RESEARCH ARTICLE OPEN ACCESS

Development of a Taguchi-based framework for optimizing two quality characteristics in Wire-EDM operations

Trad Alblawi. Joseph, C. Chen· Ye Li

Abstract

A framework based on Taguchi parameter design was developed and successfully demonstrated to optimize two quality characteristics- surface roughness and angular accuracy in Wire Electrical Discharge Machining (W-EDM) process. An orthogonal array (OA)$L_9$was used in the Taguchi experiment design for four controllable factors, each with three levels. With one non-controllable factor investigated, 18 experiments were conducted in the Taguchi-based experiment setting, compared to 3^4 (=81) parameter combination as required by a traditional DOE setting. Conducted for the two response variables, Taguchi experiments from the case study gave the optimal combination of pulse on time at 9μs (A_1), feed rate at 35 in/min (B_2), voltage at 8v (C_2), and wire tension at 165g (D_3) for surface roughness optmization, and pulse on time at 13μs (A_3), feed rate at 35 in/min (B_2), voltage at 8v (C_2), and wire tension at 160g (D_2) for angular accuracy optmization. This optimal parameter setting combination was verified through a confirmation run that confirms the optimal quality responses of 126.1μin for surface roughness and 0.024º for angular accuracy. This research ultimately showed the dual output variable improvement and the framework established itself as a means to solve similar problems in other machining applications. The developed framework can serve as guidance for researchers to obtain multi-variable optimal setting in a systematic way.

Keywords: WEDM· Taguchi method · Surface roughness · Angular accuracy

I. Introduction

As a non-traditional machining process, Wire Electrical Discharge Machining (W-EDM) erodes materials from a work piece by producing sparks between the work piece and the tool electrode. The process occurs in a dielectric liquid bath of deionized water. W-EDM has been widely used in advanced manufacturing processes for molds and die in fields such as aerospace, automotive, and surgical components. W-EDM machines are able to produce complex 2D and 3D shapes. During W-EDM process, spark erosion frequently occurs, which can create more than one thousand sparks per second between the wire (Anode) and the work piece (Cathode). These sparks jump from the wire to the work piece and erode metal at temperatures in the range of 8000 - 12000^0 [1] as shown in Fig 1[3]. The nature of W-EDM processes requires that both the work piecematerial and the wire be conductive.

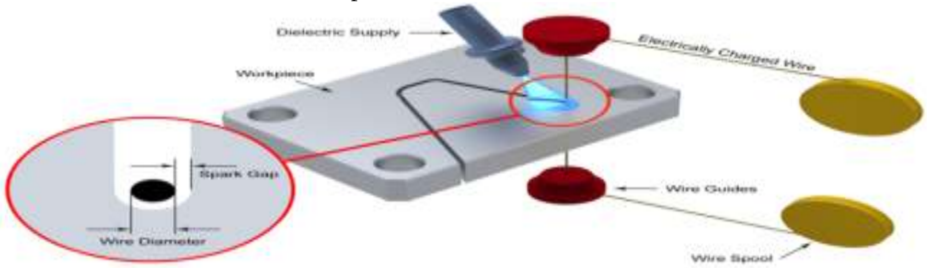


Fig.1 Principle of W-EDM [**3**]

Compared to traditional machining processes, W-EDM machines are capable of holding to closer tolerances and better surface finishes. Some W-EDM machines are extremely accurateallowing them to hold up to +/- 0.0001” and producing a surface finish (*Ra*) of around 0.037 μm [4]. The advantages from W-EDM processhave made it a reasonable alternative to other subtractive machining processes. One major advantage lies in the fact that there is little contact force between the workpiece and the wire, and hence it can machine weak or thin work pieces without causing much deflection as in traditional machining processes. Additionallya W-EDM machine has several parameters including: pulse on time(a.k.a. the duration of time) which isthe length of time that the wire releases sparks,wire feed rate or the speed in which the wire is fed through the work piece,wire tension or the axial forces exerted on wire, and voltage-the electrical charge passing from the wire to the work piece. These parameters significantly influence quality of parts made by W-EDM process [5].

Since W-EDMis widely used in many manufacturing applications, many researchers have optimized machining parameters to improve quality and reduce production costs.Taguchi method is a very useful technique used to achieve higher quality and reduce product cost [2].Taguchi method has been used to study the performance of W-ED Mto improve the output variable characteristics such as surface roughness, dimension accuracy, material removal rate (MRR).Table1 shows the summary of related research using Taguchi method to improve and optimize the performance of W-EDM.

Table 1 Summary of the researches

No	Author/Year	Parameters	Performance Measures	Remark	Technique Used
1	Harpreet et al./ (2012)[6]	pulse on/ pulse off time	MRR	It was discovered that with an increase in pulse on time the MRR decreased, and inversely with an increase in pulse off time MRR increased.	Taguchi Methodology
2	Parveen Kumar et al/(2013) [7]	Pulse on time, pulse of time, wire speed rate, wire tension	MRR, Wire Wear Rate. Surface Roughness	The result was found that the pulse on time and the wire speed rate are the most significant parameters.	Taguchi Methodology
3	Atul Kumar(2012)[8]	voltage, feed rate, pulse on time, pulse off time, wire feed, servo voltage, wire tension, flushing pressure	MRR, Surface Roughness	It was found that pulse on time and voltage have the most significant effect on MRR and surface roughness.	Taguchi Methodology
4	G.Lakshmikanth(2014)[9]	pulse on time, pulse off time, wire feed	MRR, Surface Roughness	In an investigation of the effect of pulse on time, pulse off time, and wire feed, the factor of pulse on time had the most significant effect on MRR and surface roughness.	Taguchi Methodology
5	Alpesh M. Patel et al/(2013)[10]	wire feed, wire tension, discharge current, discharge voltage	Electrode Wear Rate (EWR), MRR	The study demonstrated that discharge current, discharge voltage, and wire tension greatly influence EWR and MMR.	Taguchi Methodology
6	Sameh S. Habib (2014)[11]	pulse on time, pulse off time, discharge current, voltage	MRR, Surface Roughness, Gapsize	The study found that the pulse on time has the most significant influence on MRR, surface roughness, and gap size	Taguchi Methodology
7	Lokeswara Rao(2013)[12]	pulse on time, pulse off time, peak current, wire tension, servo voltage, servo feed	MRR, Surface Roughness	The study found the optimum cutting parameters for WEDM, the minimum surface roughness, and the maximum MRR.	Taguchi Methodology

8	Jasvinder Pal et al/(2014)[13]	pulse on time, pulse off time, peak current wire feed, servo voltage	Surface Roughness	It was found that the pulse on time, pulse off time, and servo voltage have a significant effect on surface roughness.	Taguchi Methodology
9	Jaganathan P et al/(2012)[14]	applied voltage, discharge current, pulse width, pulse interval	MRR, Surface Roughness	It was found that factors like applied voltage, pulse width, and speed have played a significant role on MRR and surface roughness.	Taguchi Methodology
10	K.Hari et al/(2014)[15]	pulse on time, pulse off time, servo voltage, wire feed, peak current, servo feed	MRR, Surface Roughness	It was found that pulse on time, pulse off time, and peak current are the most significant parameters that affect the MRR and surface roughness.	Taguchi Methodology

As seen from the literature review in Table 1, some studies show that while optimizing output variables by changing input parameters, two output variables can be improvedindividually, but not simultaneously. This would significantly hinder the application of Taguchi method in industry setting for process improvement when two output variables need to be optimized simultaneously. The objective of this research is to design an overarching framework by which dual output variable improvement can be accomplished using one parameter level setting. For the purpose of this research, Taguchi method is used to determine the optimal parameters for surface roughness and angular accuracy of workpieces machined byW-EDMmahcines. The subsequentsections will present the methodology and a case study with experimental verification used to show its efficacy

II. Methodology

In this research Taguchi method and Signal-to-Noise (S/N) ratioare used for comparative analysis of parameters' effect on response variables. Two response variables are tested for W-EDM process optimization.As shown in Fig 2, the following steps outline the procedure of experimentation in a systematic way to find the optimum results.

