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Taguchi-Based Optimization of Surface Roughness and Dimensional Accuracy in Wire EDM Process with S7 Heat Treated Steel

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***Abstract*—**This research focuses on the use of the Taguchi method to reduce the surface roughness and improve dimensional accuracy of parts machined by Wire Electrical Discharge Machining (EDM) with S7 heat treated steel material. Due to its high impact toughness, the material is a candidate for a wide variety of tooling applications which require high precision in dimension and desired surface roughness. This paper demonstrates that Taguchi Parameter Design methodology is able to optimize both dimensioning and surface roughness successfully by investigating seven wire-EDM controllable parameters: pulse on time (ON), pulse off time (OFF), servo voltage (SV), voltage (V), servo feed (SF), wire tension (WT), and wire speed (WS). The temperature of the water in the Wire EDM process is investigated as the noise factor in this research. Experimental design and analysis based on L_{18} Taguchi orthogonal arrays are conducted. This paper demonstrates that the Taguchi-based system enables the wire EDM process to produce (1) high precision parts with an average of 0.6601 inches dimension, while the desired dimension is 0.6600 inches; and (2) surface roughness of 1.7322 microns which is significantly improved from 2.8160 microns.

***Keywords*—**Taguchi parameter design, surface roughness, dimensional accuracy, Wire EDM.

I. Introduction

Wire EDM is well known for its ability to machine complex features with tough metals which normally cannot be easily machined in transitional machines. Thus, EDM is an ideal process for producing cutting tools, dies, and molds for injection molding, etc. Wire EDM, shown in Fig. 1, can only cut conductive metals because of the electrical interactions used to machine the raw material. Wire EDM works by guiding the brass wire using CNC Coding to cut the desired geometries. Electricity is passed through the wire which leaps the spark gap and rips the material away for the raw material [1]. Although critical capabilities of EDM have improved, it can be difficult to produce a better surface roughness product while maintaining dimensional accuracy.

The study [2] by Gupta and Jain focused on using the Wire EDM process to cut miniature spur gears. The objective of their study was surface roughness and the dimensional accuracy of each gear by focusing on pulse on time, pulse off time, voltage, wire feed, and cutting speed. The results of their study showed that there was a significant improvement in the surface roughness after going through the Design of Experiment (DOE), with one factor being changed at a time. The study [3] by Saleem and Awais focused on using Wire EDM to complete a taper cut to achieve a high Material Removal Rate (MRR) and low surface roughness. Their study primarily focused on the tension of the wire while cutting two types of material of varying hardness. The study concluded that the MRR is not affected significantly by the tension of the wire, while the hardness of the material significantly affects the surface roughness [3].

Rao and Pawar acknowledged the ability of Wire EDM for cutting complex geometries; however, they concluded that the high number of parameters makes it very difficult to optimize performance. Rao and Pawar adjusted pulse on time, pulse off time, peak current, and SF to reach an improvement in the complex geometries [4]. However, this research failed to include other cutting parameters. Plaza et al. focused on taper cutting, another issue associated with surface roughness. One significant issue with taper cutting is the deformations on the angle cuts that cause differences in the inclined angles. DOE was used in this research, and the angular error could be reduced significantly in 75% of cases [5]. Dongre et al. analyzed Wire EDM as a possible solution for the main process for cutting polycrystalline silicon wafers used in solar panels. The focus of the study was to find the optimal parameters to maximize cutting speed, minimize Kerf loss and surface roughness by changing pulse on time, pulse off time, voltage, and water pressure [6]. Fonda et al. focused on using a Wire EDM to cut polycrystalline diamond micro tools. This process utilized two different cuts. The parameters analyzed were discharge off time, discharge current level, arcing sensitivity, discharge voltage, SV, and WS [7].

These above-mentioned researches are able to identify significant factors among many parameters of a process to resolve quality problems. However, it is a time-consuming process to conduct full factorial DOE, which requires many experiments resulting in high cost. In recent years, Taguchi Parameter Design has been implemented in industries to optimize a process to resolve quality issues with many experiments than that from regular DOE. In particular, the Wire EDM process is a very time-consuming process.

