Parametric optimization in WEDM with H-13 hot die-hard steel using Taguchi Method

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Abstract. Good surface quality and the processing of complex shapes are the essential requirements in various manufacturing industries today. To achieve this, scientists are switching from a variety of conventional machining methods to non-traditional machining processes. Wire EDM (WEDM) is one of the most common non-traditional machining processes. In terms of quality, surface roughness (SR) is an important performance parameter in machining processes. The article summarizes the parameters that affect surface roughness.

Keywords: Analysis of Variance (ANOVA), Signal-to-noise (S/N), Surface Roughness (SR), Wire Electric Discharge Machining (WEDM).

1. Introduction
In today’s world, wire electric discharge machining is a potential method for micro material removal. The advanced adoption of conventional electric discharge machining (EDM) uses an electrode to initiate the spark [1]. The electrode is in the form of thin wire, and thus electrical energy is converted to thermal energy. Therefore, the heat produced is the cause of the cutting of materials. In this, the wire anode made of brass, thin copper, and tungsten of diameter .05 to 0.3 mm is continuously traveling during the process and can achieve minimal corner radii. This process eliminates mechanical stresses during machining as the material is eroded before the wire. This implies that there is no immediate contact between the workpiece and the wire. In the WEDM process, very distinct corrosion and & wear-resistant surface can be produced. Hard and tough materials like alloy steels, conductive and aerospace ceramic materials can be processed with WEDM. The machines exclusively focus on cutting detailed profiles that would not be possible to produce accurately using conventional methods [2]. Patil et al.(2018) after TOPSIS analysis found that optimal parameter levels are Peak Current level 3 (210 A), pulse on time at level 1 (110 μs), wire feed level 2 (3 m/min). Optimum response characteristic relative closeness is improved with 6.92% by employing TOPSIS method.[3]

The wire used as a cutting tool in this machine is made up of brass, copper, or tungsten; Galvanized and multilayer wires are also used. Electric discharge wire as a precision cutting technology enables a small range of products to be manufactured into large components. All kinds of metals with good conductivity, like carbon, steel, and copper, can be machined with a WEDM machine. Even so, the machine configuration is different for every metal. Therefore, specific parameters should be distinct for each material. When eroding, cutting two types of materials simultaneously or in parallel is a significant challenge. The machine configuration for both materials should be considered and optimized. This Machine is often used for machining conductive materials where precision is paramount.
Many researchers have optimized the WEDM process using various optimization techniques. Han et al. (2006) carried out experiments at WEDM EU64 to machine 40 mm thick alloy steel (Cr12). It has been accounted for that the surface completion has been improved by lessening the pulse duration and the discharge current. [4] Yan et al. (2005) state that the material's surface roughness to be cut depends mainly on the volume of reinforcement (Al2O3 particles) and carried out experiments with the CNC EDM wire machine FANUC W1 for cutting 10 and 20% vol. Connection reinforced with Al2O3% particles based on 6061Al alloys and 6061Al matrix material alone. The parameters used for optimization are pulse on and off time, voltage, wire feed, wire tension, and dielectric current. [5] Kanlayasiri et al. (2007) examined the influence of WEDM variables on the surface roughness of DC 53 steel with a dimension of 27(width), 65(length), and (thickness)13 mm, respectively. Significant variables are pulse on and off time, peak pulse current, and wire tension. ANOVA recognized the factors influencing surface harshness. He found that the pulse on time, pulse duration, and wire tension were significant variables responsible for the better surface finish of the DC53 steel with a wire cut machine. The most extreme model expectation blunder was around 7%, and the average prediction error was under 3%. [6] Danial Ghodsiyeh et al. (2012) tried different things with the Design of Experiment (DOE) strategy to choose the ideal boundaries during WEDM of a titanium amalgam (Ti6Al4V). The conduct of three control boundaries, such as pulse on and off times and peak current on the surface roughness (SR) is analyzed using variance analysis (ANOVA). He inferred that few ideal conditions could have resulted from the examination, including a broadly good condition that can be characterized with a pulse on time of 10 μs, a pulse off time of 6.5 μs, and a peak current of 33 A. The anticipated outcome is surface harshness: 3.122 μm. [7] S.B. Prajapati and Patel (2013) examined that the pulse on time and the pulse off time decisively influence the surface harshness in the boundaries of the instrument steel machining measure AISI A2 in EDM wire.

