Multi- Response Optimization of Wire EDM Process Parameter on Aluminium Alloy (5086)

Pradeep Kumar, Pankaj Sharma

Abstract: In the present work, the effect of process parameters on material removal rate during the machining of aluminium alloy (5086) with WEDM is studied. The four control parameter were selected i.e. pulse on time (T\text{ON}), pulse off time (T\text{OFF}), peak current (I\text{p}) and spark gap voltage (S\text{V}) to investigate their effects on material removal rate (MRR). Each control parameter had three levels. Total 27 experiments were done with a zinc coated brass wire of diameter 0.25 mm. Taguchi L9 orthogonal array technique was used for the experiment. ANOVA was used to find out the significance of control parameters and their contribution on MRR. It was found that maximum material removal rate was 41.52 mm\(^3\)/min which was due to high pulse on time and low pulse off time.

Keywords: MRR, Process parameters, Taguchi technique, WEDM.

I. INTRODUCTION

In today’s world wire electric discharge machine (WEDM) has become an important unconventional machining process. It is being used in space technology, aircrafts, nuclear, armament and other production and engineering operations. Traditional machining is recognized with the direct contact of tool and work piece. In traditional machining, the tool material should be 30% harder than the work piece material to ensure cutting. Non-traditional machining is done with no direct contact of tool and work piece. As there is no direct contact between work piece and tool, therefore, frictional losses are absent in these processes. These processes also provide better surface finish and compatible with new alloys having greater toughness, strength, hardness and impact resistance. The complex, intricate designs and geometry of work pieces can be machined with non-traditional machining techniques such as Electrical Discharge Machining (EDM), Chemical Machining (CM), Water Jet Machining (WJM) and Electrochemical Machining (ECM) etc. Kumar et al. (2019) conducted an experiment on WEDM process with inconel 718 by using response surface methodology (RSM) based NSGA-II. Pulse-on time (T\text{ON}) and discharge current were found to be the most influential parameters for machining responses. It was found that the T\text{ON} and discharge current significantly affects the MRR. It was also found that the corner deviation was almost independent of sparking factors and mostly affected by wire tension [1]. Magabe et al. (2019) investigated wire-EDM for Ni55.8Ti shape memory alloy and concluded that higher values of S\text{V}, T\text{ON}, and I\text{p} resulted in higher MRR [2]. Pramanik et al. (2018) studied the cutting parameters affecting material removal rate of Al 6061 t6 alloy. It was observed that the MRR is significantly affected by the T\text{ON}, T\text{OFF}, I\text{p} and S\text{V} [3]. Joshi and Chappaon (2017) selected CNC Wire cut EDM Machine Electronica - Maxicut 734 for experiments with AISI M42 HSS material as work material and brass wire of 0.25mm diameter as wire electrode. Taguchi L18 orthogonal array with GRA were applied for experimentation and optimization. They concluded that the most prominent factors for MRR are T\text{ON} followed by T\text{OFF} [4]. Takale and Chougule (2017) used Electronica WEDM to investigate the significant effects of process parameters on MRR. They used T149.4Ni50.6 shape memory alloy as work material and zinc coated brass wire as wire electrode for experimentation. They used Taguchi, L18 orthogonal array with ANOVA for the investigation. They concluded that T\text{ON} was most significant factor for MRR followed by T\text{OFF} [5]. Goswami and Kumar (2017) performed experiments for trim cut operations on Electronica Sprincut (Electra- Elplus 40A DLX) CNC wire electrical discharge machine with Nimonic 80A alloy as work piece and brass wire electrode of dia. 0.25 mm (soft) to determine the effects of process parameters on performance parameters. They choose GRA for analysis and optimization. They found that during trim cut machining T\text{ON} was most important parameter for MRR [6]. Garg et al. (2016) described the comparison between diffused and brass wire by using input parameters such as T\text{ON}, T\text{OFF} and S\text{V}. For experimentation, they used Stainless steel grade-SS304 as a workpiece and two wires were taken one was brass and another was diffused brass wire with 0.25mm diameter each on electronica sprintcut WEDM. They used taguchi L9 orthogonal array for the experimentation, and ANOVA for analysis the results. After analysis of experimental results found that the MRR of diffused brass wire was more as compare to brass wire. MRR increased with increase of T\text{ON}, and MRR decreased with increase of T\text{OFF} and S\text{V} [7]. Kumar et al. (2015) studied the effect of process parameter like as T\text{ON}, T\text{OFF}, peak current (I\text{p}), and S\text{V} on MRR. For experimentation, they used Monal K-500 as a workpiece on Ultima-IF Wire-cut-EDM. By using Taguchi technique, L27 orthogonal array was selected for the experiment. The Gray relational analysis (GRA) technique was used for optimization and analysis the experimental results and it was found that T\text{ON}, T\text{OFF}, I\text{p}, and S\text{V} were most significant parameters for MRR. The optimum value of process parameters was found such as T\text{ON} -123\text{μs}, T\text{OFF} -50\text{μs}, I\text{p} -13A, S\text{V} -30V [8].
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Aggarwal et al. (2015) described the effect of process parameters such as $T_{ON}$, $T_{OFF}$, $I_p$, $S_V$, wire feed ($W_F$) and wire tension ($W_T$) on MRR. For experimental work, they used zinc coated brass wire 0.25 mm diameter and Inconel 718 as a workpiece material on Electra sprintcut CNC WEDM. Response surface methodology (RSM) technique was chosen for experiments design, and ANOVA for analysis the experimental results and after analyzing the results, it was found that $T_{ON}$ was the highly affected parameter on MRR [9]. Sivaraman et al. (2015) performed experiments with titanium material as a work piece using Taguchi method was used to find out the effect of process parameters like as dielectric pressure, $T_{ON}$, $T_{OFF}$, and $W_T$ on MRR. ANOVA design approach was used for the optimization and analysis of the experimental results. They observed that Taguchi was the most suitable technique for optimization in WEDM [10].