Many researches have documented the successful outcomes of implementing Taguchi Parameter Design to optimise Wire EDM processes, and they are summarized as follows. The research of Kuruvila and Ravindra improved surface roughness, MRR, and dimensional error by adjusting the five

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controllable parameters [8]. The study of Ozan et al. focused solely on the surface roughness for different metal matrix compositions by optimizing parameters for particle ratio, pulse time on, and wire feed [9]. Boopathi and Sivakumar studied "near" dry Wire EDM to minimize pollutants and surface roughness by analyzing gap voltage, pulse on time, pulse off time, air-mist pressure, and discharge current [10]. These studies demonstrate that surface roughness optimization is an important quality characteristic in the Wire EDM process and due to its long processing time, these typical DOE researches only investigate five or fewer major controllable factors. Taguchi parameter design has been strongly recommended by Kumar et al. [11] to investigate more major factors and multiple quality characteristics in EDM process.

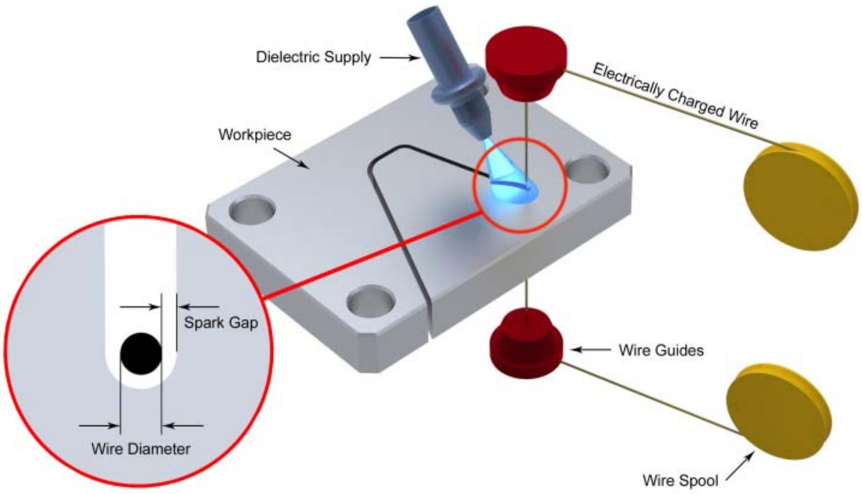

Fig. 1 Illustration of basic Wire EDM process

This paper attempts to investigate seven major controllable factors in the wire EDM process plus one non-controllable factor to define an optimum process setting to machine the best surface roughness while maintaining the highest dimensional accuracy at the same time. This paper is proposing a systematic approach to reach the optimal setting which allows the wire EDM process to produce desired dimensional accuracy and surface roughness.

II. TAGUCHI L_{18} EXPERIMENTAL SETUP

The experiment is conducted using SODICK EDM machine with S7 heat treated steel to produce gears with tapper design shown in Fig. 2. The specification limit of the diameter of the cross session is defined as 0.660±0.003 inches. The surface roughness of the tapper surface is expected to be less than 2 microns of Ra.

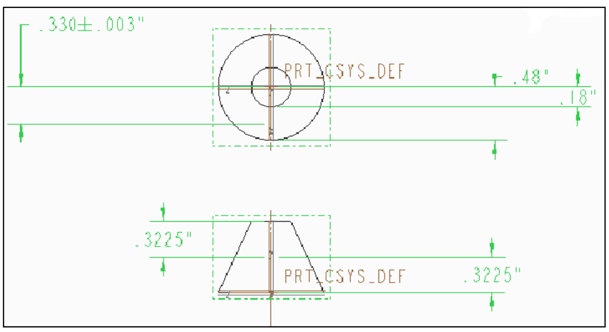

Fig. 2 Gear Die Design- half inch thick piece of steel

A. Measurement System Setup

After the product is machined by the Wire EDM machine, two measurements are conducted: one is the surface roughness which is measured by a Zegage by ZYGO, a non-contact optical profiler. The surface roughness measurement (Sa), Arithmetical Average Roughness, is defined as *"arithmetic mean of the absolute values of the surface departures from the mean plane"* [12]. The other measurement is the cross section of the product with diameter measured in inches on the Coordinate Measuring Machine (CMM). The diameter is measured and set up at the same point for diameter measurement based on CMM programming.

