Jurnal
Teknologi

Full Paper

MULTI-OBJECTIVE OPTIMIZATION IN WIRE-ELECTRICAL DISCHARGE MACHINING (WEDM) OF TITANIUM ALLOY

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Article history
Received
31 January 2015
Received in revised form
30 April 2015
Accepted
31 May 2015

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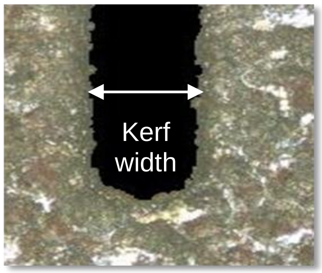
Graphical abstract



Abstract

This paper presents an investigation on influences and multiple optimizations of wire-electrical discharge (WEDM) machining performances such as cutting rate, material removal, surface roughness and kerf width processed on titanium alloy material. The experimental studies were conducted under varying machining parameters namely pulse-off time, peak current, wire tension and wire feed. The experimental works were designed base on Taguchi design of experiment. The optimum multi-objective performance characteristics was determined using analysis of variance (ANOVA) coupled with grey relational analysis (GRA). ANOVA was used to study the significance of process parameters on grey relational grade which showed the most significant factor. The grey relational grade obtained from GRA was used to optimize the wire-electrical discharge machining process. To validate the findings, confirmation experiment had been carried out using the optimal parameters and the predicted results were found in good agreements with experimental finding. Improved machining performance in the wire electrical machining process has been achieved by using this approach.

Keywords: WEDM, titanium alloy, Taguchi method, grey relational analysis, ANOVA.

1.0 INTRODUCTION

WEDM is a non-contact material removal technique which based on the principle of thermo-electric process technology. Plasma channel was formed on the tool and work piece electrodes by the repetitive sparks that initiate the wire electrodes to melt and even evaporate in some cases [1]. Following the exceptional material properties of titanium and its alloy, various industrial and commercial applications have been using it at large. The applications of these certain alloys have been widely used in aerospace, biomedical operation and in many corrosive environments. Some perks of the material are high strength-weight ratio, high temperature strength and exquisite corrosion resistance [2]. However, due to some of the intrinsic substances and inherent properties in them, titanium and its alloy are difficult-to-machine materials through the conventional machining method due to high cutting temperature, rapid tool wear and hard metal. The use of the advanced CNC WEDM machine also does not solve the matter of selecting the cutting parameters due to the complicated stochastic process mechanism [3]. Hence, it is difficult to establish precisely the relationship between the cutting parameters and the process performance.

This research work is aimed to study the influence of machining parameters to machining responses on titanium alloy (Ti-6Al-4V) through a combination of electrical and mechanical parameters. The machining parameters are such as the peak current, feed rate and wire tension while the measured machining responses are the cutting rate, material removal rate, surface roughness and kerf width. The multiple performance characteristics are analyzed based on the statistical-based analysis of variance (ANOVA) and grey relational analysis (GRA). An experiment is then conducted by using a commercial wire-cut EDM machine with the input parameters obtained from the GRA is used as the input. The experimental results have been found to be in good agreement with the analysis and this approach managed to improve machining performance in the WEDM process.

2.0 EXPERIMENTAL

The experimentation work was conducted on a commercial WEDM Mitsubishi FX Series Machine with submerged deionized water and pulse arc discharges were generated between the electrode (0.5mm diameter brass wire) and the workpiece (130mm x 63mm x 6mm titanium alloy) under submerged workpiece condition. The workpiece material used was Ti-6Al-4V grade 5 with material composition of Al (6%), Fe (0.25%), Ti (90%) and V (4%) while the hardness ~36HRC. The average cutting speed was measured directly from the display of the machine tool. The kerf width was measured using Mitutoyo profile projector at three different spots, see Fig. 1. Ten reading were taken at each spot and the average reading was calculated. Based on the preliminary testing, an orthogonal array experimental design (L_9) was used with variation of pulse-off time (1, 3 and 5 second), peak current (4, 8 and 12 A), wire tension (6, 10 and 16 N) and wire feed rate (4, 8 and 12 m/min), see Table 1. In order to select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The interaction between the machining parameters was not taken into consideration and there were 8 degrees of freedoms with three-level machining parameters used in the WEDM process. There were 27 experiments carried out (L_9 repeated twice) in order to investigate the entire machining parameter space using the L_9 orthogonal array, see Table 2. ANOVA was used to investigate the effects of the main machining parameters. The raw data is then transformed into S/N ratio values through Taguchi analysis. The criteria for the cutting rate and the material removal rate are "higher-the–better" while for the surface roughness and kerf width is "lower-the-better" [4], which can be expressed as below;

$$\text{S/N ratio} = -\log 10\left(\frac{1}{n}\right)\sum_{i=1}^{n}\frac{1}{y_{ij}^{2}} \quad \text{.........................}(1)$$

