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Investigation of the Optimal Machining Parameters on Wire Electrical Discharge Machine by Taguchi Technique

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Abstract: This paper focused on the effect of process parameters on material removal rate (MRR), feed rate (FR) and surface roughness (SR) of machining titanium by wire electrical discharge machine (WEDM). The Taguchi method had been used based on L9 orthogonal array to find out the optimal process parameters. This work also investigated the influences of machining parameters including peak current, wire-speed, wire tension and voltage. The experiment was analyzed by Minitab 16 which observed that the peak current was the most influential factor for MRR, FR and SR. However, the wire speed was significant to the feed rate. The optimum parameters of obtained MRR, FR and SR were 20.57 mm^3/min, 22.43 mm/min and 1.74 μm, respectively. Thereafter, the scanning electron microscope (SEM) was used to identify the microstructure of the workpiece. It could be seen that craters had more by the high discharge of thermal energy that caused the formation of larger cracks and craters, leading to an increase in surface roughness.

Keywords: Material removal rate (MRR); Feed rate (FR); Surface roughness (SR); Taguchi method; Wire electrical discharge machining (WEDM)

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1. Introduction

Wire electrical discharge machining (WEDM) is a non-traditional process that is widely used for machining a variety of difficult-to-use materials, including titanium alloys with complex shapes. This article characterizes the surface produced by thermal processes. From observations, a more consistent surface was achieved using coated wire electrodes. Among various parameters affecting the surface characteristics such as time between pulses, duration of pulses, injection pressure, wire speed and wire tension, the time between pulses was determined as the most suitable [1].

Technological developments of high hardness materials in manufacturing processes proceed at a rapid pace. WEDM utilizes the principle of an electric current passing through a wire electrode to cut high hardness materials that are difficult to machine with high accuracy [2]. WEDM causes the metal to evaporate, leaving debris while following a very accurate route [3]. Machining process parameters such as voltage (Vo), discharge current (I), wire speed (Ws), pulse on-off time (T-on, T-off), nozzle distance and wire tension were correlated with performance characteristics of surface roughness and material removal rate [1-5]. Each discharge factor generates high heat transfer resulting in evaporation and melting in nearby material from the surface roughness finish [6]. The cutting mechanism of WEDM depends on the electrical conductivity of the wire and the material used in the process. The electrical spark, as a spark gap between the wire electrode and the material under its influence, occurs as a short duration discharge that generates melting, while particles are removed from the workpiece by flushing with deionized water [7-8]. The surface response method technique was used in the development of mathematical models as well as WEDM parameter optimization. Variance analysis was conducted to test the accuracy of the proposed model. Increasing the pulse on time (T-on) can reduce surface roughness [6].

The Taguchi method is the greatest for the design of the experiment. Taguchi method used widely in engineering system is one of the greatest tools for the design of experiment. This method focuses more on the effective application of engineering advanced statistics. Moreover, the Taguchi method investigates the effect of process parameters. This research used this method to determine the optimal value setting in wire electrical discharge machine in addition to original response values transferred to the S/N ratio. Further analysis is performed according to this S/N ratio and assessed by analysis of variance (ANOVA) to determine the significant machining parameter [9-11]. Therefore the optimal value of

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machining parameter to obtain the optimal combination levels of machining parameters for material removal rate (MRR), feed rate (FR), surface roughness (SR).

In order to increases the efficiency of wire electrical discharge machining process, this paper focuses on analyzing the process parameters affecting the material removal rate surface characteristics and feed rates such as peak current, wire speed, wire tension and open voltage were determined as the most suitable for wire electrical discharge process. The influence of process parameters by the Taguchi method was used to determine the optimal value of the parameters affecting material removal rate, feed rate and surface roughness.

2. Materials and Methods

2.1 Titanium Alloy

Titanium alloys are recently developed advanced materials. Titanium grade 2 has numerous applications such as engine parts, heat exchangers, and orthopedic uses in the medical industry [7-10]. Titanium has high strength, with oxidation resistance and high melting temperature and is difficult to machine. A simulation of the machining process is shown in Fig. 1. The chemical composition of titanium grade 2 is shown in Table 1.

