Modelling of WEDM Parameters Using Taguchi & Fuzzy Logic

Siddharth Sharma1*, Ashish Goyal1, Love Kishore Sharma2

1Department of Mechanical Engineering, Manipal University Jaipur, Dehni Kalan, Rajasthan, 303007, India
2Department of Mechanical Engineering, Arya College Of Engineering & Information Technology, Kukas, 302028 Jaipur, India

Email: siddharthsharma987@gmail.com, ashish.goyal@jaipur.manipal.edu, sharma.ajmer31@gmail.com

Abstract. This work highlights the Fuzzy Logic approach for predicting best operating parameters of WEDM. This process is attracting the industries/researchers due to precision in machining. The only limitations that exist are high tool costing and lower value of finished surface. Four parameters are opted for conducting experiments viz Ton, Toff, Wire Feed & Current and their impacts are calculated for SRR and Ra. The DOE is done using Taguchi (L9) OA. ANOVA test for identification of parameters with high significance is considered.

1. Introduction

WEDM (Wire Electric Discharge Machining) process uses thin wire electrode along with dielectric fluid to machine difficult to cut contour in materials by repeated sparks of short duration. The wire tension is important factor to avoid occurrence of taper on machined surface. Temperature reaches nearly 10,000°C in machining zone. The movement of wire is continuous to cut the material with spark (electrical discharge) in the vicinity between electrode and material. The wire material also gets damaged after certain duration due to high/ temperature generated during machining. Also it suffers forces of electromagnetic type, electric field type, pressure energy of bubbles, shock due to pressurised dielectric and wire driving force. Thus wire tension becomes unstable after certain duration of operation. Thus short circuit occurs and abnormal discharges leading to loss of surface integrity, also cutting is also affected severely [1]. The machining gap is classified into 3 categories viz Open status, discharge status and short circuit. Open Status- the gap that exists without breaking down. Both the wire & work piece are well insulated. Due to higher resistance in gap the discharge current value is zero, hence low machining rate. Discharge status- is best condition for machining. With establishment of discharge-channel in machining zone the discharge operating voltage & current appears. Short-Circuit resistance generated is of low value with weak high frequency component [2]. Some drawbacks include energy consumption, null material ablation and poor surface quality. The process finds application in industries viz aerospace, biomedical etc. D-3 steel, 1.2080 (Werkstoff), inherits air hardening, %carbon high, high-chromium. It possesses excellent resistance (wear) and shows dimensional stability along with higher compressive strength. D3 Steel finds application for forming dies, blanking, Press tools Punches. The wire electrode for performing cutting operation on workpiece travels a predefined path as described by end user through program (CNC). Fig. 1 shows the wire path travel for cutting operation or WEDM working process.
2. Literature
Kumar et al. [4] used MONEL-400 alloy to investigate the effect of responses on MRR, Dimensional Deviation, spark gap. The results show that Ip (Current) is significant factor followed by other factors. Lodhi & Agarwal [5] worked on D3 for studying wire offset behaviour and concluded that high values of Ip and Ton (Pulse-on-Time) leads to higher wire offset values. Singh et al [6] prepared AA7075/SiC (SiC 5% wt.) to analyse Fuzzy model and shows that MRR is affected by Toff (Pulseoff-Time) while Ra by Ton. Goswami & Kumar [7] selected Nimonic 80A and studied responses MRR & WWR (WireWearRatio). It was seen that interaction terms (Ton x Toff & Ton x Ip) are significant for TWR while for MRR, Ton & Toff are of significance. Nain et al [8] proposed ANN (Artificial Neural Network) and Fuzzy for studying behaviour of Ra & Waviness on Udimet L605 and concluded that the results for former are superior than later. Vellingiri et al [9] prepared alloy of LM13 SiC composite and LM13 Alloy, and found that MRR for LM13Alloy is 36.654 mm³/min, Ra 2.311 µm. MRR for LM13 SiC composite is 28.251 mm³/min, Ra 4.72 µm. Goyal et al [10] worked on Ni₄₉T₃₁ using brass electrode and concluded that surface under investigation contains cracks and uneven crater formation also Ton and Ip are significant parameters for MRR.

