Enhancing of Material Removal Rate and Surface Roughness in Wire EDM Process using Grey Relational Analysis

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ABSTRACT

Wire Electrical Discharge Machining (WEDM) is a non-conventional machining technique that utilizes electrical discharges to remove material from a workpiece. This study investigates the effects of three WEDM parameters: feed rate (500, 600, and 700 m/min), pulse-on time (20, 25, and 30 μs), and pulse-off time (10, 30, and 50 μs) on the Material Removal Rate (MRR) and surface roughness (Ra) of stainless-steel workpieces. Experiments were conducted based on an L9 orthogonal array, and the results were analyzed using Analysis of Variance (ANOVA) and Grey Relational Analysis (GRA). ANOVA revealed that the pulse-on time had the most significant influence on both MRR and Ra. GRA was employed to determine the optimal combination of machining parameters, which were found to be a pulse-on time of 25 μs, pulse-off time of 10 μs, and feed rate of 600 m/min. Under these conditions, the highest MRR (12.444 g/min) and best surface finish (2.169 μm) were achieved. The findings of this study demonstrate the effectiveness of using GRA in conjunction with ANOVA to optimize the WEDM process for improving the MRR and Ra in stainless steel machining.

Keywords-material removal rate; surface roughness; grey relational analysis; wire-EDM

I. INTRODUCTION

Non-traditional methods of machining include WEDM, in which the removal of material takes place with the help of electrical discharges. It has invariably been employed for manufacturing complicated pieces that are difficult to machine. Ever since its invention in the 1960s in Japan, there had been considerable improvement in WEDM [1]. A thin electrically conductive wire guided through the computer-controlled rollers is used to cut the workpiece. The wire-work gap is cooled and insulated by the dielectric fluid. This has revolutionized manufacturing because of complicated and complex parts, which are made with high precision and accuracy. WEDM is an important tool within industry, and further growth will give avenues and applications. WEDM involves both electrical engineering and machining. Thin, electrically conductive brass or copper wires (0.1 mm to 0.3 mm) were used in the procedure. Computer-controlled rollers move the wire through the workpiece and cut it to form. Aerospace, automotive, medical, and electronics manufacturers employ WEDM. Applications involving turbine blades, injection molds, and even electronic components require precision and accuracy. More recently, improvements have been forthcoming in WEDM technology, in the areas of wire materials, machine design, and control systems. With improvement in accuracy and efficiency, and increased versatility, the WEDM has now begun to find wider areas of applications [2, 3].

The precision and accuracy of WEDM have improved the machining process since WEDM does not involve tool-workpiece contact, tool wear, and distortion. WEDM is appropriate for complex and sensitive items since it can approach 0.002 mm tolerances [3]. WEDM vit is a versatile machining technology which can be applied in electronics, aviation components, cars and medical devices [4]. WEDM generates products with low residual stress, resulting in high dimensional stability and low distortion. The machining did not cause mechanical tension. Recently, WEDM technology has improved wire materials, machine design, and control systems. The progress of technology in the area of wire materials, machine design, and control systems has advanced WEDM in accuracy, efficiency, and flexibility, opening new frontiers for this unique machining method [5]. The parameters of the WEDM process can have a significant impact on the final product and have been extensively studied. For instance, in [6] the effects of pulse-on, pulse-off, and wire tension on the Metal Removing Rate (MRR) and Ra of a WEDM-machined titanium alloy were investigated. The pulse-on time affected the MRR more than the pulse-off time did. Similarly, in [7, 8], the WEDM of Inconel 718 and the effect of peak current, pulse-on, and pulse-off time on MRR and RA were investigated. The materials that were machined with WEDM and the effect of the processing parameters on MRR and Ra include AISI D2 [9, 10], AISI 304 stainless steel [11], stainless steel [12], aluminum matrix composites [13], and other materials [14].