2.2 Design of the Experiments

The titanium workpiece with a size of 13.97 x 13.97 x 6.35 cm is prepared by wire electrical discharge machine JSEDM series W-B430. In this experimental work, the brass wire with a diameter of 0.25 mm is used as an electrode. The deionized water is used as a dielectric fluid. This work aims to thoroughly investigate the impact of the machine according to observe the effect of various process parameters such as peak current, wire speed, wire tension and open voltage which have been investigated.

Table 1 Chemical composition of titanium grade 2

Element	Ti	Si	Fe	Sn
Weight%	99.84	0.10	0.03	0.02

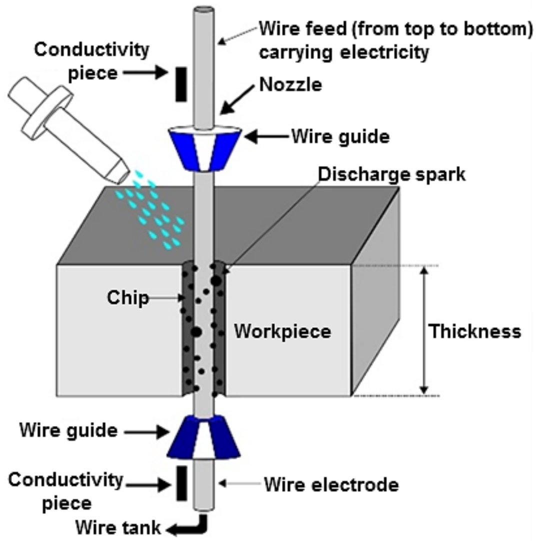

Fig. 1 Simulation of the machining process

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The employ of the experimentation base on the machine capacity refers to workpiece capacity, four parameters are considered as minimum levels. The machining experiments were processed for determining the performance of WEDM machines, process parameters and their range of parameters. The experiment was performed using the Taguchi testing method with 3 levels, 4-factor. The experiment was carried out as per the design of experiment approach L9 (3^2) orthogonal array each of the combinations shown in Table 2. The signal-to-noise ratio (S/N) method is used to measure quality characteristics that deviate from the desired value by the Taguchi technique. The method is also used to represent the mean to convert the experimental results into values for evaluation of characteristics to obtain the analyzing the appropriate parameters. The experimental result can be observed of the experiment value was impacted on material removal rate (MRR), feed rate (FR) and surface roughness (SR).

The Taguchi method was suggested signal to noise ratio (S/N) objective function for the matrix experiment. The optimum level for factors that result in MRR and FR were evaluated as “higher is better”, while SR focused in the inverse direction as “lower is better”. The observed values were calculated following Equations (1) and (2) [11].

$$\eta_{MRR,\ FR} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^{-2}\right] \quad (1)$$

$$\eta_{SR} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^{2}\right] \quad (2)$$

Where n is the number of experiments is the repeated num of each experiment and y_i is the observed data.

The S/N ratios have been computed the optimal values were analyzed by ANOVA. The higher S/N ratios value to identify the effect of peak current-voltage and wire speed on MRR, FR and SR 0.05 (95% confidence) level of significance were selected for this research.

2.3 Experimental setup

In this paper, the experiment was carried out with the parameters were selected from the machining handbook such as peak current, wire-speed, wire tension, and open voltage each parameter has three levels namely low, medium and high, denoted by Level1, Level2 and Level3, respectively. The factors and their respective levels have been selected based on trial experiments. The parameter settings are shown in Table 2.

Table 2 : Process parameters

Parameter	Unit	Level 1	Level 2	Level 3
Peak current (IP)	A	4	6	8
Wire speed (WS)	m/min	4	8	10
Wire tension (WT)	kgf	8	10	12
Open voltage (Vo)	Volt	12	14	16

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The wire feed rate depends on the machining process. The wire feed rate was investigated to evaluate the material removal rate, which was calculated using Equation (3) [12].

$$MRR = FR \times b \times h \quad (3)$$

Where FR = Feed rate (mm/min)

b = Width of cut (mm) = 2Kw + d

Kw = Kerf width (mm)

d = Diameter (mm)

h = Thickness workpiece (mm)

The possibility of fracturing the wiring involves selecting the parameters resulting in higher cutting speed or good surface [13]. Fig. 2 shows a wire EDM machine of the experimental setup that deals with the equipment used for the experiment.