3. Research Methodology

3.1. Taguchi Method
Genichi Taguchi proposed a concept which studies the weight of inputs on the way they deviates means and variance from actual and the performance of process is indicated. Classical approach for DOE (design of experiment) is complex and difficult to apply. The experimental sets increase when parameters and their corresponding level increases. To avoid this OA (orthogonal array) are introduced, which defines design consisting of small digit of experiment sets for examination [11]. These OA are basically FFD (full factorial design) which eliminates interaction focus on end goal (response) estimation. For any process there exists input factors (controlled by observer), which have direct effects magnitude of responses and noise factors (cannot be controlled e.g. environmental factors) which have negative influence on quality characteristics of any process. Finally design is obtained, which is least sensitive to variations offered in uncontrolled factors. S/N (signal/noise) ratio is dependent on type quality characteristics. In our research the ratios considered are:

- Larger-Better: for maximizing SRR

\[
S/N(\eta) = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{B}1/y_i^2\right] \tag{1}
\]

- Smaller-Better: for minimizing Ra
\[
S/N(\eta) = -10 \log_{10} \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{y_i^2}{s_i^2} \right]
\]  \hspace{1cm} (2)

3.2. Fuzzy Logic

FLS (Fuzzy Logic System) reasoning is centered on the model of fuzzy sets. Fuzzy logic consists of a set of “if-then” statements based on combining fuzzy sets. FLS performs a nonlinear correlation of multiple inputs dataset to output data. It contains 4 main parts viz, fuzzifier, rules (if/then), inference-engine, defuzzifier. Membership functions (MF’s) are used for steps (fuzzification/defuzzification) to correlate the input (non-fuzzy) parameters to fuzzy language terms. The various MF’s, defined as triangular, trapezoidal etc.[12]. The selection of each MF is context dependent and based on user experience. In present case the model for knowledge base is created using IF/THEN and joined by AND connective. The Fuzzy value is attained by interface engine performing a fuzzy reasoning.

| S.no | Ton | Toff | (W.F.) | Ip | SRR | Ra |
|------|-----|------|--------|----|-----|----|
| 1    | L   | L    | L      | L  | M   | VVH|
| 2    | L   | M    | M      | M  | SM  | S  |
| 3    | L   | H    | H      | H  | VS  | VVS|
| 4    | M   | L    | M      | H  | MH  | MH |
| 5    | M   | M    | H      | L  | VVS | H  |
| 6    | M   | H    | L      | M  | VH  | VS |
| 7    | H   | L    | H      | M  | S   | VH |
| 8    | H   | M    | L      | H  | VVH | M  |
| 9    | H   | H    | M      | L  | H   | MS |

(L=Low, V=Very, S=Small, M=Medium, H=High)

4. Experimentation

The performance/input parameters for our research work are opted after thorough analysis of literature, which provides brief description of overall WEDM operational parameters and enables the researchers for selecting the data. The workpiece dimensions are 65mmx65mmx0.75mm. The wire(brass) [13] used for conducting experiment is 0.25mm diameter. The variation in hardness number of specimen (D3 steel) is done by heat treatment (hardening & tempering) and oil quenching prior to experimentation, so that the material hardness is considerably altered (56 HRC).Machine equipment, Electronica Tool Master 6S at CIPET.

The efficiency of any process is calculated in terms SRR/MRR (Stock/Material Removal Rate) is calculated using difference of weight method and unit is gm/min. the mathematical expression is;

\[
SRR = \frac{(W_i - W_f)}{\text{MachineOperatingtime}}
\]  \hspace{1cm} (3)

Wi = initial specimen weight
Wf = final specimen weight
The surface roughness can be described as Ra, unit (µm), where Ra is mean roughness of machining surface.
\[ Ra = \int_0^L Y(X) \, dx \]  
\[ (4) \]

\( L \) = length for evaluation, \( Y \) = profile curve ordinate

Ra measurement is done using roughness tester (Mitutoyo SG-410)