Grey Relational Analysis (GRA) has been employed to determine the most crucial parameters of WEDM and optimize them. In [15], the GRA method was used to ascertain the most favorable WEDM process parameters for the servo voltage and wire speed, considering their impact on the Machining Rate Ratio (MRR) and surface roughness. The authors in [16] used GRA to examine how the spark gap and wire diameter affect the MRR and surface roughness. GRA [17] was used to evaluate the multi-objective effects of dielectric fluids on WEDM MRR and surface roughness. The authors in [13] introduced the WEDM multi-objective optimization of process variables, focusing on MRR and surface roughness, using GRA to elucidate complex interconnections. In [18], the effect of pulse duration on the MRR and surface roughness was studied, and GRA was used to evaluate the process performance. The GRA multi-objective process optimization was employed to elucidate the impact of the wire material on the MRR and surface roughness [19].

Design of experiments and statistical analysis, such as Analysis of Variance (ANOVA), have been used to optimize the WEDM process for various materials. For instance, the authors in [20] examined WEDM of Inconel X-750 alloy with boron carbide (B4C) powder in a dielectric fluid. ANOVA was used to determine the optimal process parameters and percentages for discharge current, pulse time, pulse-off time, and boron carbide powder concentration. The Taguchi technique with orthogonal L9 improved the WEDM machining parameters of AA6063/SiCb and SiCg composites [21]. The response surface (4 factors 3 level) design of experiment approach was used to evaluate the machining capabilities of sintered pure titanium [22]. The authors of [23] machined Tungsten carbide (93% WC and 7%Co) with a copper electrode. The experiments were carried out based on the response surface method and adopted a Box-Behnken design. Furthermore, to find the optimum combination, a Gray relational approach was used. The ideal validation factor in the point-by-point measurement mode is rarely used, and in [24], the effect of the manufacturing process, surface roughness, and low number of points in the measurement strategy affect the accuracy. This study examined four typical cutting procedures on flat surfaces with nine roughness classifications. Statistical regression models and neuro-fuzzy logic were used to determine the functional relationship between input and output variables. Statistical regression and neuro-fuzzy models successfully matched the experimental results.

This paper employed GRA to optimize the method variables such as feed rate, pulse-on, and pulse-off in WEDM to maximize MRR while minimizing surface roughness Ra.

II. EXPERIMENTAL PROCEDURE

Three machining parameters, which included feed (500, 600, 700 m/min), pulse-on time (20, 25, and 30 μs), and pulse-off time (10,30,50 μs) were taken during the experimental tests. The cutting process was tested using a 4-axis Smart EDM (ELEKTRA EDM 400 A) EL PULSE 5 wire-cutting machine. A stainless-steel workpiece was milled using a 0.25 mm zinc-coated brass wire in these experiments. We selected stainless steel because it has many engineering applications in the shipping and automobile industries, space, and medical applications. Figure 1 shows the dimensions of the workpiece and Figure 2 shows the final machined workpiece. The dielectric fluid was diced to 16 bits (25 × 15 × 10 mm). Figure 3 illustrates the WEDM machine in which the sample was placed on the working table of the machine under various settings. Table I lists the chemical composition of the stainless-steel sample.

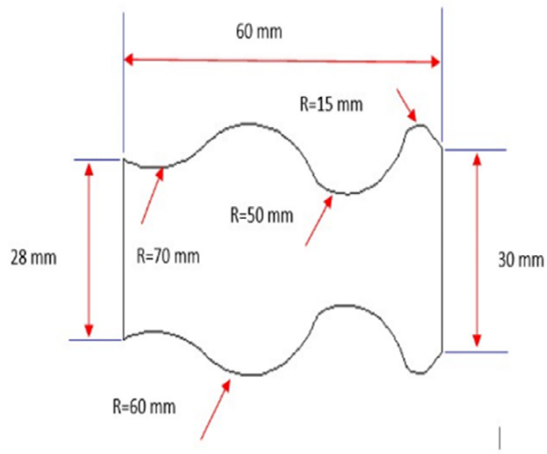

Fig. 1. Workpiece dimensions.