Fig. 2 The JSEDM series W-B430 machine

3. Result and Discussion

The designs of Taguchi method utilized four parameters L9 orthogonal array to obtain the results of MRR, FR and SR. The experimental result was shown in Table 3.

Table 3 Experimental Results

No.	IP	WS	WT	Vo	FR (mm/min)	MRR (mm^3/min)	SR (μm)
1	4	4	8	12	23.59	18.03	1.74
2	4	8	10	14	23.92	18.91	2.11
3	4	10	12	16	24.43	19.96	2.16
4	6	4	10	16	23.58	18.86	2.54
5	6	8	12	12	23.63	19.77	2.57
6	6	10	8	14	23.92	20.42	2.79
7	8	4	12	14	23.26	19.18	3.33
8	8	8	8	16	23.39	19.33	3.25
9	8	10	10	12	23.62	20.57	3.12

NOTE: No. = Experimental Number

3.1 Effect of parameter on MRR

The MRR was determined by the mass of workpiece, hence result-focused highest of MRR. The effect of process parameters on MRR was shown in Fig. 3. The results showed that MRR increased with peak current, while voltage also increased because a high peak current led to a voltage increase [13]. This high energy resulted in melted material, causing rising MRR [12].

3.2 Analysis of MRR

The main effects plot for S/N ratio of process as shown in Fig. 3. The main effects plot for S/N ratio of the parameters gave a high level at 8 A in peak current, 10 m/min in wire speed, 12 kgf in

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wire tension, and 14 V in voltage, Hence MRR increased with peak current, wire tension, voltage, and wire speed increased.

3.3 Effect of parameter on feed rate (FR)

Fig. 4 showed an increase in MRR as the feed rate of the machine also increased. Smaller feeds produced fewer MRR results. This was due to the fact that greater feed estimation created a close gap between the wire and the workpiece. Corrosion of the material was affected by sparks. As the feed rate increases similarly, the MRR increases until the appropriate level was reached. The MRR decreases as the feed rate decreases.

3.4 Analysis of feed rate (FR)

Fig. 4 showed the effect of wire feed rate**.** The main effected plot for S/N ratio of the parameters gave a high level at 4 A in peak current, 10 m/min in wire speed, 12 kgf in wire tension, and 16 V in voltage. Larger is better, with a feed rate was 24.43 mm/min. The MRR increased as the feed rate increased [13-15].

3.5 Effect of parameter on surface roughness (SR)

The effect of the parameters on surface roughness using lower was better as shown in Fig. 5. The surface roughness was investigated at lower peak current at 4 A, wire-speed at 4 m/min, wire tension at 8 kgf and voltage at 12 V because as the discharge current increased, the voltage declined to melt the surface material. Surface roughness was measured at 1.74 µm; however, as the discharge current increased, voltage also increased with greater melting of the workpiece.