The impacts of different machining boundaries such as pulse time, wire tension, delay time, wire feed speed, and ignition current were researched in 2005 by Ramakrishnan and Karuna Moorthy during wire EDM of a steel tool. They figured out that pulse time and start current had a more substantial impact than different boundaries. It has likewise been discovered that the material evacuation rate, surface harshness and the wire wear factor in the WEDM cycle can be improved by setting different interaction boundaries to their optimal qualities [8]. Parashar et al. (2009) built up an exploratory task utilizing the Taguchi strategy to streamline surface harshness. He found a parametric condition that was proper for the specific steel case chose as the part material, for example, SS304L. The optimization results show that the surface finish is enhanced if we decrease the pulse duration and the discharge current [9]. (Sorabh et al. (Jan.- Feb. 2013). It is said that the surface quality can be enhanced by diminishing the pulse duration and the discharge current. This implies short pulse lengths [10]. Huang and Liao (2003) discussed using gray relation analysis and the S/N ratio to decide the ideal setup of the WEDM cycle boundaries. The outcomes are that the MRR and the surface harshness are somewhat impacted by the table's feed speed and the pulse time [11].

2. Experimentation
The tests were done on a WEDM machine (ELEKTRA SPRINTCUT 734) from Electronica Machine Tools Limited. An H-13 high-carbon steel plate measuring 131.45 mm x 90.12 mm x 17.23 mm was used as the workpiece material for these experiments. Chrome-plated steels for hot work tools are named group H steels as indicated by the AISI arrangement framework. This steel arrangement goes from H1 to H19. H13 chrome-plated steel for hot work is widely used in hot and cold working tools. Due to its brilliant mix of high toughness and fatigue strength, H13 is used more than any other tool steel in tool applications. The compound arrangement of material is given in Table 1: (Electro Dispersive X-ray Spectroscopy).
Table 1. Compound arrangement of Material.

| Elements   | Weight (%)   |
|------------|--------------|
| Carbon     | 0.32-0.45    |
| Chromium   | 4.75-5.50    |
| Molybdenum | 1.10-1.75    |
| Vanadium   | 0.80-1.20    |
| Manganese  | 0.25-0.50    |
| Silicon    | 0.80-1.25    |
| Sulphur    | 0.30 max.    |
| Phosphorus | 0.30 max.    |
| Iron       | Balance      |

In this work, a brass electrode wire with a standard diameter of 0.25 mm was utilized as the anode. After studying various researches, the four primary interaction boundaries are pulse ON time, switch-OFF time, voltage, and wire feed.

2.1. Selection of Orthogonal Array (OA)

The prerequisite for the determination of the suitable OA is:

i. Select the cycle boundaries and/or interactions to be evaluated

ii. To select level count for the identified parameter.

The assurance of the boundaries to be considered relies upon the item properties or the performance of the process or interest reactions. Taguchi proposes a few techniques for deciding the boundaries to include in the test. These are:

a) Brainstorming
b) Block diagram
c) Fishbone diagram

The total number of degrees of freedom (DOF) of a test is a primary function of the preliminaries' absolute quantity. As the number of levels for a boundary increment, the boundary's degree of freedom likewise increments because the boundary's degree of freedom is the quantity of levels less than one. In this way, expanding the amount of the boundary levels increases the total number of degree of freedom in the examination, which raises the complete number of tests. Therefore, it is prescribed to utilize two levels for every boundary to limit the size of the analysis [12]. If a curve or a higher-order polynomial is standard between the tried boundaries and the response, at any rate, three levels ought to be considered for every boundary [13]. The standard four-level OA is the L16 matrix. The index number in the array name demonstrates the quantity of endeavors in this array. The total degrees of freedom (DOF) accessible in OA is the quantity of endeavors less than one. A reasonable OA is chosen to rely upon the number of boundary levels and the total DOF needed for the examination.

