher surface roughness, kerf width and MRR compared to other conditions. In addition, the statistical comparison indicated significant difference on surface roughness for every type of categories except power supply 3 (LA) as indicated by Tukey's multiple comparisons. For kerf width, only power supply 2 (HP/MP) rejected alternative hypothesis which indicated that all the means are equal where P-value = 0.746.

KEYWORDS: *WEDM, ANOVA, MRR, Kerf Width, Surface Roughness.*

1.0 INTRODUCTION

Ti6Al4V is generally used in aerospace and automotive applications due to its high strength-to-weight ratio and heat resistant properties. This material is also chosen for biomedical applications for its biocompatibility and excellent resistance to corrosion [4-6]. Nevertheless, Ti6Al4V is categorized as a difficult-to-cut material which has low machinability ratings. Problems in machining titanium alloy are mainly due to the high cutting temperatures, low modulus of elasticity of the material and chemically reactions with the tools. Wire electrical discharge machining (WEDM) provides an effective solution for machining difficult-to-cut material like Ti6Al4V because the process is not dependent upon the hardness of the materials.

The process parameters are essential in WEDM. According to a study [6], wire breakage in machining Ti6Al4V is sensitive to electrical parameters. Besides obtaining excellent surface finish and high material removal rate (MRR), the occurrences of wire breakage should be avoided in machining Ti6Al4V. The authors investigated the effects of process parameters in machining Ti6Al4V, focusing on cutting speed, wire rupture and surface integrity.

In terms of machining Ti6Al4V by WEDM, not all of the commercial WEDM machines contain specific parameter library for cutting delicate parts made by rare and exotic materials. Mostly, the provided parameter library is only used for common type of materials in general cutting applications. Therefore, several researchers [2] investigate the influences of WEDM process parameters on MRR. Compared to other type of WEDM machines, these authors use FA10S Mitsubishi WEDM machine which applies 'notch' as a parameter unit. Basically, 'notch' represents the unit for actual value of the parameters specifically designed for Mitsubishi WEDM machine (model FA10S and RA90). The literature on appropriate parameters for this kind of machine is minimal, however the applications of this machine is widely used on various machining purposes including slits cutting [3]–[5].

Therefore, this paper presented an initial screening method to further optimization for cutting Ti6Al4V by Mitsubishi RA90 WEDM machine by which the suitable parameters for Ti6Al4V is not included in parameter library. A one way analysis of variance (ANOVA) with Tukey's multiple comparison was also used for an effective comparison. The comparison was made according to existing conditions in parameter library; Aluminium, Copper, Tungsten Carbide and Steel emphasizing on surface roughness, kerf width and MRR.

2.0 EXPERIMENTAL SET-UP

A non-submersible type WEDM, Mitsubishi RA90 (Figure 1) with 0.25 mm brass wire and deionized water dielectric fluid was utilized in this experimental study. Ti6Al4V with 10 mm thickness was used as a workpiece. The investigated machining performance were surface roughness (Ra), kerf width and MRR. The nozzle distance of upper and lower to the workpieces were set to 0.3 mm and 0.1 mm respectively. The surface roughness was measured by Mitutoyo SJ-301 portable surface roughness tester and the kerf width was measured by Meiji Zoom stereo microscope. Theoretical equations (1) was used to calculate MRR denoted as K which is the kerf width (mm), h is the workpiece thickness (mm) and FR is cutting speed (mm/min).

$$MRR = KhFR \ (mm^3/min) \tag{1}$$

Figure 1: WEDM machine Mitsubishi RA90

3.0 EXPERIMENTAL DESIGN

Mitsubishi RA90 machine has unique features in which this machine utilizes parameter library that represents actual parameters unit which is known as 'Notch' except for Voltage Gap. The parameter conditions for this machine were grouped to four categories which were Aluminium, Copper, Tungsten Carbide and Steel. Each of the material category was grouped to three types of power supply namely Power Supply 1 known as ‘HP’ which was used for rough machining, Power Supply 2 known as ‘HP/MP’ used for medium finish and Power Supply 3 known as ‘LA’ used to obtain good surface finish. Table 1 describes the details of each parameter.