Step 1:The first step in this procedure is to select the machining operation that will be used in experiment. Once the machining operation is selected, measurable output variables should be identified as well. Measurable output variables (OV in **Fig. 2**) are those variables chosen to meet the needsfrom industry, such as dimensional accuracy, angular accuracy, surface roughness, material removal rate, and electrode wire rate, etc.

Step 2: After choosing measurable output variables, the next step involves running a baseline experiment for analysis. The baseline experimentproduces initial results of each output variable as a starting point for optimization. From the baseline analysis, an initial understanding of the machine capability with respect to the output variables is established. The baseline experiment result is then used as a gauge to compare with the result from Taguchi method to verify the improvement.

Step 3: Select proper controllable factors and noise factor. Proper selection of controllablefactors is vital to product quality. In order to understand those factors affecting the process, a fishbone diagram is used to identify the possible causes of a problem.

Step 4: Taguchi Parameter Design and Orthogonal Array (OA) Matrix. Taguchi method has three segments: system design, parameter design, and tolerance design [17]. In this study,Taguchi parameter design is used to determine the optimal levels for the controllable system parameters. InTaguchi parameter design there are two types of factors that can affect product quality -controllable factors and noise factors. A factor is considered controllable if it iseasily manipulatedandhas a significant impact on product quality.In W-EDM process, pulse on time, wire tension, and voltage are examples of controllable factors.A noise factor may have a negative effect on product quality, but cannot be controlled; temperature, vibration, or humidityare typicalexamples of noise factors in the application of Taguchi method [17]. Taguchi parameter design has been proved to be a reliable way to evaluate and implement improvements on product and process [18]. Moreover Taguchi method usesOAin its experiment design [5]. The advantage of using OA is the ability to study a large number of variables with a smaller number of experiments [8], and therefore the experiment can be conducted in a much more economical way compared to traditional Design of Experiment practices.

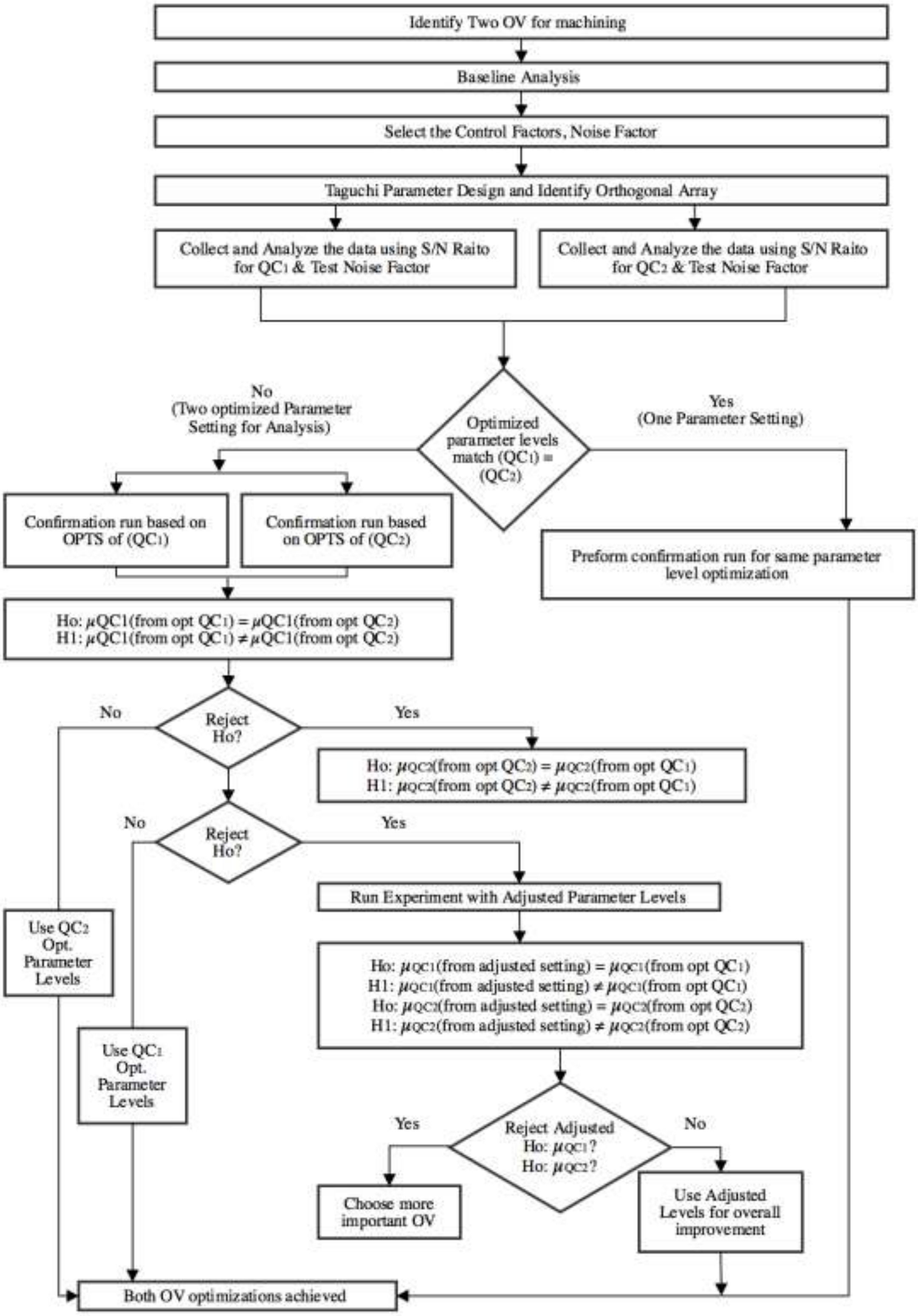


Fig. 2 **Methodology framework for two output variables using Taguchi method**

Step 5: After the requiredOA matrix is determined, machining experiment can be performed and data can be collected from the machined workpieces through measurement using appropriate measurement instruments. Once the data is collected, S/N ratio is calculated to analyze the measurement data. S/N ratio is able to determine which controllable factors have moreimpact on the quality characteristics of the product. There are three possible situations whereS/Nratio can be calculated depending on the quality characteristic to be optimized.

Smaller the better $\frac{S}{N} = -10\log(\frac{1}{n}\sum_{i=1}^{n} y_i^2)$ (1)

Nominal the better $\frac{S}{N} = 10\log(\frac{(\frac{1}{n}\sum_{i=1}^{n} y_i)^2}{S_y^2})$ (2)

Larger the better $\frac{S}{N} = -10\log(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2})$ (3)

Where y_i^2 is the result of the observed value, and n is the number of times the experiment is repeated.In this research S/N ratio is defined as *Smaller the better* for optimizingboth quality characteristics.