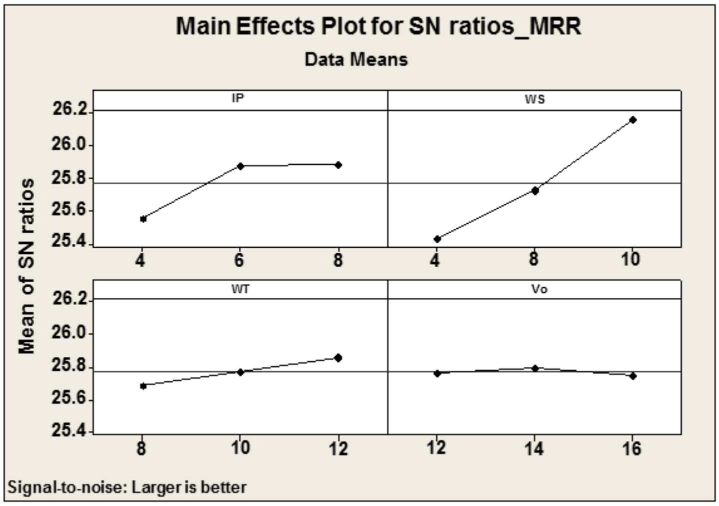

Fig. 3 Main effects plot for S/N ratio of MRR

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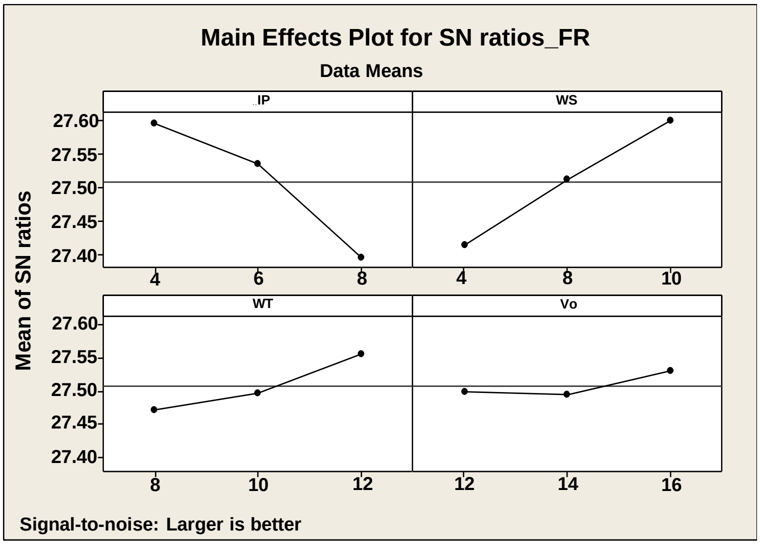

Fig. 4 Main effects plot for S/N ratio of FR

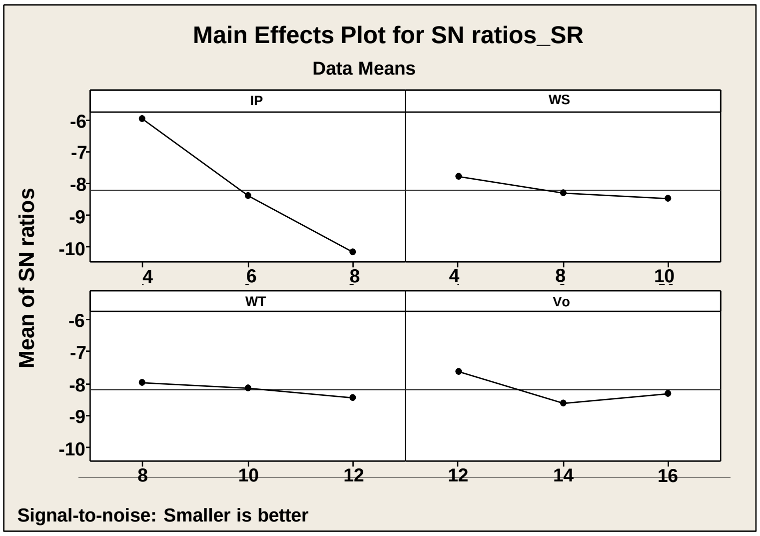

Fig. 5 Main effects plot for S/N ratio of SR

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3.6 Analysis of surface roughness (SR)

The main effects of SR of each factor for various level conditions were investigated. Surface roughness had increased with peak current, wire tension, and wire speed. Larger craters were produced by higher peak current, possibly producing larger discharge energy. The influence of peak current with various settings was shown in Fig. 6 and Fig. 7.

Variations of crater diameter, depth, and volume concerning peak current were consistent with the literature. Higher currents generate larger craters and, therefore, produced a rougher surface [13-15]. The significance for surface roughness was peak current that could be observed by SEM analysis which was shown in Fig. 6, 7 and 8. It showed that the surface roughness integrity for titanium with peak currents at 4, 6, and 8 A. In experiment No.1, surface variation with peak current at 4A was 1.74 µm, while the surface variation of No. 7 experiment was 3.33 µm. The increase in surface roughness with decreasing peak current could be explained by the high discharge of thermal energy that caused the formation of larger cracks and craters, leading to an increase in surface roughness.

4. Evaluation of S/N Ratios

Base on the main effect plot for the S/N ratio of MRR, FR and SR as shown in Fig. 3 to Fig. 5.

