Optimization of gap of width and surface roughness in wire cut EDM of AISI O1 using the Taguchi - fuzzy method

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Abstract. The aim of this paper is to optimize of kerf (gap of width) and surface roughness in wire cut EDM of AISI O1 using Taguchi fuzzy method. The quality characteristics of gap of width and surface roughness are lower the better. The machining process variables is considered on time, wire feed, servo voltage, and arc on time. The machining variables studied has three levels and the experiment design used L9 orthogonal array with two replications. Taguchi fuzzy is used to investigate the performance characteristic in wire cut EDM AISI O1. The results of this experiments confirm that fuzzy logic based Taguchi increase significantly the performance characteristics of quality in wire cut EDM. The experiment results shows that on time of 2 µs, wire feed of 8 mm/sec, servo voltage of 55 Volt and arc on time of 5 A are the optimum value for wire cut EDM of AISI O1.

1. Introduction
A non conventional machining process such as wire cut electrical discharge machining in material AISI O1 tool steel widely used to produce dies, punches, molds, and automotive industries. This process effectively applied to conductive electricity material irrespective of their hardness, toughness, fragile and complex shape [1-2]. The advanced materials such as metal matrix composites, bismuth ferrite, barium titante, Al2O3, Ti3SiC2 ceramics was applied in wire-EDM machining [3-7]. The machining variables in wire-EDM such as on time, off time, wire feed, servo voltage, flushing pressure and arc on time, affect multiple characteristics quality that is gap of width and surface roughness. G. Rajyalakshmi et al. [8] have studied material removal rate, surface roughness and spark gap using wire-EDM with parameter process i.e pulse on time, pulse off time, corner servo, flushing pressure, wire feed, wire tension, and servo feed. From those parameters, pulse on time give the significant contribution of performance characteristics. Ramakrishnan et al. [9] analyzed MRR and surface roughness using ANN with Taguchi’s L9 orthogonal array. The Taguchi fuzzy method in wire-EDM to optimize gap of width, MRR, surface roughness of tungsten carbide was explained by A. Shah et al [10].

This work investigates the use of Taguchi fuzzy method to optimize gap of width and surface roughness in wire cut EDM of AISI O1. The experiment using Taguchi method and fuzzy logic to obtain minimum gap of width and surface roughness. It is very necessary to establish optimal machining variables combination with the purpose of obtaining increased machined quality performance. The experiment is done on the basis of Taguchi L9 orthogonal array. The four significant input wire-EDM variables are chosen. The response variables are gap of width and surface roughness.
2. Experimental Methods
Experiments are performed on wire cut EDM machine which all the axes of this machine are controlled by servo and CNC systems. The electrode material use brass wire with diameter 0.25mm. The material AISI O1 are used for this experiment having 55-60 HRC. The chemical composition of AISI O1 consists of 0.95% C, 1.00% Mn, 1.40% S, 0.03%-0.1% Si, 0.3% V, and 0.4-0.6% W. The surface roughness is measured using a surfest machine. The microscope Eumex is used to measure gap of width. The experimental design using Taguchi method involves orthogonal array L9 for four process variables that is on time (5, 7, 8 µs), wire feed (3, 7, 12 mm/sec), servo voltage (37, 55, 70 Volt) and are on time (2, 3, 4 A)][11].

3. Results and Discussion

3.1 Calculation signal to noise (S/N) ratio
The experiment results for gap of width and surface roughness and their S/N ratio is shown in Table 1. In wire cut electrical discharge machining, the performance characteristic of gap width and surface roughnesses are smaller the better. It means the more minimum the gap of width and surface roughness, the better their performance characteristics. The equation 1 for calculating S/N ratios for their performance characteristics [12]:

\[
S/N = -10 \log \sum_{i=1}^{b} \frac{x_i^2}{b}
\]

Where b is the total number of experiments and \(x_i^2\) is the measured of response variable value.