Followed by the data collection and analysis, a T-test for 99% confidence is used to findout if the noise factor significantly affects the quality characteristics.

H_0: $\mu_{\text{LEVEL1 of NOISE FACTOR}} = \mu_{\text{LEVEL2 of NOISE FACTOR}}$

H_1: $\mu_{\text{LEVEL1 of NOISE FACTOR}} \neq \mu_{\text{LEVEL2 of NOISE FACTOR}}$

Where$\mu_{\text{LEVEL1 ofNOISE FACTOR}}$is the mean collected from level one of the noise factor and $\mu_{\text{LEVEL2 of NOISE FACTOR}}$is the meancollected from level two of the noise factor.

Step 6: After analyzing the data,the optimal parameter settings will either be identical or not. If the optimal parameter settings are identical, then one confirmation run is performed. In this situation, the confirmation run is an additional set of experiments performed to validate that improvement for both first quality characteristic (QC_1)and second quality characteristic (QC_2)areachieved. However, if the optimal parameter level settings are not identical, then two confirmations runs are needed. Each confirmation run uses itsownparameter level settingto test both output variables of QC_1 and QC_2. Even though there are two confirmation runs performed on varying parameter levels, only one parameter level setting is needed eventually for both output variables improvement.

Step 7: If the outcome does not lead to anoptimized parameter setting for the two quality characteristics, then further tests are needed. Using the results from each of the confirmation runs for QC_1 and QC_2, two separate hypotheses are proposed to test whether or not a single optimized parameter level setting is possible.

The first hypothesis test is executed to see ifQC_1 mean usingoptimized parameter levelsettings for QC_1will be significantly different fromQC_1mean from running the machining operation using the optimized level settings for QC_2.

H_o: $\mu_{\text{QC1 (from opt Q1)}} = \mu_{\text{QC1 (from opt QC2)}}$

H_1: $\mu_{\text{QC1 (from opt Q1)}} \neq \mu_{\text{QC1 (from opt QC2)}}$

Where $\mu_{\text{QC1(from opt QC1)}}$is the QC_1mean from running experiments using the optimized parameter level settingsfor QC_1, and $\mu_{\text{QC1(from opt QC2)}}$ is the QC_1mean from running experiments using the optimized parameter level settingsfor QC_2.

Similarly, the second hypothesis test is conducted to see if QC_2mean using optimized parameter level settings for QC_2will be significantly different from theQC_2mean from running the experiment using the optimized level settings for QC_1.

H_o: $\mu_{\text{QC2 (from opt QC2)}} = \mu_{\text{QC2 (from opt QC1)}}$

H_1: $\mu_{\text{QC2 (from opt QC2)}} \neq \mu_{\text{QC2 (from opt QC1)}}$

Where $\mu_{\text{QC2(from opt QC2)}}$is the QC_2mean from running experiments using the optimized parameter level settings for QC_2, and $\mu_{\text{Q2(from opt Q1)}}$is the QC_2mean from running experiments using the optimized parameter level settings forQC_1.

From the hypothesis test, there are two possible outcomes. The first outcome is that the null hypothesis is not rejected. This is possible in three different ways. The first is that both null hypotheses are not rejected and the second and third are that we fail to reject one of the two null hypotheses. In case of the first outcome where the null hypothesis is not rejected, one confirmation run is enough to improve both output variables. The second outcome is that both null hypotheses are rejected. In that situation, additional testing must be performed as follows.

From the previous stage of the framework if both null hypotheses are rejected, an adjustment confirmation run will be performed. The parameter level settings that are not identical are first adjusted to a value between the two non-identical parameter values. The experiment is then performed and two final hypotheses are tested. The first hypothesis test is done to see if QC_1mean from the optimized parameter level settings for QC_1will be significantly differentfrom the QC_1mean obtained from the adjusted parameter level settings.

Ho: $\mu_{\text{QC1 (from adjusted setting)}} = \mu_{\text{QC1 (from opt QC1)}}$

H1: $\mu_{\text{QC1 (from adjusted setting)}} \neq \mu_{\text{QC1 (from optQC1)}}$

Where $\mu_{\text{QC1(from adjusted setting)}}$is the$QC_1$mean from the adjusted parameter level settings, and$\mu_{\text{Q1(from opt Q1)}}$is the QC_1mean from the optimized parameter level settings forQC_1.

The second hypothesis test is conducted to see if QC_2meanfrom the optimized parameter level settings forQC_2will be significantly different from the QC_2meanobtained from the adjusted parameter level settings.

Ho: $\mu_{\text{QC2 (from adjusted setting)}} = \mu_{\text{QC2 (from opt QC2)}}$

H1: $\mu_{\text{QC2 (from adjusted setting)}} \neq \mu_{\text{QC2 (from optQC2)}}$

Where $\mu_{\text{Q2(from adjusted setting)}}$ is the QC_2mean from the adjusted parameter level settings and $\mu_{\text{Q2(from optQ2)}}$is the QC_2mean from the optimizedparameter level settings for QC_2.

Ideally if both output variables are expected for optimization, one prefers to see that neither of thetwo null hypotheses is rejected. In this case the output from the adjusted parameter level settings is not significantly different from the output from the optimized parameter settings for each quality characteristic. However if one of the null hypotheses is rejected, then simultaneous improvement for both output variables was technically not possiblewith a single parameter level setting. When this happens, there are two options for the user. One is to select the parameter level settings based on the more importantquality characteristicfrom the two under investigation. However in reality the practitioner of this methodology may inquire into the difference of the output from the adjusted parameter level settings and the output from the baseline study for both QC_1 and QC_2. If there turns out to be a considerable improvement for both QC_1 and QC_2 by using the adjusted parameter settings, then the second option is to continue to use the adjusted parameter settings for both QC_1 and QC_2, for they both can still be improved although not optimized.

III. Case Study

The experiment was carried out on aSodick VZ 300LW-EDM machine. The wire used in this experiment is made of brass with adiameter of 0.25mm, and the work piece material is1080 steelsheet with a thickness of 0.175”. Dimensions of the work pieceare shown in Fig 3.

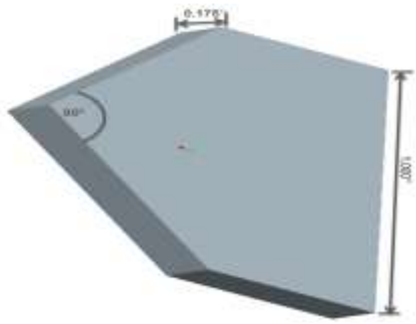


Fig. 3 Work piece dimension

3.1 Selection of output variables

In this research surface roughness and angular accuracy were selected as response variables. A Mitutoyo SJ-301profilometerwas used for measuring surface roughness and a Mitutoyo RV507 CMM machine was used for angular accuracy measurement.

3.2 Baseline analysis

The baseline run in this study was conducted using the default parameter level setting for the W-EDM operation. The parameter levels are: pulse on time at 12µs, wire feed rate at 35units, voltage of9v, and wire tension of 160 gram. These settings produced the following results as shown in Table 2.

