Multi objective optimization for kerf and material removal rate in wire electrical discharge machining using Taguchi method combined grey relational analysis

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Abstract. This paper investigated the multi performance characteristics of wire electrical discharge machining for an optimal machining parameters to get low kerf and high material removal rate at the same time. The machining parameters i.e arc on time, on time, servo voltage and wire feed were used in this experiment. Based on L_9 orthogonal array, the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) was used to study the machining parameters of DIN 1.2510 tool steel. Multi response characteristics were solved by Taguchi method combined grey relational analysis. Experimental results are provided to demonstrate the effectiveness of this method i.e. kerf decreased from 354 μm to 345 μm , while material removal rate (MRR) increased from 9,313 mm^3/min to 13,989 mm^3/min . From the optimization result validated in the confirmation experiment the machining parameters combination that could produce the optimum responses are arc on time of 2 A, pulse on time of 8 μs , servo voltage 80 V and wire feed 60 mm/min.

1 Introduction

The process of wire dielectrical discharge machining is a thermo-electric non conventional machining process based on the erosion due to electric sparks to produce complex shapes, accurate and precision using brass wire electrode [1]. Wire EDM is used on materials that are conductive with varying hardness and high precision to make workpieces such as tools, punch and dies. In wire-EDM, kerf (gap of width) and material removal rate (MRR) is two of the most significant performance. Goyal [2] has investigated the effect of tool electrode, current density, pulse on time, pulse off time, wire feed and wire tension during the wire electrical discharge machining of Inconel 625. It was suggested that the most significant factors that influence maximum material removal rate and surface roughness are current, pulse on time, cryogenic treated tool electrode. The wire electrical discharge machining can

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be used for advanced ceramics such as bismuth ferrite, barium titanate, Al_2O_3 , Ti_3SiC_2 ceramic [3-6]. Bobbili et al.[7] reported a comparison study was conducted for the aluminium alloy 7017 and rolled homogeneous armour steel in wire-EDM, and the result presents that the increase of pulse on time affected material removal rate significantly for both materials. T.R. Newton et al. [8] have examined the effect machining parameter wire-EDM of recast layer in inconel 718. Taguchi method has been widely used for optimization of a single performance characteristic [9-10]. The material removal rate (MRR), surface roughness and kerf in wire-EDM of D2 tool steel using Taguchi’s L_{18} orthogonal array was analyzed by Ikram et al [11]. The existance of method such as fuzzy logic, grey fuzzy logic and grey relational analysis make Taguchi method can be used to optimize of multiple responses simultaneously. Deng [12] established the theory systems of grey in 1982. It helps to solve complexed interrelationship among multi objective performance characteristics successfully. Balasubramanian et al. [13] optimized surface roughness and material removal rate width using Taguchi method and grey relational grade with Taguchi’s L_8 orthogonal array. This paper studies wire-EDM of DIN 1.2510 steel and optimize two characteristics performance, i.e. kerf and material removal rate using Taguchi combined grey relational analysis. The characteristic quality of kerf is smaller the better and material removal rate is having higher the better.

2 Experimental methods

The experimental studies were performed on a CHMER CW 32GS wire electrical discharge machine tool. This experiment used DIN 1.2510 tool steel as a workpiece material with size 300 mm x 130 mm x 40 mm. Brass wire with diameter 0,25 mm was used as an electrode. The selected machining parameters with different level have been represented in Table 1. Based on Taguchi method, an L_9 orthogonal array was selected in this experiment was represented in Table 2. The kerf was measured by Euromex Microscope. The experiment order was run randomly with two replications to gain good validity and accuracy.

Table 1. The machining parameters and their levels.

Machining parameters	Level 1	Level 2	Level 3
Arc on time (A)	2	3	4
Pulse on time (µs)	4	6	8
Servo voltage (V)	80	90	100
Wire Feed (mm/min)	45	60	75

Table 2. The experimental layout using orthogonal array L_9 .