Kubade et al. (2015) investigated the effect on MRR by using process parameters like as $T_{ON}$, $T_{OFF}$, and $W_F$. For experimentation, they used Titanium Diboride (TiB2) as a workpiece. L27 orthogonal array was used for the experimentation and AVOVA for optimization. It was found that the $T_{ON}$ and $T_{OFF}$ were the highly affected parameters on MRR. For maximum MRR, optimum setting of parameters as like $T_{ON}$-118 μs, $T_{OFF}$-48 μs and $W_F$-8 mm/min [11].

This experimental work is focuses over the process parameters optimization of machining Aluminium alloy (5086) by using wire EDM and their effect on MRR. Taguchi L9 orthogonal array technique is used for experimental design and analysis of variance (ANOVA) is used to find out the optimum process parameters as well as the most significant parameters on MRR.

II. DESIGN OF EXPERIMENT

The experiments were performed by using Wire EDM CNC machine (Electronica sprintcut WEDM) manufactured by Electronica India Limited, Pune. It uses zinc coated soft brass wire having diameter 0.25 mm as a tool electrode and distilled water as a dielectric fluid for experimentation. In the present research work the material used for experimentation is Aluminium alloy (5086). The chemical composition, physical properties of the workpiece material (Aluminium alloy 5086) are shown in the Table 1 and Table 2.

### Table- I: Chemical Composition of Aluminium alloy (5086)

| Element | Wt. (%) |
|---------|---------|
| Al      | 94.55   |
| Mg      | 4.02    |
| Cu      | 0.056   |
| Mn      | 0.49    |
| Fe      | 0.42    |
| Si      | 0.28    |
| Zn      | 0.086   |
| Ti      | 0.003   |
| Cr      | 0.09    |
| Pb      | 0.002   |

### Table- II: Physical properties of Aluminium alloy (5086)

| Property              | Density | Thermal conductivity | Electrical conductivity | Melting point |
|-----------------------|---------|----------------------|-------------------------|---------------|
| Aluminium             | 2.675 g/cm$^3$ | 127 W/mK            | 3.4×10$^7$ S/m          | 588°C         |

### III. EXPERIMENTAL PROCEDURE

The dimensions of the workpiece used for the experiment on the WEDM was 250 mm x 25 mm x 20 mm. A total of 27 experiments have been conducted. The experiment were carried out to prepare of 27 rectangular punches of size 20mm x 10mm as shown in figure 1. Taguchi L9 orthogonal array technique is used for the experiment. The four control parameters, i.e., $T_{ON}$, $T_{OFF}$, $I_p$, and $S_V$ were chosen for MRR during the machining of Aluminium alloy (5086). The experiments were performed as suggested by Taguchi technique. The whole arrangement of sequence of experiments including their inherited process parameters with different levels. In performing experiments, total 27 experiments were performed with three level of each control parameter. The control parameters and their levels are shown in the table 3. After experimentation MRR was calculated by mathematical formulation:

$$MRR= V_C \times M_x \times W_d$$  \hspace{1cm} (1)