Table 2 Baseline results

Run	1	2	3	4	5	6	7	8	9	10	Average
Surface Roughness Ra µin	147.9	141.7	136.1.9	144.2	140.2	138.9	145.7	139.1	140.9	142.6	142.4
Angular Accuracy θº	0.0958	0.0637	0.0872	0.0781	0.0692	0.0725	0.0713	0.0961	0.0734	0.1018	0.082

3.3 Controllable factor and noise factor selection

The cause and effect diagram (fishbone diagram) outlined possible significant factors that could affect the machine conditions and lead to products with inferior quality. Fig. 4 displays the cause and effect diagram. With the cause and effectanalysis, four machining parameters (pulse on time, wire feed rate, voltage, and wire tension)were selectedin this research as controllable factors. The selection of thesefour controllable factors arebased upon the previous literatures summarized in Table-1and their correlation to the output variablesof this research. Vibration was selected as noise factor in this research since it most accurately represents an uncontrollable factor as seen in the machine shop environment.

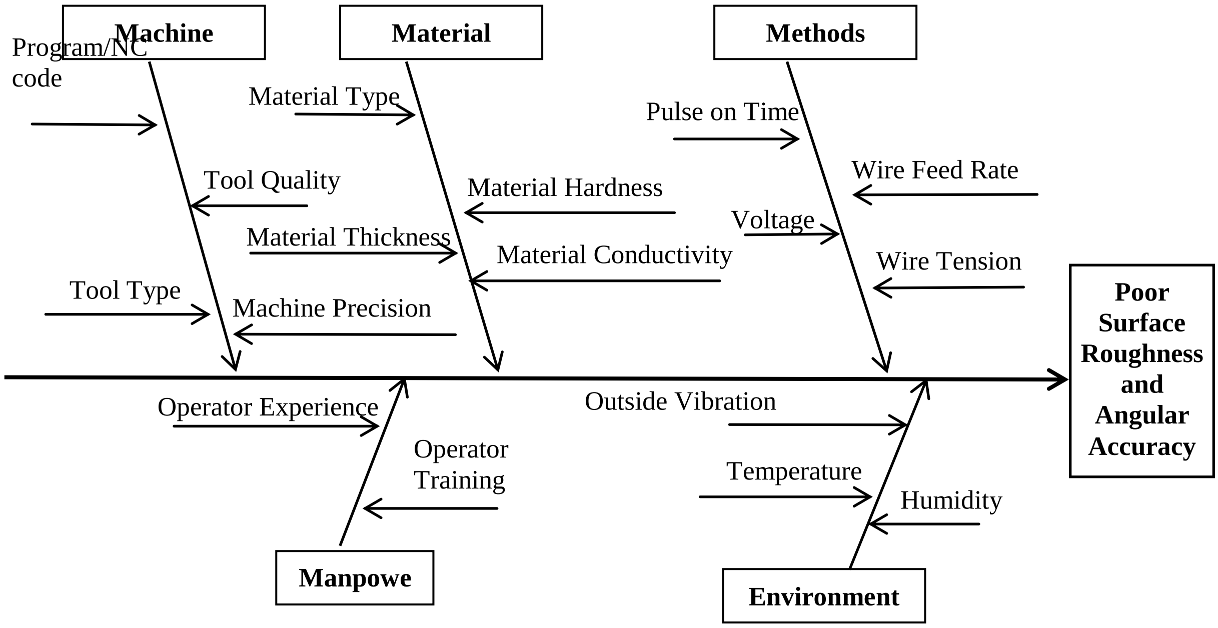


Fig. 4 Cause and effect diagram for poor surface roughness and angular accuracy

3.4 Designing OA matrix experiment

The next step is to implement Taguchi parameter design and OA matrixexperiment for the controllable factors and noise factor. Taguchi experiment is used in this research for a reduced cost incurred in the experimentation compared to traditional experiment design. Taguchi experiment involves four controllable factors including pulse on time, feed rate, voltage, and wire tension, each of which has three accompanying levels. Table 3 shows the Taguchi parameters design where vibration is considered as the noise factor for its uncontrollable effect on product quality.

Table 3 Taguchi parameters design

	---	Symbol	Level- 1	Level- 2	Level-3
P A R A M E T E R S	Pulse on time	T On(μs)	9	11	13
	Feed Rate	FR(in/min)	30	35	40
	Voltage	V(volt)	7	8	9
	Wire Tension	WT(gram)	155	160	165
Noise Factors	Vibration	V	on	Off	
Response Variables	dimensional of angles				
	surface roughness				

Selection ofOAis based on thenumber of controllable factors(4 controllable factors in this research) and their levels (3 levels for each controllable factor). In this research the OA will be a L_9 table by whichnine experiments will be done to study four controllable factors at three different levels for adequate experimental analysis. Table 4 shows the experiment design using an OA L_9 table.

Table 4 Experiments designed usingOA L9

Exp. No.	Control Factors				Noise Factor	
	T on	FR	V	WT	Vibration	Vibration
1	1	1	1	1	ON	OFF
2	1	2	2	2	ON	OFF
3	1	3	3	3	ON	OFF
4	2	1	2	3	ON	OFF
5	2	2	3	1	ON	OFF
6	2	3	1	2	ON	OFF
7	3	1	3	2	ON	OFF
8	3	2	1	3	ON	OFF
9	3	3	2	1	ON	OFF

IV. Results and Discussion

Subsequent to the Taguchi-based experiment implementation, an analysis was done to reveal the effect of the pulse on time, wire feed rate, voltage, and wire tension on the quality characteristics of surface roughness and angle accuracy. The experiments were conducted using the L_9OA matrix. Tables 5 and 6 show the experimental results for surface roughness and angular accuracy, respectively. The average value (Y-bar) and S/N ratio were calculated at different levels for the response characteristics. S/N ratio of smaller the betterwas computed using equation (1)for both surface roughness and angle accuracy. The angle accuracy value was calculated by measuring the angle first, then subtracting it from 90 degree to show the absolute angular deviation.

Table 5 Experiment results for surface roughness

Exp. No.	Control Factors				Noise Factor		Y-bar	S/N Ratio
	T on	FR	V	WT	V on	V off		
1	1	1	1	1	124.5	123.9	124.2	-41.88
2	1	2	2	2	122.6	120.2	121.4	-41.68
3	1	3	3	3	123.7	122.5	123.1	-41.81
4	2	1	2	3	128.6	124.3	126.45	-42.04
5	2	2	3	1	132.8	130.1	131.45	-42.38
6	2	3	1	2	137.2	135.9	136.55	-42.71
7	3	1	3	2	139.1	140.8	139.95	-42.92
8	3	2	1	3	134.2	137.9	136.05	-42.67
9	3	3	2	1	145.6	138.3	141.95	-43.05

Table 6 Experiment results for angle accuracy

Exp. No.	Control Factors				Noise Factor		Y-bar	S/N Ratio
	T on	FR	V	WT	V on	V off		
1	1	1	1	1	0.2366	0.2458	0.2412	12.35
2	1	2	2	2	0.1275	0.1259	0.1267	17.94
3	1	3	3	3	0.2721	0.2546	0.26335	11.58
4	2	1	2	3	0.1211	0.1312	0.12615	17.98
5	2	2	3	1	0.1446	0.1261	0.13535	17.35
6	2	3	1	2	0.1107	0.1013	0.106	19.49
7	3	1	3	2	0.0855	0.0174	0.05145	24.19
8	3	2	1	3	0.1382	0.0644	0.1013	19.35
9	3	3	2	1	0.0447	0.096	0.07035	22.51

4.1 Data analysis for surface roughness

Tables 7and 8show the responses of mean and S/Nratio ofsurface roughness. From the collected data, pulse on time is the most significant factor in affecting surface roughness while voltage and wire tension are shown to be less significant factors. It can be observed that surface roughness increases with an increase in pulse on time, and surface roughness decreases with an increase in wire tension. Also surface roughness is higher with the first level of voltage and the third level of wire feed rate but decreases when using the middle two levels. Fig.5

shows that the optimal parameter settings for surface roughnessarefirst level of pulse on time (A_1), second level of wire feed rate (B_2), second level of voltage (C_2), and third level of wire tension (D_3).