As indicated by DoE, 16 Experiments were performed on the workpiece, and surface unpleasantness is estimated. Results are given in Table 2.
3. Results and Discussion

3.1. Analysis

The data analysis is carried out according to the Taguchi method [14]. Taguchi has several data analysis methods, mainly observation method, classification method, column effect method, ANOVA, S / N, mean response plot, interaction plots, residual plots, regression equation, etc. [15]. Table 3 shows the ANOVA for S / N ratio. Table 4 and Table 5 show the responses to the S/N ratio and mean shown in Figure 1.

Table 2. Orthogonal array with measured Surface Roughness.

| S. no. | Pulse on time | Switch off time | Voltage | Wire feed | Surface roughness |
|--------|---------------|-----------------|---------|-----------|-------------------|
| 1.     | 100           | 40              | 20      | 4         | 1.985             |
| 2.     | 100           | 45              | 30      | 8         | 2.362             |
| 3.     | 100           | 50              | 40      | 12        | 2.65              |
| 4.     | 100           | 55              | 50      | 16        | 2.895             |
| 5.     | 110           | 40              | 30      | 12        | 3.601             |
| 6.     | 110           | 45              | 20      | 16        | 4.057             |
| 7.     | 110           | 50              | 50      | 4         | 1.85              |
| 8.     | 110           | 55              | 40      | 8         | 3.257             |
| 9.     | 120           | 40              | 40      | 16        | 4.518             |
| 10.    | 120           | 45              | 50      | 12        | 1.897             |
| 11.    | 120           | 50              | 20      | 8         | 3.166             |
| 12.    | 120           | 55              | 30      | 4         | 2.495             |
| 13.    | 130           | 40              | 50      | 8         | 2.154             |
| 14.    | 130           | 45              | 40      | 4         | 1.75              |
| 15.    | 130           | 50              | 30      | 16        | 2.013             |
| 16.    | 130           | 55              | 20      | 12        | 2.987             |

Table 3. ANOVA for S/N ratio.

| Source            | DF | SS     | MS   | F – Ratio | P   |
|-------------------|----|--------|------|-----------|-----|
| Pulse on time     | 3  | 21.32  | 7.106| 2.05      | 0.285|
| Switch off time   | 3  | 11.96  | 3.988| 1.15      | 0.455|
| Voltage           | 3  | 18.21  | 6.068| 1.75      | 0.328|
| Wire feed         | 3  | 35.12  | 11.706| 3.38      | 0.172|
| Residual Error    | 3  | 10.39  | 3.464|           |     |
| Total             | 15 |        |      |           |     |

Where,

\[ S = 0.0726471 \]
\[ \text{R-Sq} = 89.6\% \]
\[ \text{R-Sq (adj)} = 83.1\% \]

Where

DF – degrees of freedom
SS – sum of squares
MS – mean squares
F – Ratio of variance between groups to the variability with in groups
P – Probability < 0.05 – signifies a factor at 95% confidence level
S – standard deviation
Table 4. Response Table for S/N Ratios.

| Level | Pulse on time | Switch off Time | Voltage | Wire feed |
|-------|---------------|----------------|---------|-----------|
| 1     | -7.780        | -9.211         | -9.409  | -6.025    |
| 2     | -9.723        | -7.513         | -8.153  | -8.599    |
| 3     | -9.152        | -7.474         | -9.170  | -8.665    |
| 4     | -6.777        | -9.234         | -6.701  | -10.143   |
| Delta | 2.946         | 1.760          | 2.708   | 4.118     |
| Rank  | 2             | 4              | 3       | 1         |