12 experiments were performed on Ti6Al4V to find out which conditions provided by Mitsubishi RA90 were the best in terms of MRR, surface roughness and kerf width. Table 2 shows all the categories and conditions performed on Ti6Al4V. The feed rate for A3, C3 and S3 parameters changed from 0.25 mm/min to 0.15 mm/min to maintain the gap between wire and workpiece in which there was insufficient electric sparks to erode which led to a sudden stop of the machine, resulting in wire breakage. The feed rate value had to change in order to perform the cutting process. This method was about to push the machine limit to perform cutting process in any manner for screening purpose because this cutting process employed electrical discharge sparking phenomenon which was known as stochastic process.

Furthermore, significant differences between group means were analysed using one way analysis of variance (ANOVA), respectively, using statistical software package Minitab 16 as appropriate at α= 0.05 level of significance. Subsequently, Tukey's multiple comparison was conducted to ascertain if differences between conditions were statistically significant. Multiple comparisons assessed the statistical significance of differences between means by using a set of confidence intervals, hypothesis tests or both. Basically, the null hypothesis of no difference between means is rejected if and only if zero is not contained in the confidence interval. The benefits of the Tukey's multiple comparison are it tests all pairwise differences, simple to compute and robust with respect to unequal group sample sizes.

Table 1: Mitsubishi RA90 parameters and their descriptions [12]

Parameters	Value (Units)	Descriptions
Voltage open, Vo	1-16 Notch	This switch sets the height of the gap voltage during no-load. Voltage increases for larger notch number.
Power Setting, IP	1-18 Notch	This switch sets the size of the peak current that flows the gap. • HP: rough machining power supply mode. Notches : 4 to 16 • MP: medium finish power supply mode. Notches : 4 to 18 • LA: finish machining power supply. Notches : 1 to 3
Off Time, OFF	1-16 Notch	Switch to sets the time between end of discharge and new voltage applied. The OFF notch does not need to be set if IP is set to notch 4 or higher. OFF time decreases for lower stages and machining speed increases proportionately. However, machining is not stable, causing wire breakage or short circuits.
Stabilizer A,SA	1-8 Notch	This switch determines the machining stability and is used to finely adjust the current. The higher the value is, the faster the machining speed will be. However, if too high, wire breaks will occur. Thus, set this according wire diameter which the smaller notch value for the smaller wire diameter.
Stabilizer B,SB	1-16 Notch	This switch determines the machining stability, and is used to finely adjust the off time. The higher the value, the slower the machining speed. This parameter must be set according to the material of the workpiece.
Stabilizer C,SC	1-3 Notch	This switch is used to stabilize machining for the finishing circuit. The higher the value, the more stable is the machining. However, the results of surface roughness value will increase. When IP ≥4 notches, SC only able to set to 1.
Stabilizer E,SE	1-5 Notch	This switch sets the machining stability, and is used particularly for 1st cut machining. Notch 1 is OFF, and notches 2 to 5 are ON. As the notch value increase, the machining become slower but wire is difficult to break.
Voltage Gap, VG	1-150 Volts	This switch sets the average machining voltage used as a target value when machining with optimum feed.
Wire Speed, WS	1-16 Notch	This switch sets the wire feed rate. The higher the value, the faster the wire feed rate.
Wire Tension, WT	1-16 Notch	This switch sets the wire tension. The higher the value, the higher the tension of wire.
Pre-Tension, PT	1-16 Notch	This switch sets the wire pretension. The higher the value, the higher the pretension of wire.
Liquid Quantity, LQ	1-2 Notch	This switch sets the dielectric fluid flow rate. The flow rate is weak when set to 1 and strong when set to 2.
Liquid Resistivity, LR	1-9 Notch	This switch sets the specific resistivity of the dielectric fluid. The higher the value, the lower specific resistivity. 1 indicates that the pump is always ON.