Table 7 Response tableof mean for surface roughness $r_{a\ \mu in}$

Level	A (T on)	B (FR)	C (V)	D (WT)
1	122.9	130.2	132.3	132.5
2	131.5	129.6	129.9	132.6
3	139.3	133.9	131.5	128.5

Table 8 Response table of signal to noise (S/N) ratio for surface roughness

Level	A (T on)	B (FR)	C (V)	D (WT)
1	-41.79	-42.28	-42.42	-42.43
2	-42.37	-42.25	-42.26	-42.44
3	-42.88	-42.52	-42.37	-42.17

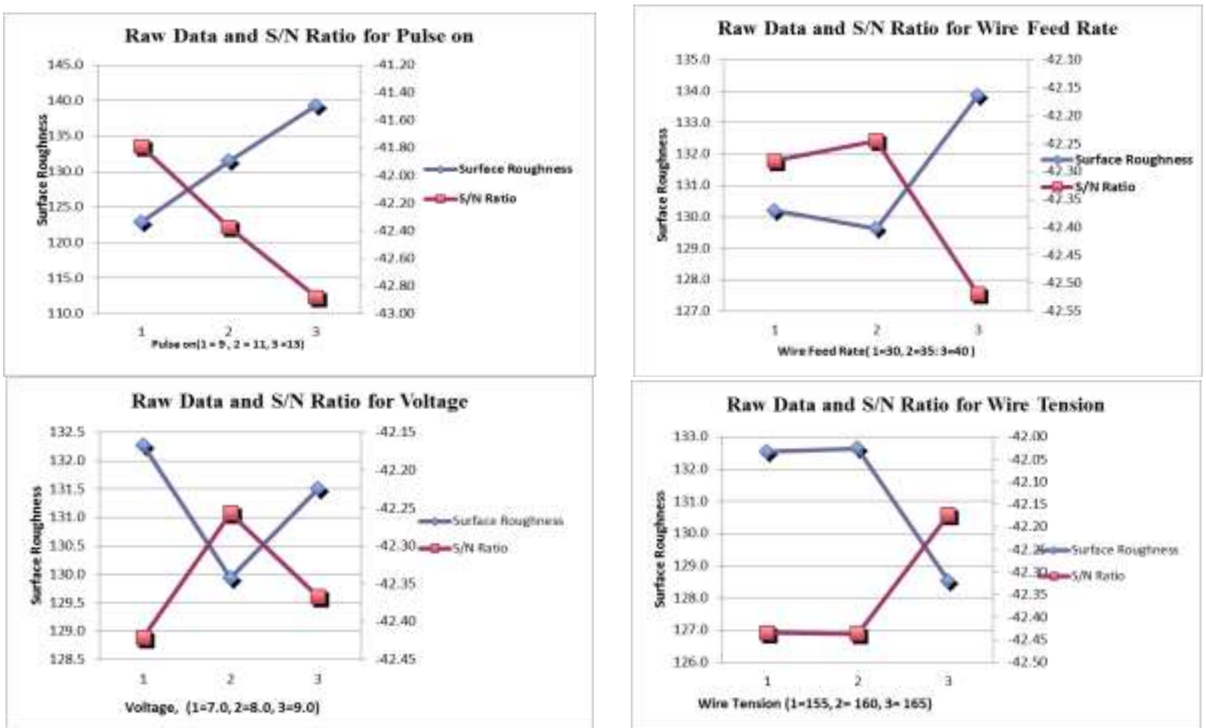


Fig. 5 Effects of controllable parameters on surface roughness and S/N ratio

After the optimization was completed,the effect of noise factor on W-EDM process was also studied by using aT-test to determine if vibration is significant to surface roughness.

H_0: $\mu_{Ra\ (vibration\ On)} = \mu_{Ra\ (vibration\ Off)}$

H_1: $\mu_{Ra\ (vibration\ On)} \neq \mu_{Ra\ (vibration\ Off)}$

Where $\mu_{Ra\ (vibration\ On)}$ is the mean of vibration-on values and $\mu_{Ra\ (vibration\ Off)}$ is the meanof vibration-off values obtained from Table 5.

By using equation,

$$t = \frac{\bar{\mu}_{Ra\ (vibration\ On)} - \bar{\mu}_{Ra\ (vibration\ Off)}}{\sqrt{\frac{S^2_{Ra\ (vibration\ On)} + S^2_{Ra\ (vibration\ Off)}}{n_{1+n_2}}}}$$

The t-value for surface roughness is 0.430 which is smaller than t critical value of 2.92(with alpha = 0.01, degree of freedom =16).Therefore the null hypothesis is not rejected, which means the vibration does not affect surface roughness.

4.2 Data analysis for angular accuracy

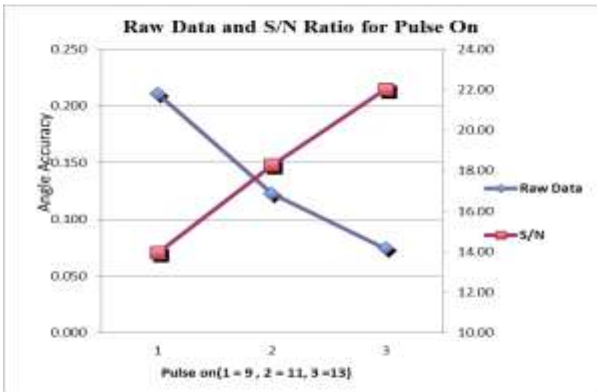
Tables 9 and 10shows the responsesof mean and S/N ratio of angular accuracy. From the collected data, pulse on time and wire tension are the most significant factors affecting angular accuracy, while voltage and feed rate are shown to be less significant. It can be observed that angular accuracy decreases with an increase in pulse on time, and angular accuracy is the best with the middle level of wire tension. When observing the results of feed rate and voltage, the middle two levels give thelowest deviation from the nominal 90-degree. Fig.6 shows that the optimal parameter settings arethird level of pulse on time (A_3), second level of wire feed rate (B_2), second level of voltage (C_2), and second level of wire tension (D_2).