"larger-the- better"

$$\text{S/N ratio} = -\log 10\left(\frac{1}{n}\right)\sum_{i=1}^{n}y_{ij}^{2} \quad \text{.........................}(2)$$

"lower-the-better"

where; n = number of replication, y_{ij} = observed response value for i = 1,2,3,….m and j = 1,2,3,…n

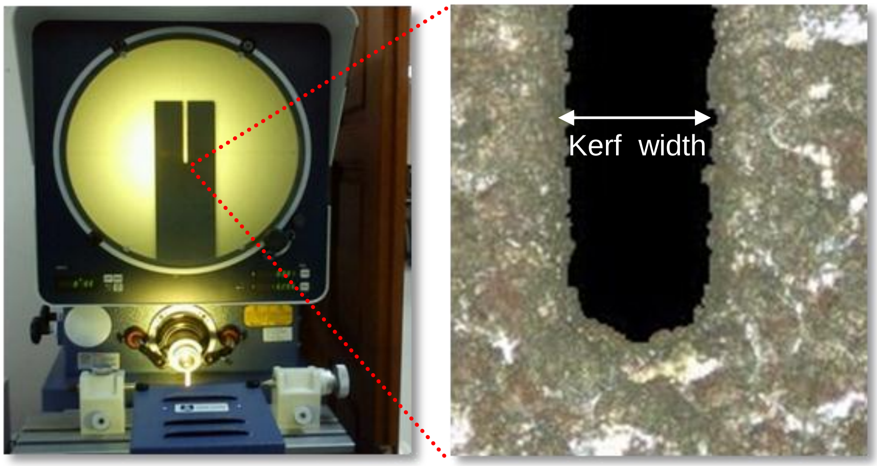


Figure 1 Mitutoyo profile projector – kerf width measurement

Table 1 Control factors and their levels.

Parameter	Symbol	Unit	Level L1	Level L2	Level L3
Pulse-off time	A	µs	1	3	5
Peak current	B	Ampere	4	8	12
Wire tension	C	N	6	10	16
Wire feed	D	mm/min	4	8	12

3.0 RESULTS AND DISCUSSION

From the experiment works, CR, MRR, Ra and kerf width have been measured. Typically larger value of CR and MRR are desirable while for Ra and kerf width, smaller values indicate better surface quality and good accuracy. The average value for CR, MRR, Ra and kerf width are tabulated and the raw data is then transformed into S/N ratio as shown in Table 2.

The S/N ratio plot of all responses with respect to the pulse-off time, peak current, wire tension and wire feed are shown in Fig. 2. Fig. 2(a) shows that the cutting rate decreases with the increase of pulse-off time from 3 to 5µs. However, it was observed that there is no significant variation in the cutting rate value at 1 to 3µs of pulse-off time. From the same figure, it was revealed that the peak current and wire feed drastically increase from 6 to 12A and from 10 to 15N, respectively. Fig. 2(b), 2(c) and 2(d) show the effect of process performances of each parameter according to their level. For an optimal cutting rate, material removal rate, surface roughness and kerf width, the combination of cutting parameters were (A_2 B_3 C_1 D_3),(A_3 B_3 C_2 D_1), (A_2 B_2 C_1 D_1) and (A_1 B_1 C_1 D_2) respectively.