Table 2 Orthogonal Array (L9)

| S.no | Ton (µsec) | Toff(µsec) | W.F. (mm/sec) | Current (A) |
|------|------------|------------|---------------|-------------|
| 1    | 2          | 7          | 6             | 6.5         |
| 2    | 2          | 8          | 6.5           | 7           |
| 3    | 2          | 9          | 7             | 7.5         |
| 4    | 3          | 7          | 6.5           | 7.5         |
| 5    | 3          | 8          | 7             | 6.5         |
| 6    | 3          | 9          | 6             | 7           |
| 7    | 4          | 7          | 7             | 7           |
| 8    | 4          | 8          | 6             | 7.5         |
| 9    | 4          | 9          | 6.5           | 6.5         |

For generating fuzzy output in fuzzy interface engine various rules are defined to predict values as per membership functions. The “If/Then” rules justifies all the necessary logics of input variables in and accordingly generates outputs.

5. Results

5.1. Taguchi & Fuzzy Logic

Table 3 Results

| S.no | Experimental | Fuzzy Logic | Error % (Actual & Fuzzy Values) |
|------|--------------|-------------|---------------------------------|
|      | SRR | Ra   | SRR | Ra | SRR | Ra   |
| 1.   | 0.6386 | 3.259 | 0.6551 | 3.2166 | 2.5186994 | 1.3010126 |
| 2.   | 0.5912 | 2.5685 | 0.6183 | 2.4283 | 4.3829856 | 5.4584388 |
| 3.   | 0.5169 | 2.1512 | 0.5447 | 2.1939 | 5.1037268 | 1.9849386 |
| 4.   | 0.6716 | 3.0516 | 0.6919 | 2.8437 | 2.93395 | 6.8128195 |
| 5.   | 0.4987 | 3.1865 | 0.5192 | 2.9823 | 3.9483821 | 6.408285 |
| 6.   | 0.7421 | 2.4677 | 0.7655 | 2.2897 | 3.0568256 | 7.2131945 |
| 7.   | 0.566 | 3.2589 | 0.5815 | 3.1207 | 2.6655202 | 4.2406947 |
| 8.   | 0.7768 | 2.9056 | 0.79098 | 2.7053 | 1.7927128 | 6.8935848 |
| 9.   | 0.6986 | 2.784 | 0.7287 | 2.5677 | 4.1306436 | 7.7693966 |

\[ \text{Error\%} = \left( \frac{\text{Experimental Value} - \text{Fuzzy Value}}{\text{Experimental Value}} \right) \times 100 \]  
\[ (5) \]
Maximum error % is calculated using eq. 5 and is found to be 7.7% for SRR while for Ra it is 5.1% only. The plot between target responses and fuzzy values for SRR and Ra is shown in fig.2 & fig3.

![Figure 2 Actual vs Fuzzy output (SRR)](image1)

![Figure 3 Actual vs Fuzzy output (Ra)](image2)

Table 4 Larger-Better for SRR

| Level | Ton (A) | Toff(B) | Feed(C) | Ip (D) |
|-------|---------|---------|---------|--------|
| 1     | -4.731  | -4.099  | -2.893  | -4.351 |
| 2     | -4.031  | -4.267  | -3.713  | -4.033 |
| 3     | -3.418  | -3.813  | -5.573  | -3.794 |
| Delta | 1.313   | 0.455   | 2.68    | 0.557  |
| Rank  | 2       | 4       | 1       | 3      |

![Figure 4 SRR (Main effect plot)](image3)

Table 4 shows s/n ratio for SRR. Also the rank of each parameter is specifically described. C1A2D3B4 is best sets/combinations of parameters for achieving target value effectively. From fig. 7 it is stated that SRR increases with higher Ton values, as more time is offered for heat energy to melt and evaporate material. Higher Toff values also leads to higher SRR as more time duration is available’ for proper flushing of debris attached to exposed layer of specimen. Lower value of SRR is obtained at high wire feed as short circuit phenomenon occurs and irregular spark discharges also takes place.
Higher Ip values gives high SRR as again high heat is generated which supports machining of work piece.