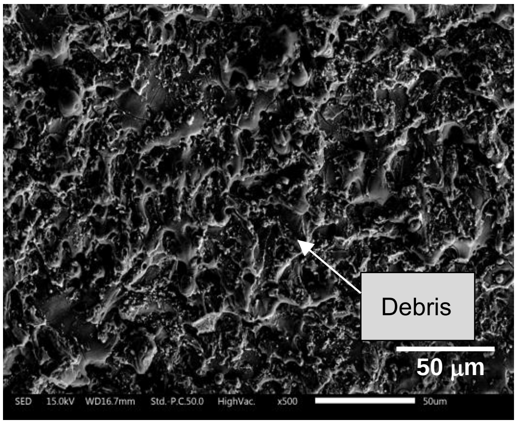

Fig. 6 Influence of peak current at 4 A

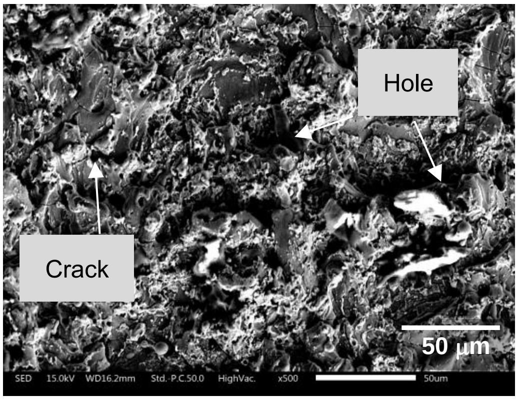

Fig. 7 Influence of peak current at 6 A

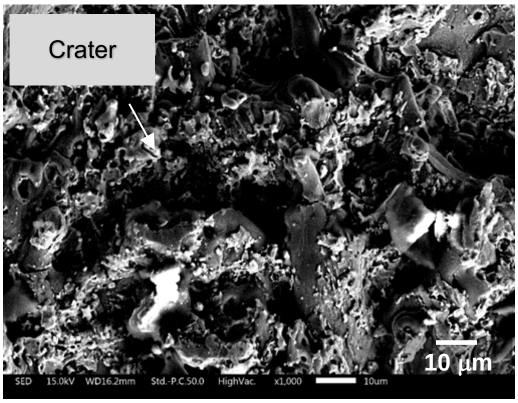

Fig.8 Influence of peak current at 6 A

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The WEDM parameter rankings were shown in Table 4 - 6. As a result, it showed the response for MRR, FR and SR. The ranks indicated the importance of each factor in response. The rank showed that peak current at level 1 was the most important factor followed by voltage, wire speed and wire tension in that order.

Table 4 Response for Means for MRR

Level	IP	WS	WT	Vo
1	8.96	10.71	10.92	10.57
2	11.34	11.24	11.09	11.54
3	13.08	11.43	11.37	11.27
Delta	4.13	0.72	0.46	0.97
Rank	1	3	4	2

Table 5 Response for Means for FR

Level	IP	WS	WT	Vo
1	27.60	24.41	27.47	27.50
2	27.53	27.51	27.50	27.49
3	27.39	27.60	27.56	27.53
Delta	0.20	0.19	0.09	0.04
Rank	1	2	3	4

Table 6 Response for Means for SR

Level	IP	WS	WT	Vo
1	-6.00	-7.79	-7.99	-7.63
2	-8.40	-8.31	-8.16	-8.62
3	-10.19	-8.50	-8.45	-8.34
Delta	4.20	0.71	0.46	0.99
Rank	1	3	4	2

4.1 Regression analysis

The Taguchi method used the signal-to-noise ratios. The Minitab software was used to analyze the experimental data showed the effect of the process parameters. The variance analysis was used to generate statistically significant machining parameters and the percentage contribution of these parameters. The ANOVA analysis result for the experimental was analyzed the main parameters affected to obtain MRR, SR and FR respectively. This experiment carried out 95% confidence level. The performance of MRR, FR and SR was developed by regression, as shown in Equations (4) - (6), The ANOVA results for machining results were shown in Tables 7 and 9. Statistically, the P-value gave a decision on the degree of confidence whether these estimates differ significantly Regression equations.