B. Define Baseline Quality Outcomes

Seven controllable parameters have been investigated in this study: pulse on time (ON), pulse off time (OFF), SV, voltage (V), SF, WT, and WS. A total of 14 experiments based on the parameter settings shown in Table I, with water temperatures in a normal 70-80 °F range, are conducted. The baseline results, with 2.816 microns of surface roughness and 0.6484 inches length are summarized in Table II.

TABLE I
BASELINE PARAMETER SETTINGS

ON	OFF	SV	V	SF	WT	WS
012	010	+055.0	7.0	0012	035	100

C. Taguchi L_{18} Orthogonal Array (OA) Design

In order to review a total of seven major factors to Wire EDM process, Taguchi L_{18} OA design is implemented in this study. Table III shows the design to have one main factor with two levels and six other factors with three levels each. In addition, one non-construable factor, the water temperature of the EDM process, is investigated. Two outputs are investigated: (a) surface roughness, which is based on the smaller the better quality characteristics and the Signal to Noise (S/N) ratio as given in (1); (b) the dimensional accuracy of the diameter (targeting 0.660 inch) is defined as the nominal the better quality characteristics with S/N as given in (2).

TABLE II
BASELINE EXPERIMENTAL ANALYSIS

Description	Surface Roughness (microns)	Dimensional Accuracy (inches)
Mean	2.816	0.6484
Standard deviation	0.142	0.0023
Desired value	The smaller the better	0.660

The completed Taguchi L_{18} OA design is shown in Table IV with a total of 36 Wire EDM experiments. If this was conducted via a full factorial DOE experimental design, it would require a total of 2916 ($2^1 3^6$ and two replications) experiments.

$$ή = \frac{S}{N} = -10\text{Log}\left(\frac{1}{n} * \sum_{i=1}^{n} Yi^2\right) \quad (1)$$

$$ή = \frac{S}{N} = 10 * \text{LOG}(\bar{Y}^2/\sigma^2) \quad (2)$$

TABLE III
FACTORS & LEVELS INVESTIGATED

	Variable	Unit	Level 1	Level 2	Level 3
A	Time on	µs	4	6	-
B	Time off	µs	6	8	10
C	Servo Voltage	V	35	45	55
D	Voltage	V	7	8	9
E	Servo Feed	in/min	0.09	0.12	0.15
F	Wire Tension	n	25	35	45
G	Wire Speed	in/min	0.80	1.00	1.20

Non-controllable factor – Temperature of the water High (70°F+) and Low (55 – 65 °F)

TABLE IV
TAGUCHI EXPERIMENTAL DESIGN TABLE WITH SEVEN PARAMETERS AND ONE NOISE FACTOR

N	Factors						
	A(ON)	B(OFF)	C(SV)	D(V)	E(SF)	F(WT)	G(WS)
1	1 (4)	1 (6)	1 (35)	1 (7)	1 (0.09)	1 (25)	1 (0.80)
2	1 (4)	1 (6)	2 (45)	2 (8)	2 (0.12)	2 (35)	2 (1.00)
3	1 (4)	1 (6)	3 (55)	3 (9)	3 (0.15)	3 (45)	3 (1.20)
4	1 (4)	2 (8)	1 (35)	1 (7)	2 (0.12)	2 (35)	3 (1.20)
5	1 (4)	2 (8)	2 (45)	2 (8)	3 (0.15)	3 (45)	1 (0.80)
6	1 (4)	2 (8)	3 (55)	3 (9)	1 (0.09)	1 (25)	2 (1.00)
7	1 (4)	3 (10)	1 (35)	2 (8)	1 (0.09)	3 (45)	2 (1.00)
8	1 (4)	3 (10)	2 (45)	3 (9)	2 (0.12)	1 (25)	3 (1.20)
9	1 (4)	3 (10)	3 (55)	1 (7)	3 (0.15)	2 (35)	1 (0.80)
10	2 (6)	1 (6)	1 (35)	3 (9)	3 (0.15)	2 (35)	2 (1.00)
11	2 (6)	1 (6)	2 (45)	1 (7)	1 (0.09)	3 (45)	3 (1.20)
12	2 (6)	1 (6)	3 (55)	2 (8)	2 (0.12)	1 (25)	1 (0.80)
13	2 (6)	2 (8)	1 (35)	2 (8)	3 (0.15)	1 (25)	3 (1.20)
14	2 (6)	2 (8)	2 (45)	3 (9)	1 (0.09)	2 (35)	1 (0.80)
15	2 (6)	2 (8)	3 (55)	1 (7)	2 (0.12)	3 (45)	2 (1.00)
16	2 (6)	3 (10)	1 (35)	3 (9)	2 (0.12)	3 (45)	1 (0.80)
17	2 (6)	3 (10)	2 (45)	1 (7)	3 (0.15)	1 (25)	2 (1.00)
18	2 (6)	3 (10)	3 (55)	2 (8)	1 (0.09)	2 (35)	3 (1.20)
Noise factor: Temperature Hot (70 F+) or Cold (60 F)							