### Table- III: Control parameters and their levels

| S. No. | Process parameter | Level 1 | Level 2 | Level 3 |
|--------|-------------------|---------|---------|---------|
| 1      | $T_{ON}$          | 116     | 120     | 124     |
| 2      | $T_{OFF}$         | 54      | 58      | 62      |
| 3      | $I_p$             | 210     | 220     | 230     |
| 4      | $S_V$             | 16      | 18      | 20      |

### IV. RESULT AND DISCUSSION

Taguchi method is used for designing and conducting various experiments. MRR is influenced by individual process parameter. Table 4 shows the experimental values of various parameters and analyzed data associated with them i.e S/N ratio and Means. The parametric effect of process parameters is shown by plotting S/N ratio and Mean value. Also the response characteristics are examined by plotting response curve.
The values of process parameters are determined through ANOVA table and response curve. Analysis of experimental results is done by using MINITAB with Taguchi through S/N ratio and Mean values.

A. S/N ratio for MRR

\[
S/N \text{ ratio } = -10 \log_{10} \left( \frac{1}{N} \sum \frac{1}{y^2} \right)
\]

(2)

Table- IV: Analytical result of MRR

| Ex. No. | T<sub>ON</sub> | T<sub>OFF</sub> | I<sub>p</sub> | S<sub>V</sub> | MRR  | S/N ratio | Mean |
|--------|---------------|---------------|-------------|-------------|------|-----------|------|
| 1      | 116           | 54            | 210         | 16          | 24.666 | 27.842    | 24.666 |
| 2      | 116           | 58            | 220         | 18          | 19.943 | 25.996    | 19.943 |
| 3      | 116           | 62            | 230         | 20          | 16.417 | 24.306    | 16.417 |
| 4      | 120           | 54            | 220         | 20          | 31.211 | 29.886    | 31.211 |
| 5      | 120           | 58            | 230         | 16          | 27.707 | 28.852    | 27.707 |
| 6      | 120           | 62            | 210         | 18          | 23.522 | 27.430    | 23.522 |
| 7      | 124           | 54            | 230         | 18          | 41.538 | 32.369    | 41.538 |
| 8      | 124           | 58            | 210         | 20          | 33.634 | 30.536    | 33.634 |
| 9      | 124           | 62            | 220         | 16          | 31.013 | 29.831    | 31.013 |

Table- V: Response table of S/N ratio for MRR (Larger is better)

| Level | T<sub>ON</sub> | T<sub>OFF</sub> | I<sub>p</sub> | S<sub>V</sub> |
|-------|---------------|---------------|-------------|-------------|
| 1     | 26.05         | 30.03         | 28.6        | 28.84       |
| 2     | 28.72         | 28.46         | 28.57       | 28.6        |
| 3     | 30.91         | 27.19         | 28.51       | 28.24       |
| Delta | 4.86          | 2.84          | 0.09        | 0.6         |

Table- VI: Response table of Means for MRR (Larger is better)

| Level | T<sub>ON</sub> | T<sub>OFF</sub> | I<sub>p</sub> | S<sub>V</sub> |
|-------|---------------|---------------|-------------|-------------|
| 1     | 20.34         | 32.47         | 27.27       | 27.80       |
| 2     | 27.48         | 27.09         | 27.39       | 28.33       |
| 3     | 35.39         | 23.65         | 28.55       | 27.09       |
| Delta | 15.05         | 8.82          | 1.28        | 1.25        |

B. Effects of process parameters on MRR

The value of MRR is found to be increased by increasing the level of T<sub>ON</sub> and I<sub>p</sub>. It is also found that the MRR decreased with increase in T<sub>OFF</sub>. MRR is first increased and then decreased with increase of S<sub>V</sub> (from figure 3). The higher order, non-random variation in relationship non-normality, and non-constant variation have been evaluated in residual plots as shown in Figure 4. Residual plots shows that in case of normal probability plot, residual trace an approximate straight line in the plot between residual and fitted value, residual is found to be constant around zero. The significance of different process parameters is determined through the values of delta and Rank (shown in table 6). T<sub>ON</sub> and T<sub>OFF</sub> were found to be the most significant factor w.r.t. to the value of rank and delta on MRR. The higher order, non-random variation in relationship non-normality, and non-constant variation have been evaluated in residual plots as shown in Figure 4. Residual plots shows that in case of normal probability plot, residual trace an approximate straight line in the plot between residual and fitted value, residual is found to be constant around zero.