$$MRR = 15.80 + 0.18\ IP + 0.26\ WS + 0.08\ ET - 0.02\ Vo \quad (4)$$

$$FR = 22.95 - 0.14\ IP + 0.08\ WS + 0.04\ WT + 0.05\ Vo \quad (5)$$

$$SR = -0.25 + 0.31\ IP + 0.03\ WS + 0.02\ WT + 0.04\ Vo \quad (6)$$

According to Table 7, which showed the effect of parameters on MRR, it could be seen that the most effective significant of MRR was peak current and wire speed which confirmed the significant confidence by the R^2 value at 76.10%. Table 8 showed the result of significant parameter was affected to FR. It could be seen that peak current and wire speed were significant to feed rate which confirmed the significant confidence by the R^2 value of 88%. Table 9 showed the effect of significant parameters to SR and it could be seen that the peak current was

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significant to surface roughness and confirmed the significant confidence by the R^2 value of 94.20%.

4.2 Confirmation experiments

The Taguchi method was used to predict the experimental results. Confirmation experiments were using the optimal parameters such as peak current at 8 A, wire speed at 10 m/min, wire tension at 10 m/min and voltage at 12V.

The optimal value of MRR was determined to be 20.57 mm^3/min. Comparison with the optimized by Taguchi method showed the main effect that influences the MRR the optimal value predict of MRR is between 25.34<MRR<25.93 mm^3/min. Table 10 showed the comparison of the results between the optimal value and the optimal value predict by the Taguchi method for confirmation experiments with the estimated process parameter settings.

Table 7 Analysis of variance for MRR

Term	Coef	SE Coef	T	P	Significance
Constant	15.80	1.54	10.29	0.00*	Significance
IP	0.18	0.08	2.24	0.09	Non -Significance
WS	0.26	0.05	4.81	0.00*	Significance
WT	0.09	0.08	1.16	0.31	Non -Significance
Vo	-0.02	0.08	-0.23	0.83	Non -Significance
Summary of Model S = 0.40 R-Sq = 88.10% R-Sq(adj) = 76.10%					

Table 8 Analysis of variance for feed rate

Term	Coef	SE Coef	T	P	Significance
Constant	22.95	0.46	49.61	0.00	Significance
IP	-0.14	0.02	-5.69	0.00*	Significance
WS	0.08	0.02	4.96	0.00*	Significance
WT	0.04	0.02	1.43	0.23	Non-Significance
Vo	0.05	0.02	1.91	0.13	Non-Significance
Summary of Model S = 0.12 R-Sq = 94.00% R-Sq(adj) = 88.00%					

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Table 9 Analysis of variance for SR

Term	Coef	SE Coef	T	P	Significance
Constant	-0.25	0.52	-0.49	0.65	Non-Significance
IP	0.31	0.03	11.36	0.00*	Significance
WS	0.03	0.02	1.45	0.22	Non-Significance
WT	0.02	0.03	0.86	0.44	Non-Significance
Vo	0.04	0.03	1.60	0.19	Non-Significance
Summary of Model S = 0.13 R-Sq = 97.10% R-Sq(adj) = 94.20%					

Table 10 Confirmation of experimental results

Response	Optimal condition	Experimental	Optimal value prediction	95 %CI
MRR	$IP_3WS_3WT_2Vo_1$	20.57	$IP_3WS_3WT_3Vo_2$	25.34<MRR<25.93
FR	$IP_1WS_3WT_3Vo_3$	24.43	$IP_1WS_3WT_3Vo_3$	23.61<FR< 23.63
SR	$IP_1WS_1WT_1Vo_1$	1.74	$IP_1WS_1WT_3Vo_2$	0.57<SR< 0.97

5. Conclusions

This paper was investigated the machining characteristics of titanium using wire electrical discharge and applied the Taguchi technique to optimize the process parameters. The results were summarized as follows.

1. Peak current was the most significant to material removal rate, feed rate and surface roughness.

2. The wire speed was the main effect of the material removal rate.

3. The confirmation results was suggested a nominal value of MRR at 20.57 mm^3/min, feed rate of 24.43 mm/min and optimal SR of 1.74 μm.

4. The ANOVA, regression analysis, and confirmation experiment for the estimated parameters for material removal rate, wire feed rate, and surface roughness indicated that the parameter relationship responses could be used to predict results.

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