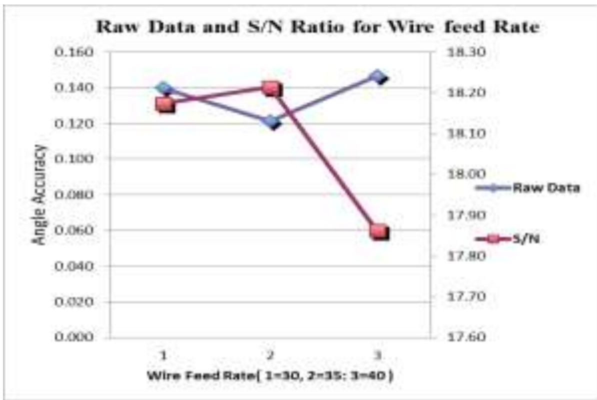
Table 9 Response table of mean for angular accuracy θº

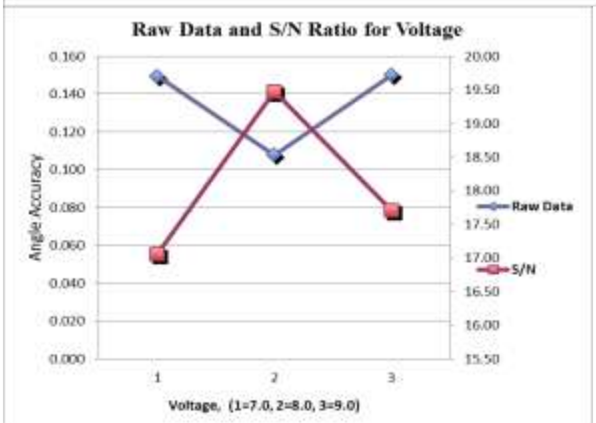
Level	A (T on)	B (FR)	C (V)	D (WT)
1	0.210	0.140	0.150	0.149
2	0.123	0.121	0.108	0.095
3	0.074	0.147	0.150	0.164

Table 10 Response table ofS/N ratio for angular accuracy

Level	A (T on)	B (FR)	C (V)	D (WT)
1	13.96	18.17	17.06	17.40
2	18.27	18.21	19.48	20.54
3	22.02	17.86	17.71	16.30







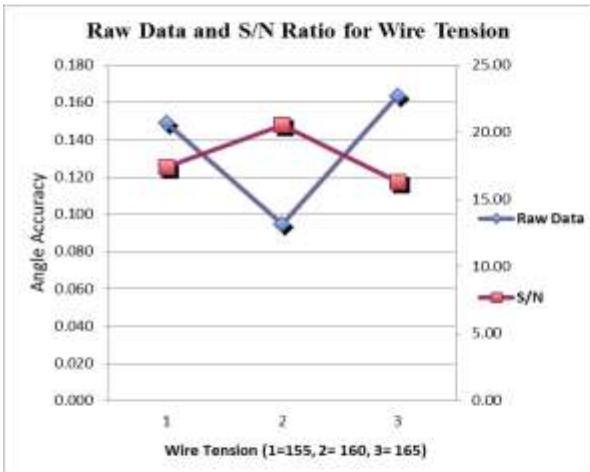


Fig. 6 Effects of controllable parameters on angular accuracy and S/N ratio

After optimization was completed for angular accuracy, another hypothesis test for noise factor on W-EDM process was conducted to determine if vibration is significant to angular accuracy.

H_0: $\mu_{\theta\ (\text{vibration On})} = \mu_{\theta\ (\text{vibration Off})}$

H_1: $\mu_{\theta\ (\text{vibration On})} \neq \mu_{\theta\ (\text{vibration Off})}$

Where $\mu_{\theta\ (\text{vibration On})}$ is the mean of vibration-on values and $\mu_{\theta(\text{vibration Off})}$ is the meanof vibration-off values obtained from Table 6.

By using equation,

$$t = \frac{\bar{x}_{Ra\ (\text{vibration On})} - \bar{x}_{Ra\ (\text{vibration Off})}}{\sqrt{\frac{s^2_{Ra\ (\text{vibration On})} + s^2_{Ra\ (\text{vibration Off})}}{n_1+n_2}}}$$

The t-value for angular accuracy is 0.3758 which is smaller than t critical value of 2.92(with alpha = 0.01, degree of freedom =16).So the null hypothesis is not rejected, which means that the vibration does not affect angular accuracy.

The above data analysisshows that the optimal parameter levelsare not identicalfor surface roughness and angular accuracy. Surface roughness has levels of A_1, B_2, C_2, and D_3, while angular accuracy haslevels of A_3, B_2, C_2, and D_2. Hencetwo confirmation runs are needed foreach quality characteristic on their own optimal parameter level settings.

V. Confirmation runs

Confirmation run is an additional set of experiments performed using the optimal parameter values as determined from the Taguchi experiments. For this researchconfirmationrunsare used to validate that improvementsfor both surface roughness and angular accuracy can beaccomplished. Tables 11 and 12show the outcomes of confirmation runs for both surface roughness and angular accuracy quality characteristics.

Table 11 Confirmation run for surface roughness and confidence interval

Run	1	2	3	4	5	6	7	8	9	10
Surface Roughness Ra µin	112.3	113.4	115.9	116.7	115.2	108.9	113.5	118.7	112.6	117.9
Mean = 114.51			Standard Deviation= 2.954				Upper CI = 117.545			
T-value (99%) = ± 3.250			N= 10				Lower CI = 111.475			

Table 12 Confirmation run for angular accuracy and confidence interval

Run	1	2	3	4	5	6	7	8	9	10
Angular Accuracy θº	0.0082	0.011	0.007	0.0084	0.0079	0.012	0.0091	0.0098	0.0095	0.0067
Mean = 0.00896			Standard Deviation= 0.0017				Upper CI = 0.01069			
T-value (99%) = ± 3.250			N= 10				Lower CI = 0.00723			

Based on the optimal setting (A_1, B_2, C_2, and D_3) forsurface roughness, the predicted optimal value for surface roughness is given as:

Predicted Ra = $\mu A_1 + \mu B_2 + \mu C_2 + \mu D_3 - 3^*$ Y-Avg = 117.30µin

Based on the optimal setting (A_3, B_2, C_2, and D_2) forangular accuracy, the predicted optimal value for angular accuracy is given as:

Predicted θ = $\mu A_3 + \mu B_2 + \mu C_2 + \mu D_2 - 3^*$ Y-Avg = 0.00935º

The letters with a number subscript in the above two representations denote the optimal parameter selections, and Y-Avg is the average of all response data. Through comparing the predicted values and the results from comfirmation runs, it can be shown thatboth confirmation runs actually rendered more improvement than what was expected, and the predicted values fell between the upper and lower bounds. The mean of surface roughness from confirmation run is 114.51 µin, which is less than the predicted 117.30 µin, and the mean of angular accuracy from confirmation run is 0.00896 º, less than the predicted 0.00935º.

Given the results from confirmation runs, a final T-test for 99% confidence interval was conducted to confirm the expected level of experimental repeatability. For surface roughness, it can be expected with 99% confidence that a part cut on aW-EDM machine will have surface roughness values between 111.475µinand 117.545µin. Likewise, an angle feature cut using aW-EDMmachine will be within the deviation range of 0.00723ºto 0.01069ºat 99% confidence.

VI. Merging two quality characteristics into one optimal parameter setting

The case study shows non-identical parameter settings for the two quality characteristics. The optimal parameter for surface roughness is A_1, B_2, C_2, and D_3andthat for angular accuracyis A_3, B_2, C_2, and D_2. In order to optimize both quality characteristics simultaneously, it is necessary to reachone optimal parameter setting that can optimize both surface roughness and angular accuracy at the same time.

In this research a T-test was used to determine if there is a significant difference in mean between the surface roughnessproduced by the optimal parameter levels for surface roughness itself and the surface roughnessproduced by the optimal parameter levels for angular accuracy.

H_o: $\mu_{Ra\ (from\ opt\ Ra)} = \mu_{Ra(from\ opt\ \theta)}$

H_1: $\mu_{Ra\ (from\ opt\ Ra)} \neq \mu_{Ra(from\ opt\ \theta)}$

Where $\mu_{Ra\ (from\ opt\ Ra)}$ is the mean of surface roughnessfrom the experiments using the optimized parameter level settingfor surface roughness, and $\mu_{Ra\ from\ opt\ (\theta)}$ is the mean of surface roughnessfrom experiments using the optimized parameter level settingfor angular accuracy.