No	AN	ON	SV	WF
1	2	5	37	3
2	2	7	55	7
3	2	8	70	12
4	4	5	55	12
5	4	7	70	3
6	4	8	37	7
7	5	5	70	7
8	5	7	37	12
9	5	8	55	3

3 Results and discussion

3.1 Calculation signal to noise ratio (S/N) ratio

The experimental result and signal to noise (S/N) ratio of MRR and kerf has shown in Table 3. The signal to noise ratio is a measure of the data set relative to the standard deviation. If the S/N is small, then the magnitude is small relative to the noise, as measured using the standard deviation. There are three S/N ratio, depending on the type of the performance characteristics, i.e the smaller the better, higher the better, and nominal the better. In wire EDM lower the better of kerf is indications better performance, while MRR higher the better is indications better performance as equation:

Smaller the better :

$$S / N = -10 \log \sum_{i=1}^n \frac{y_i^2}{n} \tag{1}$$

Larger the better :

$$S / N = -10 \log \left[\sum_{i=1}^n \frac{1/y_i^2}{n} \right] \tag{2}$$

where n is the number of measurements, and y_i is the measured characteristic value. Regardless of the category of performance characteristics, the greater S/N ratio corresponds to the better performance characteristics.

Table 3. The experimental result and S/N ratio

No. Exp	AN	ON	SV	WF	Kerf (μm)	S/N Kerf	MRR (mm³/min)	S/N MRR
1	2	5	37	3	359	-51,1019	10,209	20,179
2	2	7	55	7	367	-51,2933	12,728	22,095
3	2	8	70	12	373	-51,4342	8,213	18,290
4	4	5	55	12	342	-50,6805	9,913	19,924
5	4	7	70	3	357	-51,0534	7,747	17,782
6	4	8	37	7	380	-51,5957	14,853	23,437
7	5	5	70	7	370	-51,364	6,133	15,753
8	5	7	37	12	347	-50,8066	13,013	22,287
9	5	8	55	3	371	-51,3875	10,575	20,485

3.2 Grey Relational Analysis

Since Taguchi method is only able to optimize single response performance characteristics, then the grey relational analysis optimizes multi performance characteristics. Furthermore, the optimization using Taguchi combined grey relational analysis able to identify the most significant parameter process wire-EDM that influence kerf and material removal rate. The optimization using grey relational analysis is done in the following three steps.

1st step. Normalization of kerf and material removal rate

The characteristics quality of kerf smaller the better which equation as follows:

$$Xi^*(k) = \frac{\max Xi(k) - Xi(k)}{\max Xi(k) - \min Xi(k)} \tag{3}$$

The characteristics quality of material removal rate is higher the better which equation as follows:

$$Xi^*(k)=\frac{Xi(k)-\min Xi(k)}{\max Xi(k)-\min Xi(k)} \tag{4}$$

Where $Xi^*(k)$ and $Xi(k)$ are normalized data and observed data for i th experiment by using k th response.

2nd steps. Calculating grey relational coefficient (GRC). The grey relational coefficient can be calculated by using equation 5.

$$\xi_i(k)=\frac{\Delta_{\min}+\zeta\Delta_{\max}}{\Delta_{0,i}(k)+\zeta\Delta_{\max}} \tag{5}$$

Where $\Delta_{0,i}(k)=\|X_0(k)-X_i(k)\|$ is deviation sequence (the difference of absolute value between $X_0(k)$ and $X_i(k)$); ζ the distinguishing coefficient $\in[0,1]$; $\Delta_{\min}=\forall j^{min}\in i\forall k^{min}\|X_0(k)-X_j(k)\|$ is the minimum value of $\Delta_{0,i}$; and $\Delta_{\max}=\forall j^{max}\in i\forall k^{max}\|X_0(k)-X_j(k)\|$ is the maximum value of $\Delta_{0,i}$.

3rd step, the value of grey relational grade (GRG) is calculated by determining the average of the grey relational coefficient corresponding to each performance analysis. The equation for determining grey relational grade can be calculated as follows:

$$\gamma_i=\frac{1}{n}\sum_{k=1}^n\xi_i(k) \tag{6}$$

Where γ_i is the grey relational grade and n is the number of process response. Hence, grey relational grade can be used to select optimal and machining parameters. The optimal value of the GRG can be computed by using equation:

$$\gamma_e=\gamma_m+\sum_{i=1}^q(\bar{\gamma_i}-\gamma_m) \tag{7}$$

Where γ_m is total mean of GRG; q is number of input machining parameters; $\bar{\gamma_i}$ is mean of GRG value at the optimal level. The result of normalization, deviation sequence, GRC of kerf and MRR and GRG is shown in Table 5.