Table 5. Response Table for Means.

| Level | Pulse on time | Switch off time | Voltage | Wire feed |
|-------|---------------|----------------|---------|-----------|
| 1     | 2.473         | 3.064          | 3.049   | 2.020     |
| 2     | 3.191         | 2.517          | 2.618   | 2.735     |
| 3     | 3.019         | 2.420          | 3.043   | 2.784     |
| 4     | 2.226         | 2.909          | 2.199   | 3.370     |
| Delta | 0.965         | 0.645          | 0.850   | 1.350     |
| Rank  | 2             | 4              | 3       | 1         |

Figure 1. Main effect plot for means.

3.2. Regression Analysis
To comprehend the WEDM cycle, the tests’ aftereffects were utilized to create mathematical models utilizing the surface roughness (Ra). An industrially accessible mathematical software package (MINITAB 15) was utilized to calculate the regression constants and exponents in this investigation. Linear regression examines and models the direct connection between the response and the indicator. Both the appropriate response and the indicator are nonstop factors. Specifically, linear regression analysis is frequently used to decide how the response changes when specific prescient variable changes and anticipates the estimation of the reaction to any estimation of the prescient variable or a mix of estimations of the expected variable. Table 6 shows the adjusted value and residuals, and Table 7 is the coefficient table for the indicators. The first-order model based on functional dependency is as follows:

The regression equation is

\[
\text{surface roughness} = 4.03 - 0.0091 \text{ pulse on time} - 0.0113 \text{ pulse off time} - 0.0212 \text{ voltage} + 0.103 \text{ wire feed}
\]
Table 6. Fitted values and residuals.

| Pulse on time | Switch off time | Voltage | Wire feed | Surface roughness | Fitted value | Residuals |
|---------------|----------------|---------|-----------|-------------------|--------------|-----------|
| 100           | 40             | 20      | 4         | 1.985             | -7.3508      | 1.39557   |
| 100           | 45             | 30      | 8         | 2.362             | -6.9709      | -0.49467  |
| 100           | 50             | 40      | 12        | 2.650             | -8.0141      | -0.45082  |
| 100           | 55             | 50      | 16        | 2.895             | -8.7829      | -0.45009  |
| 110           | 40             | 30      | 12        | 3.601             | -10.6784     | -0.45009  |
| 110           | 45             | 20      | 16        | 4.057             | -11.7133     | -0.45082  |
| 110           | 50             | 50      | 4         | 1.850             | -4.8488      | -0.49467  |
| 110           | 55             | 40      | 8         | 3.257             | -11.6519     | 1.39557   |
| 120           | 40             | 40      | 16        | 4.517             | -12.6023     | -0.49467  |
| 120           | 45             | 50      | 12        | 1.897             | -6.9569      | 1.39577   |
| 120           | 50             | 20      | 8         | 3.166             | -9.5601      | -0.45009  |
| 120           | 55             | 30      | 4         | 2.495             | -7.4906      | -0.45082  |
| 130           | 40             | 50      | 8         | 2.154             | -6.2141      | -0.45082  |
| 130           | 45             | 40      | 4         | 1.750             | -4.4107      | -0.45009  |
| 130           | 50             | 30      | 16        | 2.013             | -7.4724      | 1.39557   |
| 130           | 55             | 20      | 12        | 2.987             | -9.0100      | -0.49467  |

Table 7. The coefficient table for the indicators.

| Predictor       | Coef | SE Coef | T     | P    |
|-----------------|------|---------|-------|------|
| Constant        | 4.032| 2.528   | 1.59  | 0.139|
| Pulse on time   | -0.00914| 0.01624 | -0.56 | 0.585|
| Switch off time | -0.01128| 0.03249 | -0.35 | 0.735|
| Voltage         | -0.02123| 0.01624 | -1.31 | 0.218|
| Wire feed       | 0.10251| 0.04061 | 2.52  | 0.028|

S = 0.0726471  \hspace{1cm} R-Sq = 89.6\%  \hspace{1cm} R-Sq(adj) = 83.1\%

Table 8 contains an analysis of variance (ANOVA) that shows the measure of variety in the response information clarified by the indicators and the extent of unexplained type.