Table 13 shows boththe surface roughnessdata from the optimized parameter level for surface roughness itself and the data from the optimized parameter level for angular accuracy (θ).

By using equation, $t = \frac{\bar{x}_{Ra\ (from\ opt\ Ra)} - \bar{x}_{Ra\ (from\ opt\ \theta)}}{\sqrt{\frac{S^2_{Ra\ (from\ opt\ Ra)} + S^2_{Ra\ (from\ opt\ \theta)}}{n_1+n_2}}}$

The t-value is -16.05 which falls outside of t-critical value +/-2.898 (with alpha=0.01 degree of freedom=18). Thus the null hypothesis is rejected. The conclusion is that the non-identical parameter setting doesaffect surface roughness.

Table 13 T-test comparing of two data (surface vs. angular) for Ra

No.	(Ra) from opt Surface Roughness	(Ra) from opt Angular accuracy
1	112.3	133.6
2	113.4	141.1
3	115.9	145.6
4	116.7	134.7
5	115.2	138.6
6	108.9	139.7
7	113.5	135.2
8	118.7	137.9
9	112.6	135.6
10	117.9	138.2
Average	114.51	138.02
Standard Deviation	2.95	3.57
SE Mean	1.46	
T-value	-16.05	
Degree of Freedom	17	
T- alpha value .01	± 2.898	

Table 14 T-test comparing of two data (surface vs. angular) for θ

No.	(θ) from opt Angular accuracy	(θ) from opt Surface Roughness
1	0.0082	0.0514
2	0.011	0.044
3	0.007	0.0925
4	0.0084	0.067
5	0.0079	0.0566
6	0.012	0.0426
7	0.0091	0.0866
8	0.0098	0.0372
9	0.0095	0.0361
10	0.0067	0.0964
Average	0.00896	.0610
Standard Deviation	0.00168	0.0232
SE Mean	0.00737	
T-value	-7.067	
Degree of Freedom	9	
T- alpha value .01	± 3.250	

Similarly T-test was also used to determine if there is a significant difference between the mean of angular accuracyproduced bythe optimized parameter levels for angular accuracy itself and the mean ofangular accuracy produced by the optimized parameter level for surface roughness.

H_o: $\mu_{\theta(from\ opt\ \theta)} = \mu_{\theta\ (from\ opt\ Ra)}$

H_1: $\mu_{\theta(from\ opt\ \theta)} \neq \mu_{\theta(from\ opt\ Ra)}$

Where $\mu_{\theta(from\ opt\ \theta)}$ is the mean of angular accuracy from the experiments using the optimized parameter level for angular accuracy, and $\mu_{\theta(from\ opt\ Ra)}$ is the mean of angular accuracy from the experiments using the optimized parameter level for surface roughness.

Table 14 shows both the angular accuracy data from the optimized parameter level for angular accuracy and the data from the optimized parameter level for surface roughness.

By using equation, $t = \frac{\bar{x}_{\theta(from\ opt\ \theta)} - \bar{x}_{\theta\ (from\ opt\ Ra)}}{\sqrt{\frac{S^2_{\theta(from\ opt\ \theta)} + S^2_{\theta\ (from\ opt\ Ra)}}{n_1+n_2}}}$

The t-value is -7.067 which falls outside of t-critical value ±3.250 (with alpha=0.01 degree of freedom=18), and therefore the null hypothesis is rejected. The conclusion is that the non-identical parameter setting does affect angular accuracy.

Since both null hypotheses were rejected with the above two T-tests, the optimal parameter settings for surface roughness and angular accuracy need to be adjusted into one optimal setting. With surface roughness optimal levels of A_1, B_2, C_2, and D_3 and angular accuracy optimal levels of A_3, B_2, C_2, and D_2, the adjusted optimal levels are made at the middle points of each individual parameter. Hence the adjusted optimal levels in this case study are A_2, B_2, C_2, and $D_{2.5}$.A final run was conducted using the adjusted parameter level setting. Table 15 shows the data collected from the finalrunwith the measurement of the surface roughness and angular accuracyunder the newly adjusted parameter settings of A_2, B_2, C_2, and $D_{2.5}$. This data was then further compared in another T-test to the data collected from the confirmation runs made using each separate optimized parameter level setting.

Table 15 Final runs with adjusted parameter for surface roughness and angular accuracy

Run	1	2	3	4	5	6	7	8	9	10	Average
Surface Roughness Ra µin	123.6	118.9	124.7	125.6	117.2	123.1	124	119.3	121.9	119.1	121.7
Angular Accuracy θº	0.0423	0.0234	0.0306	0.0365	0.0317	0.0487	0.0503	0.0291	0.0467	0.0483	0.0388

A T-test was used to determine if there is a significant difference between themean of surface roughness(Ra)from the adjusted parameter levels and themean of surface roughness(Ra)from the optimized parameter levels for surface roughness.
Ho: $\mu_{Ra(\text{from adjusted setting})} = \mu_{Ra(\text{from opt Ra})}$
H1: $\mu_{Ra(\text{from adjusted setting})} \neq \mu_{Ra(\text{from opt Ra})}$
Where $\mu_{Ra(\text{from adjusted setting})}$ is the mean ofsurface roughness (Ra)from the adjusted parameter level setting, and $\mu_{Ra(\text{from opt Ra})}$is the mean of surface roughness (Ra) from the optimized parameter level setting forsurface roughness.Table 16 shows thesurface roughness (Ra)from the adjusted parameter level and thesurface roughness(Ra)from the optimized parameter level for surface roughness.
By using equation,

$$t = \frac{\bar{x}_{Ra\ (\text{from adjusted setting})} - \bar{x}_{Ra\ (\text{from opt Ra})}}{\sqrt{\frac{s^2_{Ra\ (\text{from adjusted setting})} + s^2_{Ra\ (\text{from opt Ra})}}{n_1+n_2}}}$$

The t-value is -5.52 which falls outside of t-critical value +/-3.250 (with alpha=0.01 degree of freedom=18),therefore the null hypothesis is rejected. This result means that the adjustment of parameter levels does affect surface roughness.

Table 16T-test comparing of two data (surface vs. adjusted) for Ra

No.	(Ra) from opt Surface Roughness	(Ra)from Adjusted Parameter
1	112.3	123.6
2	113.4	118.9
3	115.9	124.7
4	116.7	125.6
5	115.2	117.2
6	108.9	123.1
7	113.5	124
8	118.7	119.3
9	112.6	121.9
10	117.9	119.1
Average	114.51	121.74
Standard Deviation	2.95	2.90
SE Mean	1.31	
T-value	-5.52	
Degree of Freedom	9	
T- alpha value .01	±3.250	

Table 17 T-test comparing of two data (angular vs. adjusted) for θ

No.	(θ) from opt Angular accuracy	(θ)from Adjusted Parameter
1	0.0082	0.0423
2	0.011	0.0234
3	0.007	0.0306
4	0.0084	0.0365
5	0.0079	0.0317
6	0.012	0.0487
7	0.0091	0.0503
8	0.0098	0.0291
9	0.0095	0.0467
10	0.0067	0.0483
Average	0.00896	0.0388
Standard Deviation	0.00168	0.0097
SE Mean	0.0031	
T-value	-9.56	
Degree of Freedom	10	
T- alpha value .01	±3.169	

T-test was also used to determine if there is a significant difference in mean value between the angular accuracy(θ) collected from the adjusted parameter level and theangular accuracy(θ)collected from the optimized level for angular accuracy.
Ho: $\mu_{\theta(\text{from adjusted setting})} = \mu_{\theta(\text{from opt }\theta)}$
H1: $\mu_{\theta(\text{from adjusted setting})} \neq \mu_{\theta(\text{from opt }\theta)}$
Where $\mu_{\theta(\text{from adjusted setting})}$ is the mean of angular accuracy(θ) from the adjusted parameter level setting, and $\mu_{\theta(\text{from opt }\theta)}$ is the mean ofangular accuracy(θ) from the optimized level settingfor angular accuracy.
Table 17 shows theangular accuracy(θ)from the adjusted parameter level and the angular accuracy(θ)from the optimized level for angular accuracy.