Table 2 Different level of process parameters

Test	Orthogonal array				Responses				Signal –to- noise (S/N) ratio values				Grey Relational Gred
	A	B	C	D	CR (mm /min)	MRR (g/min)	Ra (µm)	Kerf width (µm)	CR	MRR	Ra	Kerf width	
1	1	1	1	1	10.044	0.74	3.807	0.530	20.038	-2.615	-11.612	5.514	0.507
2	1	2	2	2	9.135	0.9	3.555	0.534	19.214	-0.915	-11.017	5.449	0.550
3	1	3	3	3	10.790	0.98	3.326	0.532	20.660	-0.175	-10.438	5.482	0.734
4	2	1	2	3	10.637	0.78	3.668	0.527	20.536	-2.158	-11.289	5.564	0.571
5	2	2	3	1	9.635	0.98	4.254	0.523	19.677	-0.175	-12.576	5.630	0.677
6	2	3	1	2	10.170	0.94	3.697	0.522	20.146	-0.537	-11.357	5.647	0.526
7	3	1	3	2	9.094	0.78	2.688	0.52	19.175	-2.158	-8.589	5.680	0.432
8	3	2	1	3	9.472	0.9	2.852	0.517	19.529	-0.915	-9.103	5.730	0.463
9	3	3	2	1	9.822	1.08	2.989	0.514	19.844	0.668	-9.511	5.781	0.685

Table 3 ANOVA results for CR, MRR, Ra and Kerf width

Factor	Level 1	Level 2	Level 3	DOF	Sum of squares	Mean square	F value	Contribution (%)
A	**0.5970**	0.5916	0.5267	2	0.0092	0.0046	0.4162	10%
B	0.5033	0.5635	**0.6485**	2	0.0319	0.0159	1.4436	36%
C	0.4988	0.6024	**0.6141**	2	0.0242	0.0121	1.0949	27%
D	**0.6230**	0.5028	0.5894	2	0.0231	0.0115	1.0453	26%
Error					0.0000			
Total				8	0.0884	0.0110		