| Exp | ON | WF | SV | ANN | Gap of width (µm) | S/N Gap of width | Surface Roughness (µm) | S/N SR |
|-----|----|----|----|-----|------------------|------------------|----------------------|-------|
| 1   | 5  | 5  | 37 | 2   | 359              | -51.1019         | 2.75                 | -8.79718 |
| 2   | 7  | 7  | 55 | 2   | 367              | -51.2933         | 2.52                 | -8.02801 |
| 3   | 8  | 8  | 70 | 2   | 373              | -51.4342         | 2.49                 | -7.91235 |
| 4   | 5  | 5  | 55 | 3   | 342              | -50.6805         | 2.60                 | -8.29947 |
| 5   | 7  | 7  | 70 | 3   | 357              | -51.0534         | 2.86                 | -9.12732 |
| 6   | 8  | 8  | 37 | 3   | 380              | -51.5957         | 2.51                 | -8.005   |
| 7   | 5  | 5  | 70 | 4   | 370              | -51.364          | 2.69                 | -8.58428 |
| 8   | 7  | 7  | 37 | 4   | 347              | -50.8066         | 2.45                 | -7.7715  |
| 9   | 8  | 8  | 55 | 4   | 371              | -51.3875         | 2.47                 | -7.84221 |

3.2 Optimisation of multi objective characteristics using fuzzy logic
A fuzzy logic unit consist of five conceptual components, that is a fuzzifier, membership function, a fuzzy rule base, an inference system and a defuzzifier [12]. First, uses membership functions to fuzzify the S/N ratios. Then, the inference system performs a fuzzy reasoning on fuzzy rules to obtain a fuzzy value. Finally, the defuzzifier converts the fuzzy value into a fuzzy reasoning grade (FRG). In this research, FRG is based on the two input (gap of width and surface roughness) become one output fuzzy logic unit. Fuzzy rules are made based on grouping with the form of if-then rules with the two input (process) variables, gap of width dan surface roughness, and response variable (FRG):

Rule 1: if gap of width is small (S) and surface roughness is small (S), then FRG is very small (VS)
Rule 2: if gap of width is small (S) and surface roughness is medium (M), then FRG is small (S)

...
Rule 9: if gap of width is large and surface roughness is large, then FRG is very large.

For input variables (gap of width and surface roughness) has three fuzzy subsets, while for output variable (FRG) has five fuzzy subsets are presented in Fig. 1(a,b, and c).

Figure 1. Membership functions (a) for gap of width, (b) for surface roughness, (c) for FRG.

Various degree of membership to the fuzzy sets is calculated based on the values of these rules of \( x_1 \), \( x_2 \), and \( y \). By taking the max-min compositional operation [12], the fuzzy reasoning of these rules yields a fuzzy output. Supposing that \( x_1 \) and \( x_2 \) are two input values of the fuzzy logic, the membership function of the output of fuzzy reasoning can be expressed as equation 2:

\[
\mu_{Co}(y) = \left( \mu A_1(x_1) \land \mu B_1(x_2) \land \mu C_1(y) \right) \lor \ldots \lor \left( \mu A_n(x_1) \land \mu B_n(x_2) \land \mu C_n(y) \right)
\]  

where the notation of \( \land \) and \( \lor \) are the minimum and maximum operation. The last step, a defuzzification method, called the centroid gravity [12], is adopted to convert the fuzzy inference output \( \mu_{Co} \) into a non-fuzzy value as follows equation 3.

\[
y_o = \frac{\sum y \mu_{Co}(y)}{\sum \mu_{Co}(y)}
\]

where \( y_o \) is called fuzzy reasoning grade (FRG). Table 2 presents the result of FRG and Table 3 shows the computation for overall average of the FRG for the nine experiments.