Table 2: Parameters categories and conditions in cutting Ti6Al4V [12]

ALUMINIUM	E-PACK	Vo	IP	OFF	SA	SB	SC	SE	VG	WS	WT	PT	LQ	LR
		Notch							Volts	Notch				
A1 (0.25mm/ min)	HP 5571 (H295)	16	6	1	3	11	1	5	47	12	11	14	2	9
A2 (0.25mm/ min)	HP 5573 (H160)	9	4	1	2	15	1	1	57	12	13	14	1	9
A3 (0.15mm/ min)	LA 5575 (H133)	5	3	10	2	3	1	1	70	12	13	14	1	9
COPPER	**E-PACK**	**Vo**	**IP**	**OFF**	**SA**	**SB**	**SC**	**SE**	**VG**	**WS**	**WT**	**PT**	**LQ**	**LR**
C1 (0.25mm/ min)	HP 5151 (H276)	16	7	1	5	9	1	5	52	12	11	14	2	9
C2 (0.25mm/ min)	HP 5153 (H151)	9	4	1	2	15	1	1	57	12	13	14	1	9
C3 (0.15mm/ min)	LA 5155 (H135)	6	3	10	2	5	1	1	70	12	13	14	1	9
TUNGSTEN CARBIDE	**E-PACK**	**Vo**	**IP**	**OFF**	**SA**	**SB**	**SC**	**SE**	**VG**	**WS**	**WT**	**PT**	**LQ**	**LR**
T1 (0.25mm/ min)	HP 2211 (H229)	16	6	1	4	9	1	5	42	12	11	14	2	9
T2 (0.25mm/ min)	MP 2212 (H149)	10	12	1	2	15	1	1	55	14	13	14	1	9
T3 (0.25mm/ min)	LA 2214 (H134)	8	3	10	2	3	1	1	50	12	14	14	1	9
STEEL	**E-PACK**	**Vo**	**IP**	**OFF**	**SA**	**SB**	**SC**	**SE**	**VG**	**WS**	**WT**	**PT**	**LQ**	**LR**
S1 (0.25mm/ min)	HP 1212 (H242)	12	4	1	2	12	1	1	44	12	13	14	1	9
S2 (0.25mm/ min)	HP 1213 (H147)	8	4	1	2	12	1	1	48	12	13	14	1	9
S3 (0.15mm/ min)	LA 1215 (H134)	4	3	8	2	3	1	1	70	12	13	14	1	9

4.0 RESULTS AND DISCUSSIONS

4.1 Surface Roughness

Figure 2 shows the surface roughness for Ti6Al4V for all conditions. The Power Supply 1 (HP) produced higher surface roughness value followed by Power Supply 2 (HP/MP). The excellent surface roughness value was achieved by Power Supply 3 (LA) with mean value as much as 0.584 μm for condition S3 with feed rate of 0.15 mm/min (Table 3). Moreover, condition T3 produced the excellent surface finish with less variations compared to the other conditions.

However, by employing Tukey's family error method to account in multiple comparisons among the categories in this Power Supply 3 (LA), the ANOVA indicated there was no significant difference due to each condition shared the same letter. Thus, the use of any conditions in this type of power supply produced similar results in statistical perspective. Furthermore, by comparing between categories, all the conditions met all assumptions for parametric statistical analysis. One way ANOVA indicated P-value less than 0.05 (Table 4). Hence, there were significant differences among the categories mean and concluded each condition produced different results according to its categories.

The main parameters that contributed to the surface roughness results by means of variation for each Third Condition (LA) parameters were Vo, OFF, SB, VG and WT as shown in Table 2. According to literature, peak current (IP) should influence the surface roughness value [13-15]. However, the highest value of current can only be set from 1 to 3 notches in Third Condition (LA).