Total Mean Value of the Grey Relational Grade = 0.5715

**Optimal level are indicated by bold*

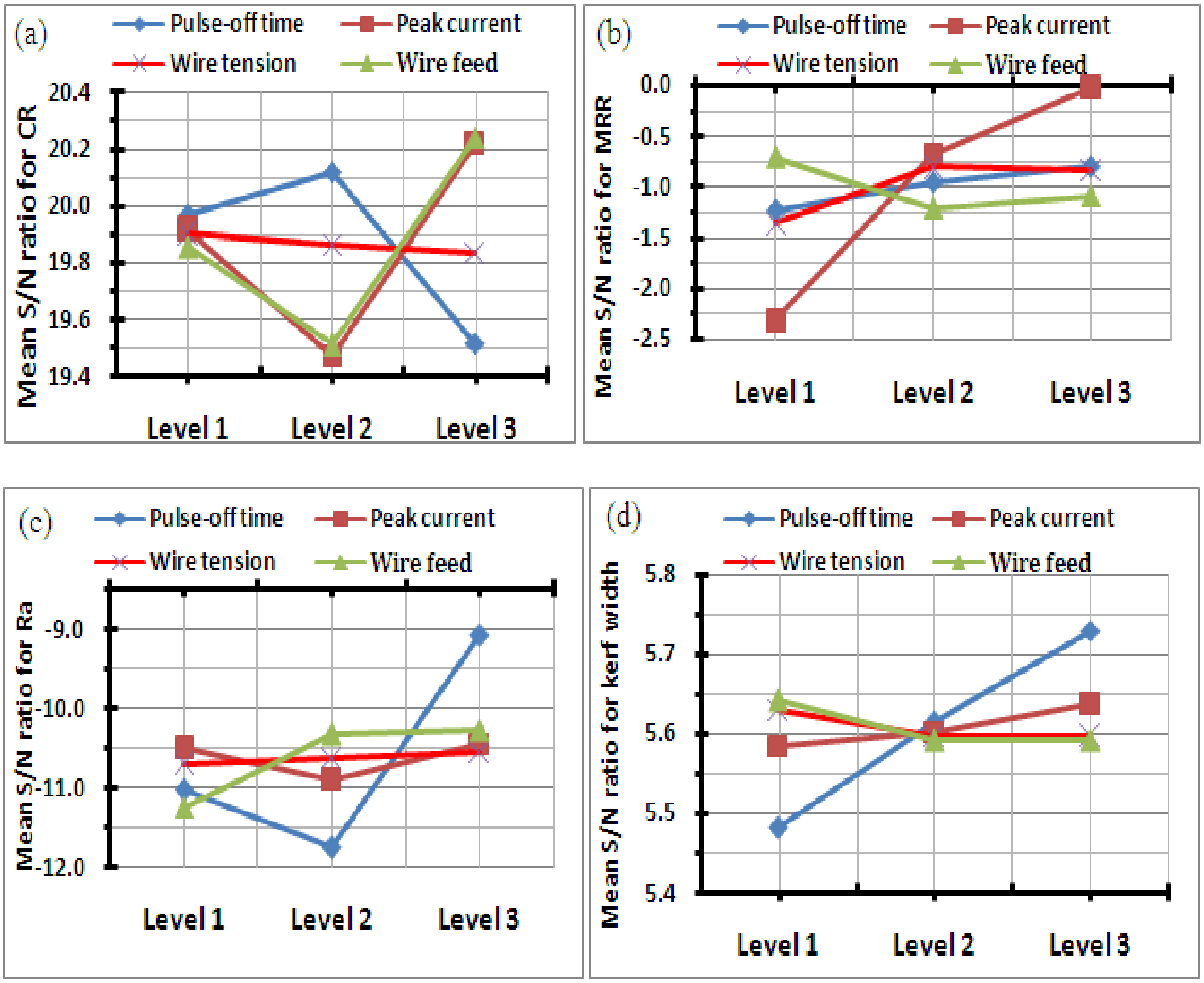


Figure 2 Grey relation co-efficient and grey relational grade values: (a) Cutting rate. (b) Material removal rate .(c) Surface roughness (d) Kerf width

The effect of each machining parameter on the grey relational grade (GRG) at different levels can be separated due to the orthogonal experimental design. For instance the mean of GRG for the pulse-off time at levels 1, 2 and 3 can be calculated by averaging the GRG for the experiments 1 to 3, 4 to 6 and 7 to 9, respectively. The mean of GRG for each level of the other machining parameters also can be computed using the same procedure. Thus, the optimal combinations of the machining parameter levels can be determined by ANOVA.

Table 3 shows the ANOVA results of the performance criteria with calculated F-values of the particular control factors. Results of ANOVA indicate that the peak current is the most significant machining parameter (36% contribution) that influences the multiple performance characteristics. The other factors such as pulse off time, wire feed and wire tension contribute about 10%, 27% and 26%, respectively. Hence, the optimal machining parameters are pulse-off time at level 1, peak current at level 3, wire tension at level 3 and wire feed at level 1. Once the optimal machining parameters are selected the improvement of the cutting performance is verified. Table 4 shows the results of the confirmation experiment using the optimal machining parameters. The cutting rate and material removal rate are improved by 16% and 21%, respectively. On the other hand surface roughness and kerf width also improved by 8% and 4%, respectively. From the findings, it can be seen that the multiple performance characteristics in the WEDM process were greatly improved.

Table 4 Comparison between initial level and optimal level

	Initial parameters	**Optimal machining parameters**		
	Orthogonal Array	**Prediction by Grey Relational Analysis**	**Confirmation Experiment**	**% Improvement**
Setting level	$A_3B_1C_3D_2$	$A_1B_3C_3D_1$	$A_1B_3C_3D_1$	
Cutting rate	9.094		10.841	16%
Material removal rate	0.78		0.991	21%
Surface roughness	2.688		2.495	8%
Kerf width	0.520		0.502	4%
Grey relational grade	0.432		0.713	
Improvement of the grey relational grade =0.281				

4.0 CONCLUSION

The use of the orthogonal array with GRA to optimize the WEDM process with the multiple performance characteristics has been presented in this paper. The GRA of the experimental results of cutting rate (CR), metal removal rate (MRR), surface finish (Ra) and kerf width can convert optimization of the multiple performance characteristics into optimization of a single performance characteristic called the GRG. This approach greatly simplifies the optimization process. The optimal machining parameters are the pulse-off time at 1μs, peak current at 12A, wire tension at 16N and wire feed at 4 mm/min. It is concluded that the performance characteristics of the WEDM process are improved by using the proposed method.

Acknowledgement

The authors would like to thank the Faculty of Mechanical Engineering (AMTEX), Research Management Institute (RMI-600-RMI/FRGS 5/3 (20/2013)), Universiti Teknologi MARA and Ministry of Education, Malaysia for the research funding under Fundamental Research Grant Scheme (FRGS).

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