III. EXPERIMENTAL ANALYSIS AND RESULTS

After all experiments are randomized and conducted, Tables V and VI summarized surface roughness and dimensional measurements, respectively.

A. Noise Factor Analysis via T-Test

To determine if noise factor is significantly affecting the surface roughness, the following hypothesis is defined.

$$H_0: \mu_{\text{Temp hot}} = \mu_{\text{Temp Cold}}$$
$$H_1: \mu_{\text{Temp Hot}} \neq \mu_{\text{Temp Cold}}$$

where $\mu_{\text{Temp Hot}}$ = Mean of the Hot Cuts, and $\mu_{\text{Temp Cold}}$ = Mean of the Cold Cuts.

The t critical value based on the 34 degrees of freedom with $\alpha = 0.05$ is ± 2.0322. The calculated t-test statistic is -0.09, which does not exceed the defined t critical value. Consequently, it concludes that it is failed to reject H_0, which means the water temperature has no significant effect on the surface roughness in the Wire EDM process. Similarly, for dimensional accuracy (data from Table VI), the calculated t-test statistic is 0.4247, which does not exceed the t-critical values. Consequently, it concludes that it has failed to reject H_0, which means the water temperature has no significant effect on the dimensional accuracy in the Wire EDM process.

TABLE V
SURFACE ROUGHNESS MEASUREMENTS AND ANALYSIS

N	Temperature		Y-Bar	S/N Ratio
	Hot	Cold		
1	1.905	1.757	1.831	-5.261
2	1.863	1.887	1.875	-5.458
3	2.034	1.924	1.979	-5.931
4	1.906	1.796	1.851	-5.353
5	1.992	1.898	1.945	-5.780
6	1.986	1.878	1.932	-5.723
7	2.191	1.900	2.046	-6.238
8	1.926	2.083	2.005	-6.047
9	1.812	1.767	1.789	-5.055
10	2.687	2.683	2.685	-8.579
11	2.699	2.736	2.718	-8.685
12	2.146	2.331	2.238	-7.005
13	2.858	2.799	2.829	-9.032
14	2.489	2.699	2.594	-8.287
15	2.407	2.669	2.538	-8.101
16	2.655	2.809	2.732	-8.733
17	2.205	2.340	2.272	-7.133
18	2.491	2.584	2.538	-8.091

TABLE VI
DIMENSIONAL MEASUREMENTS AND ANALYSIS

N	Temperature		Y-Bar	S/N Ratio
	Hot	Cold		
1	0.658670	0.656500	0.65759	52.640
2	0.654830	0.655930	0.65538	58.512
3	0.668870	0.654500	0.66169	36.274
4	0.664300	0.657870	0.66109	43.251
5	0.663000	0.663300	0.66315	69.900
6	0.660230	0.660600	0.66042	68.043
7	0.662330	0.662870	0.66260	64.787
8	0.660400	0.655930	0.65817	46.371
9	0.663900	0.655300	0.65960	40.706
10	0.655270	0.662230	0.65875	42.533
11	0.666570	0.661430	0.66400	45.234
12	0.655730	0.660630	0.65818	45.573
13	0.657830	0.655070	0.65645	50.536
14	0.658300	0.658100	0.65820	73.357
15	0.657500	0.657530	0.65752	89.826
16	0.656570	0.656270	0.65642	69.812
17	0.660230	0.672770	0.66650	37.520
18	0.671030	0.654830	0.66293	35.249