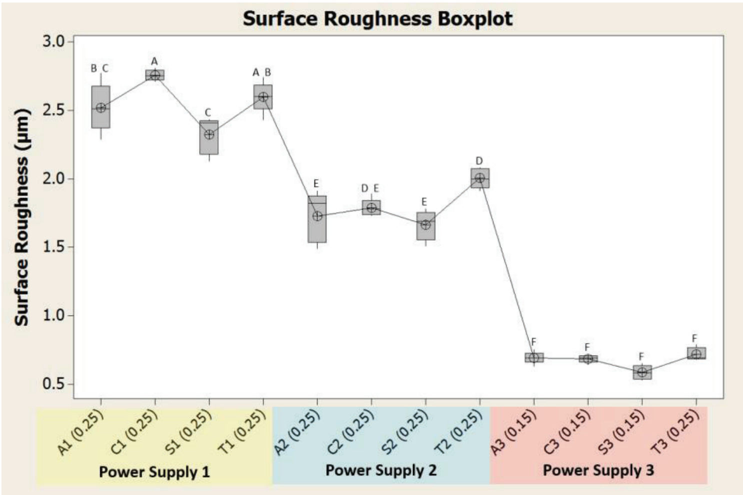

Figure 2: surface roughness for Ti6Al4V for all conditions. (*Letter indicate grouping according to Tukey's test at 0.05 family error rate, means that do not share a letter are significantly different*)

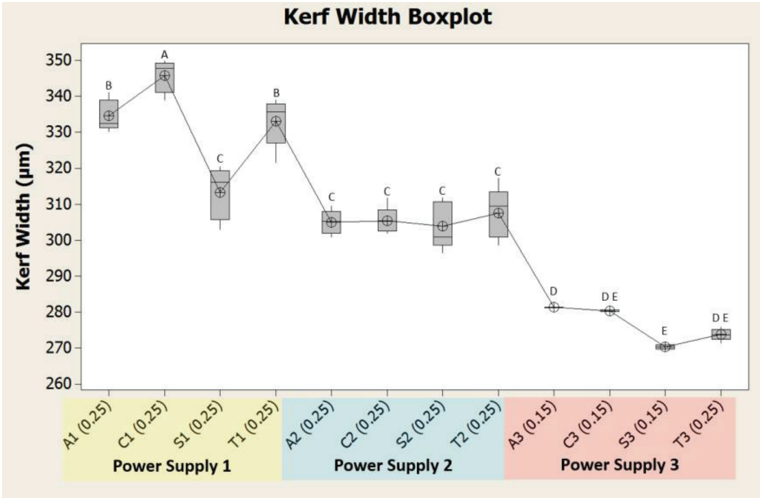

Figure 3: Box plots summarising kerf width for Ti6Al4V results for all conditions. (*Letter indicate grouping according to Tukey's test at 0.05 family error rate, means that do not share a letter are significantly different*)

Table 3: Performances measures results for each parameters in machining Ti6Al4V

Parameter	Surface Roughness			Kerf Width			Material Removal Rate		
	StDev	Average Ra (μm)	Ra Rank	StDev	Average Kerf Width (μm)	Kerf Width Rank	StDev	Average MRR (mm^3/min)	MRR Rank
A1 (0.25)	0.1761	2.520	10	4.360	325.6	10	0.0109	0.837	2
A2 (0.25)	0.1821	1.728	6	3.310	294.6	5	0.0083	0.762	7
A3 (0.15)	0.0427	0.692	3	0.090	285.3	3	0.0001	0.422	10
C1 (0.25)	0.0397	2.756	12	4.520	339.3	12	0.0113	0.864	1
C2 (0.25)	0.0618	1.788	7	3.810	298.3	9	0.0095	0.764	6
C3 (0.15)	0.0270	0.684	2	0.490	285.3	4	0.0007	0.421	11
S1 (0.25)	0.1363	2.324	9	7.300	296.3	7	0.0182	0.783	4
S2 (0.25)	0.1076	1.662	5	6.470	298.1	8	0.0162	0.760	8
S3 (0.15)	0.0513	0.584	1	0.770	274.3	1	0.0012	0.405	12
T1 (0.25)	0.1112	2.598	11	6.880	326.6	11	0.0172	0.833	3
T2 (0.25)	0.0723	2.004	8	7.080	296.2	6	0.0177	0.769	5
T3 (0.25)	0.0466	0.718	4	1.620	275.6	2	0.0040	0.685	9

Table 4: One-way ANOVA results for surface roughness for different type conditions

One-way ANOVA: Surface Roughness															
	First Condition(HP)					Second Condition(HP/ MP)					Third Condition(LA)				
Source	DF	SS	MS	F	P	DF	SS	MS	F	P	DF	SS	MS	F	P
Factor	3	0.4836	0.1612	10.15	0.001	3	0.3295	0.1098	8.17	0.002	3	0.0519	0.0173	9.41	0.001
Error	16	0.2541	0.0159			16	0.2152	0.0134			16	0.0294	0.00184		
Total	19	0.7377				19	0.5447				19	0.0813			

4.2 Kerf Width and MRR

The kerf width values significantly influenced the MRR and could be obtained through Equation (1). Table 3 indicates the kerf width value ranked based on the lowest value that correspond with the lowest MRR value.The higher MRR was achieved by condition C1 at feed rate of 0.25 mm/min.