By using equation,

$$t = \frac{\bar{x}_{\theta(\text{from adjusted setting})} - \bar{x}_{\mu\theta(\text{from opt }\theta)}}{\sqrt{\frac{S^2_{\theta(\text{from adjusted setting})} + S^2_{\mu\theta(\text{from opt }\theta)}}{n_1+n_2}}}$$

The t-value is -9.56 which is falls outside of t-critical value +/-3.169 (with alpha=0.01 degree of freedom=18),and the null hypothesis is rejected. Consequently the adjustment of parameter levels affects angular accuracy.

The finding of T-test shows that for both surface roughness and angular accuracy the null hypotheses are rejected. With both null hypotheses rejected, it is concluded that a single optimized parameter level setting could not be used for optimizing both output variables at the same time. In this situation, one optimized parameter level setting, either for surface roughness or angular accuracy, should be chosen depending on which quality characteristic is more important to the user. Alternatively the user could compare the outputs from the adjusted parameter level setting with the outputs from baseline study. If there is considerable improvement for both quality characteristics from the responses of baseline study, it is still worthy of using the adjusted parameter level setting.

VII. Conclusion

This research presents a framework based on Taguchi parameter design to optimize two quality characteristics- surface roughness and angular accuracy in Wire Electrical Discharge Machining (W-EDM) process. Four factors were investigated as controllable factors including pulse on time, wire feed rate, voltage, and wire tension, while one factor- vibration is considered as noise factor. The analysis of experimental results concludes that pulse on time is the most significant factor that impacts both surface roughness and angle accuracy. Wire tension is secondarysignificantto angle accuracy but was shown to have lessinflunece on surface roughness. Voltage was shown to have some effect on the outputvariables while wire feed rate had little or no effect.

From the initial baseline study, the output variables of surface roughness and angular accuracy were found to have average values of 142.4µin and 0.082º. By using Taguchi method with a L_9 table experiment design, the optimized parameter level setting for each individual quality characteristic was found. The confirmationrun conducted for surface roughness had an average value of 114.51µin while the confirmationrunconducted for angular accuracy had an average value of 0.00896º.The difference in optimal parameter level setting for these two output variableslead to the adjustment of parameter levels into one setting for further data analysis. Hence two more runs of experiments were performed for each output variable using the adjusted parameter setting. Data analysis shows that the surface roughness value was found to be 121.7µin, and the angular accuracy value was found to be 0.0388º under the adjusted parameter setting. Although the adjusted parameter setting did not yield the same results compared to the optimized parameter setting for each output variables, overall improvement was still observed. As future work, the authors plan to apply this methodology to study the effect of other machining conditions such as different wire type and work piece material on other quality characteristics such as material removal rate (MRR) and electrode wear ratio (EWR).

References

[1.] Singaram Lakshmanan, & Mahesh Kumar. (2013). Optimization of EDM Parameters Using Response Surface Methodology for EN31 Tool Steel Machining. Retrieved from http://www.ijesit.com/Volume%202/Issue%205/IJESIT201305_10.pdf

[2.] Jiju Antony, Frenie Jiju Antony, (2001) "Teaching the Taguchi method to industrial engineers", Work Study, Vol. 50 Iss: 4, pp.141 – 149.

[3.] Allcock, Andrew, (2014) “Wire-cut EDM overview and integrated CADCAM programming's importance.” Retrieved from:http://www.machinery.co.uk/machinery-features/wire-cut-edm-vero-software-uk/58350/

[4.] Sommer, C.,& Sommer, S. (2005). *Complete EDM handbook*. Houston, TX: Advance Pub.

[5.] Introduction to Taguchi Methods. Retrieved from https://openair.rgu.ac.uk/bitstream/10059/358/5/Viswanathan%20E%20Chapter%203.pdf

[6.] Harpreet Singh,& Amandeep Singh. (2012). *Effect of Pulse On/Pulse Off Time On Machining Of AISI D3 Die Steel Using Copper And Brass Electrode In EDM. International Journal of Engineering and Science*, *1*(9).

[7.] Parveen Kumar et al. Int. Journal of Engineering Research and Applications ISSN: 2248-9622, Vol. 3, Issue 5, Sep-Oct 2013, pp.907-912.

[8.] AtulKumar, & DR.D.K.Singh. (2012). *Performance Analysis of Wire Electric Discharge Machining (W-EDM)*, *1*(4).

[9.] Lakshmikanth, G.,NirmalMurali, Arunkumar, G.,&Santhanakrishnan, S. (2014). *Investigation on Optimization of Machining Parameters in Wire EDM Using Taguchi Technique. International Journalfor Scientific Research & Development*, *1*(9).

[10.] Alpesh M. Patel,& Vishal Achwal. (2013). *Optimization of Parameters for WEDM Machine for Productivity Improvement. IOSR Journal of Mechanical and Civil Engineering*, *9*(5).

[11.] Habib, S. S. (2014). Parameter optimization of electrical discharge machining process by using Taguchi approach. Journal of Engineering and Technology Research, 6(3), 27-42.

[12.] Lokeswara Rao T, &Selvaraj, N. (2013). Optimization of WEDM Process Parameters on Titanium Alloy Using Taguchi Method. International Journal of Modern Engineering Research, 3(4).

[13.] JasvinderPal,&Nishant. (2014). *PARAMETERS OPTIMIZATION OF WIRE EDM FOR SURFACE ROUGHNESS USING TAGUCHI. International Journal of Technical Research*, *3*(1).

[14.] Jaganathan, P., Naveen kumar, T.,& Dr. R.Sivasubramanian. (2012). *Machining Parameters Optimization of WEDM Process Using Taguchi Method. International Journal of Scientific and Research Publications*, *2*(12).

[15.] Hari Narayana, K.,Dr.BaluNaik, B.,Srinivasa R Nandam, &AnandRao, A. (2014). *Experimental Investigations of HSS M2 Alloy on Wire Electric Discharge Machining Process Using Taguchi Methodology. International Journal of Engineering Science and Innovative Technology*, *3*(3).

[16.] Wysk, R. A., Niebel, B. W., Cohen, P. H., and Simpson, T. W. Manufacturing Processes: Integrated Product and Process Design, McGraw Hill, New York, 2000

[17.] Unal, R.,&Dean, E. B. (1991). TAGUCHI APPROACH TO DESIGN OPTIMIZATION FOR QUALITY AND COST: AN OVERVIEW.

[18.] Sanghani, C. R., & Dr. Acharya, G. D. (2014). *A Review of Research on Improvement and Optimization of Performance Measures for Electrical Discharge Machining. Journal of Engineering Research and Applications*, *4*(1(Version 2)), 433-450