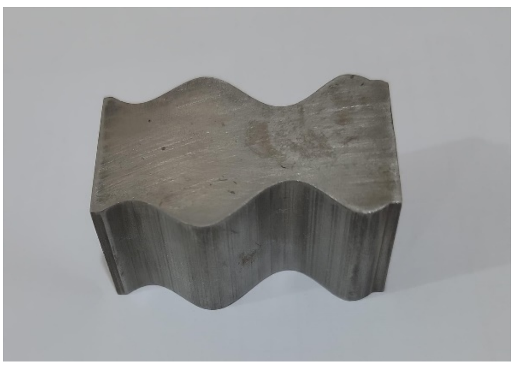

Fig. 2. Final stainless-steel workpiece.

Fig. 3. The WEDM machine used in the experiments.

TABLE I. CHEMICAL COMPOSITION OF STAINLESS STEEL WORKPIECE

Metal	% amount in sample
Si%	0.214
C%	0.0229
MN%	1.54
P%	0.0171
S%	0.0005
Cr %	25.73
Mo%	0.0036
Ni%	20.05
Al%	0.0073
Cu%	0.0123
Fe%	Bulk

III. RESULTS

Surface roughness was assessed on all machined surfaces using the Surface Gauge Pocket Surf portable roughness gauge. For each sample, three readings of Ra were collected and the average value was recorded.

The MRR was determined using a sensitive electronic balance to determine the weight differences between machined samples. The results of these measurements are listed in Table II.

TABLE II. PARAMETERS OF WEDM PROCESS AND EXPERIMENTAL RESULTS

No	Pulse on time (μs)	Pulse off time (μs)	Feed (m/min)	Surface roughness (μm)	MRR (g/min)
1	20	10	500	1.368	3.336
2	20	30	600	1.242	3.012
3	20	50	700	1.368	3.804
4	25	10	600	2.169	12.444
5	25	30	700	1.494	7.212
6	25	50	500	1.395	5.868
7	30	10	700	1.836	14.484
8	30	30	500	1.746	9.108
9	30	50	600	2.079	9.576

IV. ANALYSIS METHODS TO ESTIMATE OPTIMAL CUTTING PARAMETERS

A. Grey Relational Analysis

The GRA is a technique for identifying and understanding the links between multiple responses. GRA is divided into four steps, as outlined below [4].

In step 1 is performed the data pre-processing and Grey relational generation, which normalizes outputs from 0 to 1. The experimental results are used to calculate the GRA performance. Two forms of data pre-processing are used for Grey relational generation. Surface roughness data pre-processing, which has low performance, expressed as shown in (1):

$$X_i^*(K) = \frac{\max X_i^0(K) - X_i^0(K)}{max X_i^0(K) - min X_i^{0*}(K)} \tag{1}$$

Or MRR data pre-processing, which has a better-than-average performance, as shown in (2):

$$X_i^*(K) = \frac{X_i^0(K) - \min X_i^0(K)}{max X_i^0(K) - min X_i^0(K)} \tag{2}$$

where i is the test number (1–9), K is the k[th] performance characteristic, the performance characteristics are represented by the normalized value $X_i^*(K)$, the original value $X_i^0(K)$, the smallest value $minX_i^0(K)$, and the biggest value $maxX_i^0(K)$.

In step 2 the Grey relational coefficients are estimated, which are used in an equation for expressing the relationship between ideal and true normalized experimental outcomes. The Grey relational coefficient is expressed:

$$\mathcal{E}_i(K) = \frac{\triangle\min + \mathcal{E}\triangle\max}{\triangle_{oi}(K) + \mathcal{E}\triangle\max} \tag{3}$$

where Δmin is the minimum value of $\triangle_{oi}$, Δmax is the maximum value of $\triangle_{oi}$, $\triangle_{oi}$ (K) is the deviation sequence determined using the equation $\triangle_{oi}(K) = \| X_0^*(K) - X_i^*(K) \|$, ε is a positive number (0, 1). The value of ε may be changed to fit the needs of service users, and a smaller value of ε indicates a better distinguishing ability.