The kerf width data indicates no violations of statistical assumptions thus, the one way ANOVA model fits the data relatively well. Only Power Supply 2 (HP/MP) shows weak evidence of statistical differences among the means at the 0.05 level of significance where P value= 0.746 (Table 5). Thus, the use of any conditions in this type of power supply gives similar results in statistical perspective.

Thus, the large variations produced for Power Supply 1 (HP) parameters with high MRR in terms of surface roughness and kerf width, as proven by standard deviation for parameter S1 (0.25mm/min). Figure 3 shows the comparison of variations by stereo microscope in obtaining kerf width. Hence, the Power Supply 1 (HP) produced more variations results compared to the Power Supply 3

(LA) with Power Supply 1 (HP) which produced high surface roughness value. By employing Tukey's family error method to account in multiple comparisons among the categories, the ANOVA indicates condition C1 has significant and has high value of kerf width indeed because condition C1 do not share a letter.

Table 5: One-way ANOVA results for kerf width for different type conditions

One-way ANOVA: Kerf Width															
	First Condition(HP)					Second Condition(HP/ MP)					Third Condition(LA)				
Source	DF	SS	MS	F	P	DF	SS	MS	F	P	DF	SS	MS	F	P
Factor	3	2738.6	912.9			3	36.3	12.1			3	419.69	139.9		
Error	16	559.8	35.0	26.09	0.000	16	469.5	29.3	0.41	0.746	16	13.82	0.863	162.02	0.000
Total	19	3298.4				19	505.8				19	433.50			

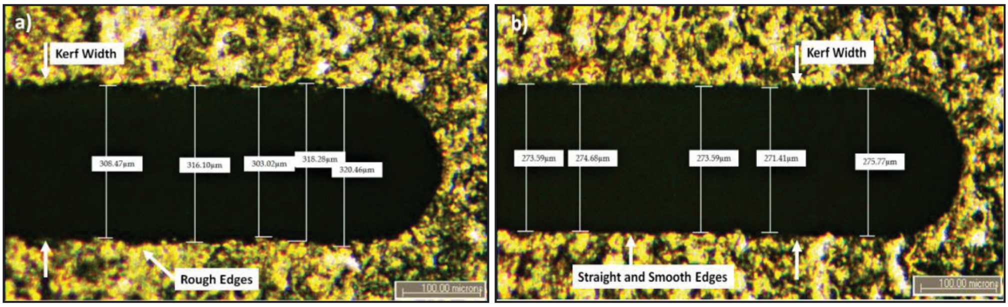

Figure 4: Stereo microscope results for kerf width a) parameter S1 and b) parameter T3

5.0 CONCLUSIONS

In conclusion, several findings are obtained such as:

1. At 0.25 mm/min, excellent surface finish is obtained through condition T3 (Power Supply 3: 0.718 µm). In addition, at 0.15 mm/min, condition S3 (Power Supply 3: 0.584 µm) produces the lowest surface roughness. However, variations for condition S3 are larger than T3 and the feed rate for condition S3 (0.15 mm/min) is slower than T3 (0.25 mm/min).
2. The lowest kerf width value can also be achieved by parameter S3 (Power Supply 3, category: Steel) as well as the lowest MRR value.
3. The large variations on surface roughness results can also be seen by stereo microscope in obtaining the kerf width. The straight and smooth kerf width edges indicate lower surface roughness values due to the craters produced by electrical discharges are smaller.

4. The statistical analysis indicates significant difference on surface roughness results for every category type and there is no significant difference for Power Supply 3 (LA) as indicated by Tukey's multiple comparison. For kerf width, only Power Supply 2 (HP/MP) rejects alternative hypothesis which indicates all the means are equal where P-value = 0.746.

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