Table 8. Analysis of Variance.

| Source          | DF | SS   | MS   | F-Ratio | P    |
|-----------------|----|------|------|---------|------|
| Regression      | 4  | 4.4952| 1.1238| 2.13    | 0.145|
| Residual Error  | 11 | 5.8054| 0.5278|         |      |
| Total           | 15 | 10.3005|      |         |      |
3.3. Residual Plots
The residual diagrams show the behavior of the residuals with a normal distribution. In this study, residual plots are drawn with the surface roughness (Ra) as the answer. Figure 2 shows a diagram of the normal residual probability, and Figure 3 shows residuals in the fitting function. The normal residual probability plot shows the residuals versus their expected values when the distribution is normal. Analysis residues should be normally distributed. The residuals in the fit function represent the residual values concerning the fitted values. The rest must be randomly scattered around zero. [16]

Figure 2. Normal Probability Plot.

Figure 3. Residuals versus Fits.
3.4. Prediction of Mean
After determining the ideal status, the average response under ideal conditions is predicted. Only relevant parameters are used to determine the mean. ANOVA identified the relevant parameters. The ideal surface roughness value (Ra) is excepted at the chose level of the appropriate boundaries, as demonstrated in Table 9.

| Pulse on time | Switch off time | Voltage | Wire feed |
|---------------|----------------|---------|-----------|
| 130           | 130            | 50      | 4         |

Predictive mean = 0.682813

3.5. Confirmation Experiment:
Three affirmation tests for the reaction properties (SR) had been accomplished at the optimal ranges of the chosen process variables to approve the outcomes acquired. The average values of the characteristic properties were acquired and then compared with the expected values. The results are shown in Table 10. The SR values obtained in the confirmatory tests are inside 95% confidence interval of the corresponding response properties.

| Sample | Ra(μm) |
|--------|--------|
| 1      | 0.6756 |
| 2      | 0.7865 |
| 3      | 0.8456 |
| Mean Ra(μm) | 0.7692 |

The reaction taken in the confirmation final run was the average surface roughness(Ra). The table shows confirmatory test results that include the average surface roughness (Ra) and the general average surface roughness (Ra).

4. Conclusion
The experimental WEDM test of H13 tool steel is performed to correlate process parameters with an efficient measurement of surface roughness. The process was successfully modeled using the Taguchi methodology, and the analysis was performed using Minitab 15. Finally, an attempt was made to estimate precise treatment situations that allows you to gain the best possible response within the experimental limitations.

i. A model for four elements (pulse on time, switch off time, wire feed, and voltage) and four levels on H13 tool steel is developed.

ii. It turns out that selected parameters and their levels mainly affect the surface roughness. The surface roughness value will increase with increasing wire feed and pulse on time and decreases with increasing voltage and switch-off time.

iii. Wire feed has the most nuanced impact on surface roughness, followed with the aid of pulse activation time, voltage, and pulse deactivation time. The ideal surface roughness parameters are as follows:

\[ \text{Pulse on time} = 130 \, \mu\text{s}, \]
\[ \text{Switch off time} = 130 \, \mu\text{s}, \]
\[ \text{Voltage} = 50 \, \text{volts and Wire feed} = 4 \, \text{mm/s}. \]

iv. The analysis indicates that the predicted surface roughness is 0.682813 μm.
5. Future Scope

1. By the combination of different materials as workpieces and electrodes, mathematical modeling can be done.
2. Other than Surface Roughness, many more response characteristics can be considered, like material removal rate, kerf width, roundness and machining cost, etc.
3. Validation of the developed optimal results can be done by using suitable software, and a standard process for optimization can be developed.

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