Step 3: Calculate the grey relational grade, which adds a grade to each coefficient for each performance characteristic to rank the experiments, as shown in (4):

$$GRG = \frac{1}{n}\sum_{k=1}^{n} \mathcal{E}_i(k) \tag{4}$$

where n refers to the number of output characteristics (n = 2 in this study). The GRA results are presented in Tables III and IV.

Step 4: Rank each Grey relationship by selecting the largest value. Table IV displays the gray relational grade for each test. There is a positive correlation between the Grey relationship grade and the product quality. Hence, the impact of each independent variable and the optimal quantity for each adjustable variable is selected via Grey relational grading. Figure 4 illustrates the Grey relational grade chart representing the several degrees of processing parameters. To calculate the optimal combinations of the method parameter values, the relative values of the parameters for numerous output characteristics must be known [2, 3].

TABLE III. NORMALIZED VALUES FROM GREY RELATIONAL GENERATION OF OUTPUT

Test No.	Normalized values	
	Surface roughness (µm)	MRR (g/min)
1	0.1733	0.0651
2	0.0000	0.0000
3	0.1733	0.1487
4	1.0000	0.9033
5	0.3313	0.5560
6	0.2084	0.4247
7	0.7011	1.0000
8	0.6109	0.7046
9	0.9240	0.7365

TABLE IV. GREY RELATIONAL COEFFICIENTS AND GRADES WITH RANKING

No	Grey relational coefficients		Δ_{oi}		Grey relational	
	Surface roughness (µm)	MRR (g/min)	Surface roughness (µm)	MRR (g/min)	Grade	Rank
1	0.376	0.348	0.826	0.934	0.362	8
2	0.333	0.333	1	1	0.333	9
3	0.376	0.370	0.826	0.851	0.373	7
4	1	0.837	0	0.096	0.918	1
5	0.427	0.529	0.668	0.444	0.478	5
6	0.387	0.464	0.791	0.575	0.426	6
7	0.625	1	0.298	0	0.812	2
8	0.562	0.628	0.389	0.295	0.595	4
9	0.868	0.654	0.076	0.263	0.761	3

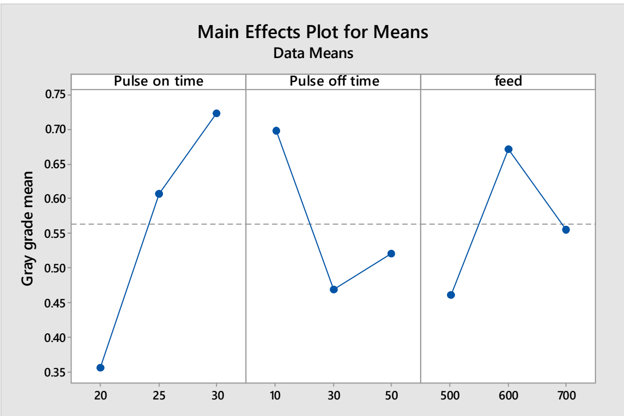

Fig. 4. Main effects chart of the Grey relational grade to the levels of the processing parameters

B. *Analysis of Variance*

ANOVA is a statistical method used to calculate the percentage contribution of each variable to the operational response. The primary goal of ANOVA is to determine which operating parameter has the greatest impact on performance attributes. A greater contribution indicates that this component has a greater influence on the output characteristics [25]. The main effect plot of the surface roughness is illustrated in Figure 5.

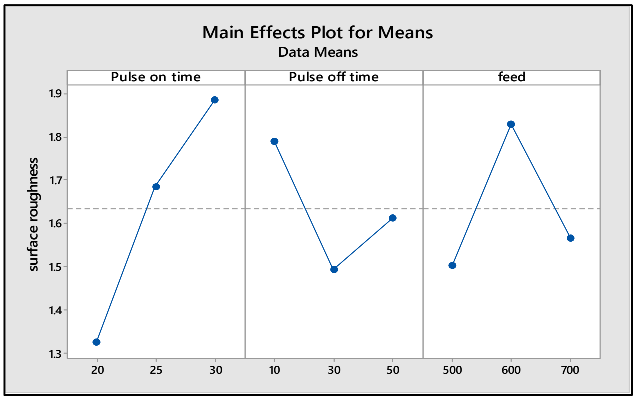

Fig. 5. Main effect plot of surface roughness Ra.