Table 4. The results of GRG

No. Exp	Normalization		Deviation Sequence		GRC		GRG
	Xi*Kerf	Xi*MRR	Δ Kerf	Δ MRR	Kerf	MRR	
1	0,4604	0,5761	0,5396	0,4239	0,4810	0,5412	0,5111
2	0,6696	0,8255	0,3304	0,1745	0,6021	0,7412	0,6717
3	0,8235	0,3302	0,1765	0,6698	0,7391	0,4274	0,5833
4	0,0000	0,5429	1,0000	0,4571	0,3333	0,5224	0,4279
5	0,4074	0,2641	0,5926	0,7359	0,4576	0,4046	0,4311
6	1,0000	1,0000	0,0000	0,0000	1,0000	1,0000	1,0000
7	0,7469	0,0000	0,2531	1,0000	0,6639	0,3333	0,4986
8	0,1378	0,8504	0,8622	0,1496	0,3670	0,7697	0,5684
9	0,7725	0,6159	0,2275	0,3841	0,6873	0,5656	0,6264

Based on Table 6 and Figure 1, the optimum setting of the machining process parameters is found to the experimental run no. 9, arc on time at level 1 (2 A), pulse on time at level 3 (8 μ s), servo voltage at level 1 (80 V), and wire feed at level 2 (60 mm/min). The use of these conditions will minimize kerf and maximize MRR at the same time.

Table 5. The response table for the S/N ratio of GRG

	level 1	level 2	level 3	Max-Min	Rank
Arc on time (A)	-4,657	-4,894	-5,005	0,348	4
Pulse on time (µs)	-6,416	-5,224	-2,915	3,501	1
Servo voltage (V)	-3,579	-4,964	-6,012	2,433	3
Wire Feed (mm/min)	-5,734	-3,167	-5,655	2,567	2

Fig. 1. Grey Relational Grade (GRG) Graph

The analysis of variance (ANOVA) is used to determine significant machining parameters which influence the multi performance characteristics and the percentage contribution of each machining parameters on the responses [14]. Due to very small difference between variances of arc on time, on time, servo voltage and wire feed, no single factor can be integrated as a non influential factors [15]. Thus, ANOVA takes directly the proportion of each sum of squares of the factor effect vector (SS_{factor}) as the sum of squares of the total variation vector (SS_{total}) as a reference degree of contribution. The most influence process parameters for the GRG in order are on time, wire feed, servo voltage and arc on time. Table 7 presents the analysis of variance of GRG.

Table 6. The analysis of variance (ANOVA) of GRG

Source	DF	SS	MS	F	%contribution
Arc on time	2	0,19	0,09498	*	0,46
On time	2	19,0115	9,50574	*	46,46
Servo voltage	2	8,9337	4,46687	*	21,83
Wire Feed	2	12,7816	6,39082	*	31,24
Residual Error	0	-	-		
Total	8	40,9168			

The predicted GRG using the optimal level of machining parameters can be calculated by equation 7. Table 8 shows the confirmation experiment of kerf and MRR using the machining parameters. As shown Table 8, kerf is minimized from 354 µm to 345 µm, MRR is increased from 9,131 mm³/min to 13,989 mm³/min. Also Table 8 presents that the GRG in the wire EDM machining of DIN 1.2510 with optimum setting are effectively improved through this study.

Table 7. The result of confirmation test

	Initial	Optimal Process Condition		Improvement
		Prediction	Experiment	
Level of process parameters	AN ₂ ON ₂ SV ₂ WF ₂	AN ₁ ON ₃ SV ₁ WF ₂	AN ₁ ON ₃ SV ₁ WF ₂	
Kerf (μm)	354		345	decreased 2.54%
Material Removal Rate (mm ³ /min)	9,131		13,989	increased 53.20 %
GRG	0,4513	0,9690	0,6167	increased 36.64%

4 Conclusion

In this present paper, wire-EDM of DIN 1.2510 is carried out input parameters considered as arc on time, on time, servo voltage, and wire feed, and the response parameters as kerf and MRR. Taguchi’s L₉ orthogonal array design is used for performing wire EDM.

- 1) It was found that an arc on time of 2 A, on time of 8 μs, servo voltage of 80 V, and wire feed of 60 mm/min is the optimal combination of input parameters.
- 2) ANOVA explained that pulse on time is the most influence parameter in effecting the response machining parameters.
- 3) The optimization using Taguchi combined grey relational analysis improved significantly the production of wire EDM of DIN 1.2510.

This research is supported financially by Grant of research for beginner lecturer, through letter of number decree of 0045/E3/LL/2018, January 16th, 2018, Ministry of Research and Technology, DIKTI, The Republic of Indonesia and letter of number decree of 39/KP/LPKT-ITI/III/2018, March 29th, 2018, Institut Teknologi Indonesia and the authors would like to thank to BPPT BT MEPPPO and Department of Mechanical Engineering, University of Indonesia.

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