C. Regression analysis for MRR

Regression equation is established between process parameters and responses. For the calculation of predicted value of MRR the following equation was used.
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MRR = -145 +1.88T_{ON} -1.10T_{OFF} +0.0640I_{P} -0.1775S_{V}(3)

The predicted values are obtained using regression equation are tabulated along with experimental results (experimental values) to differentiate the experimental and predicted values of MRR. Table 7 shows the experimental and predicted values of MRR. The comparison of predicted value and the experimental values in the form of response curve is shown in figure 5 and from the response curve it is observed that the experimental values are very close to the predicted values.

Table- VII: Experimental and predicted values of MRR

| Ex. No. | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|---------|------|------|------|------|------|------|------|------|------|
| Predicted| 24.288 | 20.174 | 16.06 | 31.74 | 28.688 | 22.654 | 40.254 | 34.22 | 31.168 |
| Experimental| 24.666 | 19.943 | 16.417 | 31.211 | 27.707 | 23.522 | 41.538 | 33.634 | 31.013 |

Figure 5 Comparison between predicted and experimental values

D. TWO WAY ANOVA RESULTS

To analyze the effect of parameter Two-way ANOVA method was used. The value of F is calculated in two-way ANOVA. The T_{ON} has maximum value of F according to rank/delta (shown in table 10), therefore T_{ON} has more effect on MRR of Aluminium alloy (5086) during machining on WEDM as followed by T_{OFF}. According to table 8, 9 and 10, T_{ON} and T_{OFF} has maximum and I_{P}, S_{V} has minimum effect on MRR.

Table- VIII: Two way ANOVA for MRR V/s T_{ON} and I_{P}

| Source    | DF | SS    | MS    | F     | P    |
|-----------|----|-------|-------|-------|------|
| T_{ON}    | 2  | 340.191 | 170.096 | 5.63  | 0.069 |
| I_{P}     | 2  | 3.009  | 1.504 | 0.05  | 0.952 |
| Error     | 4  | 129.93 | 30.233 |       |      |
| Total     | 8  | 464.13 |       |       |      |

Table- IX: Two way ANOVA for MRR V/s T_{ON} and S_{V}

| Source    | DF | SS    | MS    | F     | P    |
|-----------|----|-------|-------|-------|------|
| T_{ON}    | 2  | 340.191 | 170.096 | 5.60  | 0.069 |
| S_{V}     | 2  | 2.347  | 1.173 | 0.04  | 0.962 |
| Error     | 4  | 121.592 | 30.398 |       |      |
| Total     | 8  | 464.13 |       |       |      |

Table- X: Two way ANOVA for T_{ON} and T_{OFF}

The tabulated data represents the percentage contribution of different factors in machining operation. The analysis is done through ANOVA by using mean values of MRR

Table- XI: ANOVA table of S/N data showing percentage contribution

| Factor | SS               | DF | Variance | F Ratio | % Contribution |
|--------|------------------|----|----------|---------|----------------|
| T_{ON} | 35.60402007      | 2  | 17.8021  | 1.00216E+15 | 73.6597956     |
| T_{OFF}| 12.1737952       | 2  | 6.0868976 | 3.42662E+14 | 25.1852548     |
| I_{P}  | 0.013579845       | 2  | 0.0067899 | 3.82239E+11 | 0.02809474     |
| S_{V}  | 0.544504011       | 2  | 0.272252  | 1.53264E+13 | 1.126500221    |
| Error  | 3.55271          | 2  | 1.776E-14 |         | 7.35005E-14    |
| Total  | 48.33589912      | 10 |          |         |                |

E. SELECTION OF OPTIMUM LEVEL OF PARAMETERS FOR MRR

Optimum process parameters have been selected by using response table 6. ANOVA is used to investigate the optimum process parameters for MRR. Average of every response characteristics is shown in table 5 and 6, for every level of every factor. Delta statics is included in the table on the basis of rank for comparison of the relative effects and magnitude. Delta and rank is assigned by MINTAB. The highest value of Delta, Rank should be 1, for second highest value of Delta; Rank should be 2 and so on. These ranks indicate the relative significance of each factor to the response (MRR). According to rank and delta values, MRR has most influenced by T_{ON}, T_{OFF}, S_{V} and I_{P}. As MRR is characterized by the “larger is better” type quality characteristics, it can be seen from figure 3, that the first level of T_{OFF} and second level of S_{V} and third level of T_{ON} and I_{P} should be taken to achieve the maximum value of MRR. The optimum value of MRR is found at the optimum process parameters that are T_{ON} has maximum and I_{P}, S_{V} has minimum effect on MRR.
MRR_{opt} = 41.523 \text{ mm}^3/\text{min}