Figure 5 shows that the pulse-on time has a greater effect on Ra. Increasing the pulse-on time increases Ra. On the other hand, as the pulse duration increases, the discharge will stay longer, generating more energy and resulting in a decrease in Ra from 10 to 30 µs. Then, Ra increased with increasing duration from 30 to 50 µs. Ra seems to increase when the feed increases from 500 to 600 and has an inverse relationship when the feed is from 600 to 700. Table V lists the effects of the machining parameters on Ra.

TABLE V. EFFECT OF PROCESS PARAMETERS ON SURFACE ROUGHNESS

Machining parameters	Parameters level			Delta (max-min) µm	Rank
	Level 1	Level 2	Level 3		
Feed Rate (mm/min)	500	600	700	0.327	2
Pulse on time (µs)	20	25	30	0.561	1
Pulse-off time (µs)	10	30	50	0.297	3

The effects of the process parameters on MRR are illustrated in Figure 6.

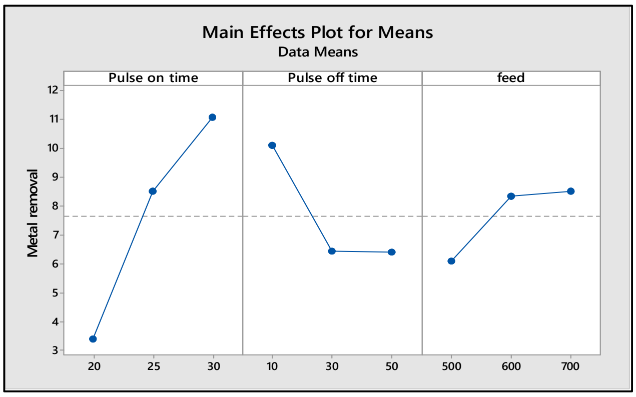

Fig. 6. Effect of preocess parameters on MRR.

The pulse-on time affects the MRR; the pulse-off time is less, and the feed rate has the least impact. The MRR increased linearly with the pulse-on time because of the increased machining time, and the same effect appeared with the feed rate. However, the MRR was inversely proportional to the pulse-off time. Table VI shows the main effect of the MRR.

TABLE VI. MAIN EFFECT FOR METAL REMOVAL

Machining parameters	Parameters level			Delta (max-min) µm	Rank
	Level 1	Level 2	Level 3		
Feed Rate (mm/min)	500	600	700	2.396	3
Pulse on time (µs)	20	25	30	7.672	1
Pulse-off time (µs)	10	30	50	3.672	2

V. CONCLUSIONS

The present study involved the experimental evaluation of surface roughness, Ra, and Metal Removal Rate (MRR) on a stainless-steel alloy workpiece in Wire Electrical Discharge Machining (WEDM) utilizing the Taguchi design technique. Three machining parameters were employed for this evaluation. The following conclusions were derived:

The analysis was conducted using the Taguchi method and Gray Relation Analysis (GRA) and took into account three different WEDM machining parameters: feed rate, pulse-on time, and pulse-off.

In terms of surface roughness and MRR, the pulse-on time emerged as the most significant factor. Both Ra and MRR exhibited a linear rise as the pulse-on time increased. Nevertheless, increased pulse-off duration resulted in decreased Ra and MRR. Although the feed rate influenced Ra, it did not have a substantial effect on the MRR.

Based on the findings of the GRA, the ideal WEDM machining parameters for milling stainless steel were determined to be a pulse-on time of 25 µs, a pulse-off time of 10 µs, and a feed rate of 600 m/min.

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