Table 5 Smaller-Better for Ra

| Level | Ton(A) | Toff(B) | WF(C) | Ip(D) |
|-------|--------|---------|-------|-------|
| 1     | -8.37  | -10.071 | -9.124 | -9.74 |
| 2     | -9.201 | -9.175  | -8.926 | -8.767 |
| 3     | -9.473 | -7.798  | -8.994 | -8.536 |
| Delta | 1.104  | 2.274   | 0.198  | 1.204 |
| Rank  | 3      | 1       | 4     | 2     |

Table 6 shows s/n ratio for Ra. Also the rank of parameters is specifically described as B1D2A3C4.

From fig 8 it can be verified that Ra increases with higher Ton, since it becomes higher with high removal of material. Higher Toff leads to eradication of debris on workpiece surface by pressurized fluid (dielectric) thereby decreasing Ra. Increase in feed of wire leads to irregular cutting of material due to abrupt spark discharges, which causes formation of thermal stress on work piece. Increasing Ip also leads to lower Ra as heat energy (for melting & vaporizing of material) is directly proportional to current.

5.2. ANOVA

95% confidence level is considered for statistical evaluation of SRR and Ra. The significance of any process parameter is justified by analysis of P-value, which is considered best when $P < \alpha$, where $(\alpha=.05)$, as in Table 6&7. Similarly overall model significance is justified by analyzing $R^2$ and adj. $R^2$, for SRR ($R^2 96.7\%$ and adj. $R^2 (93.41\%)$) while for Ra ($R^2 94.98\%$ and adj. $R^2 89.96\%)$. Thus overall models are statistically good. The % contribution of every individual parameter on either response is depicted using pie charts as in figures

Table 6 ANOVA (SRR)

| Source | Contribution | Adj. SS | Seq. MS | F-Value | P-Value |
|--------|--------------|---------|---------|---------|---------|
| Regression | 96.70% | 0.073647 | 0.018412 | 29.34 | 0.003 |
| Ton | 19.01% | 0.014475 | 0.014475 | 23.07 | 0.009 |
| Toff | 1.45% | 0.001104 | 0.001104 | 1.76 | 0.255 |
| WF | 72.58% | 0.055277 | 0.055277 | 88.09 | 0.001 |
| Ip | 3.66% | 0.002791 | 0.002791 | 4.45 | 0.103 |
Table 7 ANOVA (Ra)

| Source   | Contribution | Adj SS  | Seq MS  | F-Value | P-Value |
|----------|--------------|---------|---------|---------|---------|
| Regression | 94.98%       | 1.1488  | 0.2872  | 18.93   | 0.007   |
| Ton      | 12.96%       | 0.15675 | 0.15675 | 10.33   | 0.032   |
| Toff     | 64.69%       | 0.78236 | 0.782359| 51.57   | 0.002   |
| WF       | 0.02%        | 0.00021 | 0.000212| 0.01    | 0.912   |
| Ip       | 17.32%       | 0.20948 | 0.209478| 13.81   | 0.021   |
| Error    | 5.02%        | 0.06069 | 0.015172|         |         |
| Total    | 100.00%      |         |         |         |         |

Figure 6 % contribution of inputs for SRR inputs for Ra

Figure 7 % contribution of inputs for Ra

6. Conclusion & Future Scope of Work

The following statements can be successfully drawn after implementing Taguchi L9 and Fuzzy system on D3(heat treated) specimen:

1) The suitable combination of inputs as per Taguchi is found to be for C1A2D3B4 SRR and B1A2D3C4 for Ra.

2) For SRR (R² 96.7% and adj. R²(93.41%) while for Ra (R² 94.98% and adj. R² 89.96%)

3) Fuzzy Logic is applied and the maximum % error between target value & fuzzy result sets is found to be 7.7 % for SRR and 5.1% for Ra.

4) Other output parameters viz, taper angle, tool wear analysis, FEM analysis, wire offset etc can be done using other optimizing techniques.

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