Where,

\( \mu = \text{overall mean of MRR} = (\Sigma \text{MRR MEAN1})/9 = 27.739 \)

The 95 % confidence intervals of confirmation experiments (CICE) are calculated as:

\[
C_{\text{ICE}} = \sqrt{f \alpha(1, f e) \left[ \frac{1}{n_{\text{eff}}} + \frac{1}{r} \right] V_{e}}
\]

\[
C_{\text{ICE}} = \sqrt{7.71 \left[ \frac{1}{1.8} + \frac{1}{1} \right] 1.08}
\]

\[C_{\text{ICE}} = 3.6\]

Where, \( f \) is found from the ANOVA table

\[\eta_{\text{eff}} = 9/(1 + \text{total DOF}) = 9/(1 + 4) = 1.8\]

Where, \( N = \text{Total number of experiments} = 9 \)

\[V_{e} = \text{Error of Adj MS} = 1.08\]

\[r = \text{Sample size for confirmation experiment} = 1\]

\[f_{e} = \text{Error DOF} = 4\]

F0.05 (1, 4) = 7.71 (value from F table)

So, the confidence interval is 37.92\( \leq \mu_{\text{MRR}} \leq 45.123\).

The 95% confidence interval (CICE) for MRR is 37.92\( \leq \mu_{\text{MRR}} \leq 45.123\) mm\(^3/\text{min}\).

**Table- XII: Optimum values of MRR at optimum levels of parameters with CICE**

| Performance parameters | Optimum level of process parameters | Optimum value | CICE |
|-------------------------|-------------------------------------|---------------|------|
| MRR (mm\(^3/\text{min}\)) | \(T_{\text{ON}}, T_{\text{OFF}}, I_{\text{p}}\), \(S_{V}, S_{V}\) | 41.523 mm\(^3/\text{min}\) | 37.92\( \leq \mu_{\text{MRR}} \leq 45.123\) |

**V. CONCLUSION**

The following conclusions can be made from the present study:

- The value of MRR is found to be increased by increasing the level of \(T_{\text{ON}}\) and \(I_{\text{p}}\). It is also found that the MRR decreased with increase in \(T_{\text{OFF}}\). MRR is first increased and then decreased with increase in \(S_{V}\).

- \(T_{\text{ON}}\) and \(T_{\text{OFF}}\) are the most significant process parameter while \(I_{\text{p}}\) and \(S_{V}\) are less significant for MRR. It is found that Ton has maximum contribution (73.65%) followed by \(T_{\text{OFF}}\) (35.18%), \(S_{V}\) (1.12%) and \(I_{\text{p}}\) (0.03%) in WEDM operation.

- The optimum setting of process parameter for maximum MRR is \(T_{\text{ON}} = 124 \mu\text{s}, T_{\text{OFF}} = 54 \mu\text{s}, I_{\text{p}} = 230 \text{ A} \) and \(S_{V} = 18 \text{ V}\), during machining of aluminum alloy (5086) on WEDM.

- The optimum value of MRR is 41.52 mm\(^3/\text{min}\) at optimum setting of process parameter. The 95 % confidence interval (CICE) for MRR is 37.92\( \leq \mu_{\text{MRR}} \leq 45.123\) mm\(^3/\text{min}\).

**NOMENCLATURE**

\(T_{\text{ON}}\) Spark on time (\(\mu\text{s}\))

\(T_{\text{OFF}}\) Spark off time (\(\mu\text{s}\))

\(S_{V}\) Servo voltage (V)

\(W_{f}\) Wire feed rate (mm/min)

\(I_{p}\) Input current (A)

\(V_{C}\) Cutting speed (mm/min)

\(M_{t}\) Thickness of the workpiece (mm)

\(W_{d}\) Diameter of the wire

\(n\) Total number of experiments

\(y\) Mean value

CS Cutting speed (mm/min)

MRR Material removal rate (mm/min)

WEDM Wire electrical discharge machining

SS Sum of squares of the factors

MS Mean of squares of the factors

DF Degree of freedom

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