B. Optima Parameters Settings for Surface Roughness

Transferring from surface roughness values into the response table shown in Table VII, the optimal parameter setting (with bolded values in Table VII for both raw data and S/N values) is recommended as $A_1B_1C_3D_1E_2F_1G_1$, which defines the key parameters with 4 µs for on time (A), 6 µs for off time (B), 55 V for the SV (C), 7 V for the voltage (D), 0.12 in/min for SF (E), 25 n for WT (F), and 0.8 in/min for WS (G). Using this optima parameter setting defined by surface roughness, 14 experiments have been conducted, and the Wire EDM is able to produce the surface roughness with a mean of 1.7487 microns with a standard deviation of 0.000357 microns.

TABLE VII
COMPLETED RESPONSE TABLES: BOLDED DATA SIGNAL THE OPTIMAL PARAMETERS

Surface roughness (Sa)							
Level	**A(ON)**	**B(OFF)**	**C(SV)**	**D(V)**	**E(SF)**	**F(WT)**	**G(WS)**
1	**1.916**	**2.220**	2.328	**2.166**	2.276	**2.184**	**2.188**
2	2.571	2.281	2.234	2.244	**2.206**	2.222	2.224
3	N/A	2.230	**2.169**	2.321	2.249	2.326	2.319
S/N Ratio							
Level	**A(ON)**	**B(OFF)**	**C(SV)**	**D(V)**	**E(SF)**	**F(WT)**	**G(WS)**
1	**-5.650**	**-6.820**	-7.199	**-6.598**	-7.047	**-6.700**	**-6.687**
2	-8.183	-7.046	-6.898	-6.934	**-6.783**	-6.804	-6.930
3	N/A	-6.883	**-6.651**	-7.217	-6.918	-7.245	-7.111

A t-test was conducted to determine if the optima setting performance was better than the baseline in terms of surface roughness with a hypothesis as:

$$H_0: \mu_B \leq \mu_{SV}$$
$$H_1: \mu_B > \mu_{SV}$$

The t-critical value with one tail of 26 degree of freedom (α = 0.05) is -1.706. The test statistic is -27.778. The t-test statistic score exceeds the t-critical value; thus, the null hypothesis is rejected which means that the optimal parameters setting defined by Taguchi parameter design has been confirmed to produce smoother surface roughness from that from the baseline operation of Wire EDM.

C. Optima Parameters Settings for Dimensional Accuracy

Transferring from dimensional accuracy values (Table VI) into the response table shown in Table VIII, the optimal parameter setting (with bolded values in Table VIII) is recommended as $A_1B_2C_3D_2E_1F_1G_2$ based on dimensional accuracy raw data, However, the S/N response table recommends the optima setting of $A_2B_2C_2D_3E_2F_3G_1$. Unlike the surface roughness results, the raw data and S/N recommends two different optima parameter settings for dimensional accuracy. Thus, the researchers conduct confirmation cuts based on both abovementioned optima settings to determine which setting produces the best dimensional accuracy in Wire EDM process.

TABLE VIII
RESPONSE TABLES: BOLDED DATA ARE OPTIMAL PARAMETER SETTINGS FOR THE MEASUREMENTS AND RED HIGHLIGHTED SECTIONS ARE OPTIMAL PARAMETERS SETTINGS FOR THE S/N RATIOS