Table 2. Results for the FRG

| No. Exp | Fuzzy reasoning grade (FRG) |
|---------|-----------------------------|
| 1       | 0.4030                      |
| 2       | 0.5469                      |
| 3       | 0.5323                      |
| 4       | 0.7566                      |
| 5       | 0.3076                      |
| 6       | 0.4102                      |
| 7       | 0.3708                      |
| 8       | 0.8214                      |
| 9       | 0.5805                      |
Table 3. Respond table for the mean of FRG

| Process Variables | level 1 | level 2 | level 3 | Max-Min | Rank |
|-------------------|---------|---------|---------|---------|------|
| ON (µs)           | 0.510   | 0.559   | 0.508   | 0.051   | 4    |
| WF (mm/sec)       | 0.430   | 0.443   | 0.703   | 0.273   | 1    |
| SV (V)            | 0.545   | 0.628   | 0.404   | 0.224   | 2    |
| ANN (A)           | 0.494   | 0.492   | 0.591   | 0.099   | 3    |

The analysis of variance (ANOVA) describes those process variables which significantly influence the FRG. Because the variances of ON, WF, SV and ANN are very small, hence it can be neglected. Thus the analysis of variance takes directly the percentage of contributions by each of the process variables [13]. The analysis of variance table of the FRG for wire cut EDM AISI O1 is shown in Table 4. The result of ANOVA for FRG describe the most influence process variables in affecting the FRG are wire feed and servo voltage.

Table 4. The analysis of variance (ANOVA) of FRG

| Process Machining Variables | Degree of freedom | Sum of square | Means of square | F-value | % contribution |
|-----------------------------|-------------------|---------------|-----------------|---------|----------------|
| On time (ON)                | 2                 | 0.00496       | 0.00248         | *       | 2.03           |
| Wire feed (WF)              | 2                 | 0.14273       | 0.1427          | *       | 58.45          |
| Servo voltage (SV)          | 2                 | 0.07725       | 0.03862         | *       | 31.63          |
| Arc on time (ANN)           | 2                 | 0.01927       | 0.00964         | *       | 7.89           |
| Residual Error              | 0                 | *             | *               |         |                |
| Total                       | 8                 | 0.24421       |                 |         |                |

Based on Figure 2 the FRG graph for wire cut EDM AISI O1, the optimum process variables condition, on time setting at level 2, wire feed at level 3, servo voltage at level 2, and arc on time at level 3

Figure 2. The fuzzy reasoning grade (FRG)

3.3. Confirmation experiment

After the optimal level of process variables is chosen, the last step is predict and verify the improvement the performance characteristic using the optimal level of the process variables. The optimal value of the fuzzy reasoning grade (FRG) can be calculated using equation 4:

$$\beta_e = \beta_m + \sum_{i=1}^{n}(\bar{\beta}_i - \beta_m)$$  \hspace{1cm} (4)

Where $\beta_m$ is the average of FRG; n is total of process variables; $\bar{\beta}_i$ is average of optimal level of FRG. Table 5 presents the result of the verification experiment using the optimal process variables and also
comparison of the FRG for initial and optimal process variables. Based on Table 5, gap of width decreased 2.82% and surface roughness decreased 11.11%.

| Level of process variables     | Initial | Optimal Process Condition | Improvement |
|--------------------------------|---------|---------------------------|-------------|
|                                | Prediction | Experiment               |             |
| Gap of width (µm)              | ON₂WF₂SV₂AN₂ | ON₂WF₂SV₂AN₃             | decreased 2.82% |
| Surface Roughness/SR (µm)      | 354           | 344                       |             |
| Fuzzy Reasoning Grade (FRG)    | 2.79         | 2.46                       | decreased 11.11 % |
|                                | 0.4449       | 0.9045                     | increased 69.79% |

4. Conclusion
This work has investigated the application of the Taguchi method and fuzzy logic based on an orthogonal array L₉ to optimize the wire cut EDM process of AISI O1 with gap of width and surface roughness. The recommended levels of wire cut EDM machining variables when gap of width and surface roughness are simultaneously considered are on time of 6 μs, wire feed of 75 mm/sec, servo voltage of 90 volt, and are on time of 4 A. Based on the ANOVA, the wire feed is the most significant in wire cut EDM of AISI O1.

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