Dimension accuracy							
Level	**A(ON)**	**B(OFF)**	**C(SV)**	**D(V)**	**E(SF)**	**F(WT)**	**G(WS)**
1	**0.659**	0.659	0.658	0.661	**0.660**	**0.659**	0.658
2	0.659	**0.659**	0.660	**0.659**	0.657	0.659	**0.660**
3	N/A	0.661	**0.660**	0.658	0.661	0.660	0.660
S/N Ratio							
Level	**A(ON)**	**B(OFF)**	**C(SV)**	**D(V)**	**E(SF)**	**F(WT)**	**G(WS)**
1	53.387	46.794	53.927	51.530	56.552	50.114	**58.665**
2	**54.404**	**65.819**	**55.149**	54.093	**58.891**	48.935	58.219
3	N/A	49.074	52.612	**56.065**	46.245	**62.639**	46.526

These two confirmation runs are analyzed based on the following hypothesis:

$$H_0: \mu_V = 0.660$$
$$H_1: \mu_V \neq 0.660$$

Based on this optimal setting from S/N ratio ($A_2B_2C_2D_3E_2F_3G_1$), the confirmation run gives the mean of dimensional accuracy 0.66479 and variance 7.611 x 10^{-6}. The t-critical values for 13 degrees of freedom (α = 0.05) are ±2.160. The t-test statistic is 6.496, which exceeds the t-critical value which leads to reject null hypothesis. This concludes that the optima parameter setting ($A_2B_2C_2D_3$ $E_2F_3G_1$) recommended by S/N data is not able to produce the diameter accuracy as close as 0.660 inches.

Similarly, other confirmation runs (14 samples) based on the raw data optimal setting of $A_1B_2C_3D_2E_1F_1G_2$ were conducted. The mean of dimensional accuracy of this confirmation run is 0.6600 inches with a variance of 3.560 x 10^{-7}. With similar t-critical values of ±2.160 as mentioned, the t-test statistic in this case is 0.18813, which does not exceed the t-critical values value. Consequently, it is failed to reject the null hypothesis which means that the optimal parameter settings $A_1B_2C_3D_2E_1F_1G_2$ defined by raw data produces dimensional accuracy of 0.660 inches.

D. Define the Final Optima Parameter Setting for Best Surface Roughness and Dimensional Accuracy

The optimal parameters settings recommended from surface roughness data is ($A_1B_1C_3D_1E_2F_1G_1$) and from dimensional accuracy is ($A_1B_2C_3D_2E_1F_1G_2$), and they are not consistent. This indicates that each quality characteristic requires a different optima parameter setting. Thus, there is a need to define one final optima parameter setting to meet two quality characteristics. The researcher proposed to average parameter settings from two obtained optima settings as shown in Table IX into one final proposed optima parameter setting to be recommended for industrial production. Column 4 in Table IX is defined as the optima parameter setting obtained to produce the best dimensional accuracy (reaching 0.660 inches of diameters) as demonstrated earlier. Column 5 in Table X is the optima parameter setting obtained to produce the best surface roughness. Column 6 in Table IX is the proposed combined optimal setting by averaging from two optima settings (Columns 4 and 5).

TABLE IX
OPTIMAL PARAMETER SETTINGS

	Variable	Unit	Optimal Dimensional	Optimal Ra	**Average**
A	Time on	µs	4	4	**4**
B	Time off	µs	6	8	**7**
C	Servo Voltage	V	55	55	**55**
D	Voltage	V	7	8	**7.5**
E	Servo Feed	in/min	0.12	0.09	**0.102**
F	Wire Tension	n	25	25	**25**
G	Wire Speed	in/min	0.80	1.00	**0.9**

This final combined optimal parameters setting (shown in Table IX) enables the Wire EDM to produce parts with the following quality outcomes:

1. For dimensional accuracy - The mean of the optimal validation cuts for dimensional accuracy is 0.6611 inches, which is close to the targeted dimension of 0.6600 inches. It has been improved from the baseline cutting dimension of 0.6488 inches.
2. For surface roughness - The optima surface roughness is 1.7322 microns which is improved from 2.8160 as obtained from the base-line cuts.

IV. CONCLUSIONS

The case study presented based on Taguchi parameter design enables industries to define optima cutting parameter settings to produce products with two quality characteristics in complex manufacturing processes such as Wire EDM. It is researchers' belief that this systematic Taguchi approach can be further implemented to more complex manufacturing processes such as 3D printing or injection molding processes.

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