# Optimization of Tool Wear Rate during Electrical Discharge Machining of Advanced Materials using Taguchi Analysis

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***Abstract:* -** In electrical discharge machining tool wear is a major problem. The contribution of the tool cost in the total operation cost is approximately 50%. Because of tool wear the geometrical dimensions and form of the tool are not reproduced on the workpiece. Due to these reasons the tool wear has to be carefully handled while planning electrical discharge machining operations. In view of this, present study uses Taguchi's method to optimize the electrical discharge machining process variables for achieving minimum tool wear rate. NiTi alloy, NiCu alloy and BeCu alloy were consider as the workpiece materials and electrolytic copper was considered as tool electrode. Electrical parameters considered for the study includes gap current, gap voltage, pulse on time and pulse off time along with workpiece electrical conductivity. Experiments were carried out as per the Taguchi's $L_{18}$ orthogonal array. The most significant parameter that affects the tool wear rate was obtained by Taguchi's signals to noise ratio and analysis of variance methods. Based on the statistical analysis it was found that work electrical conductivity, gap current, and pulse on time were the most significant process parameters that affects tool wear rate. The obtained optimal parameter setting provides minimum tool wear rate.

*Key-Words:* **-** NiTi alloys, NiCu alloys, BeCu alloys, Taguchi approach, Analysis of variance, Tool wear rate.

## 1 Introduction

An ideal tool electrode in electrical discharge machining should not only remove the maximum amount of material from the workpiece surface, but it should resist self erosion. The machinability of a material is a factor of its electrical and thermal conductivity. Commonly used copper electrode has high thermal and electrical conductivity, resulting in a more effective energy transfer to the workpiece. Kolahan and Bironro developed regression model and optimized machining parameters in the PMEDM of Tungsten-Cobalt alloy using ANOVA and Genetic algorithm. Rao et al. addressed EDM of newly developed materials like Ti6Al4V, HE15, 15CDV6 and M250 considering different input variables for optimum solution with an aim to optimize MRR. Found an optimal solution by creating a model of the process using neural network and then selected the weights with the help of genetic algorithms. Wang et al. they employed the Taguchi experimental design to explore the feasibility of an EDM recast layer removal process. They concluded that EPMA analysis of recast layer and base material before and after corrosion using phosphoric acid and hydrochloric acid proved that carbon decreases dramatically during the corrosion process. The micro-hardness test of recast layer and base material proved that corrosion using phosphoric acid and hydrochloric acid could only damage the structure of the recast layer and that base material hardness would not be damaged at all. Yang et al. they proposed an optimization methodology for the selection of best process parameters in electro discharge machining using simulated annealing scheme. Saha and Choudhury used central composite design (CCD) of experiments to develop empirical models of MRR, Ra and TWR. They found that discharge current, duty factor, air pressure and spindle speed are the significant factors which affect MRR and gap voltage have significant effect on Ra. It was found that the TWR was independent of the input parameters. Bharti et al. used DOE technique to investigate the machining characteristics of Inconel 718 during die-sinking electric discharge machining. They found at higher discharge current MRR increases; deteriorate surface finish and leads for more tool electrode loss. Discharge current and pulse-on-time are identified as common influencing parameters for MRR, SR and TWR. Govindan and Joshi investigated dry EDM in drilling by employing a shield around the plasma. They studied the effect of processing conditions on MRR, TWR, and accuracy. Pulse ‘off-time’ and clearance between the shield and the electrode at the sparking region were used in conjunction with the other regular dry EDM parameters. Also, analysis of the mechanism of material removal has also been carried out by performing single- discharge experiments in dry EDM. It was observed that at low discharge energies, single-discharge in dry EDM could give larger MRR and crater radius as compared to that of the conventional liquid dielectric EDM. Kathiresan and Sornakumar developed Al alloy-SiC composites were using vortex method and pressure die casting technique. The EDM studies showed that the MRR and the surface roughness are greatly influenced by the current and percent weight silicon carbide. The MRR increases with an increase in the current and decrease in the percent weight of silicon carbide. The surface finish improves with decrease in the current and increase in the percent weight of SiC. Yildiz et al. studied the effect of cold and cryogenic treatment of Be-Cu alloy workpieces on machining performance in terms of MRR, EWR, Ra and white layer thickness formation in EDM of mesoscale holes. Results showed improvement in MRR values and marginal improvement found in EWR, Ra and white layer thickness. Gopalakannan and Senthilvelan investigated the effect of electrode materials on machining characteristics in EDM of corrosive resistant stainless steels 316 L and 17-4 PH. They concluded copper electrode has been preferred for higher MRR whereas copper-tungsten is preferred for low electrode wear, good surface finish and good dimensional accuracy. Govindan and Joshi presented a quantitative assessment of surface damage in terms of the parameters like average length and density of cracks on the surfaces in dry EDM process has been undertaken. Finally, they compared between the quality of the machined surfaces obtained using the liquid and dry dielectrics in the EDM process. Murray et al. carried a fundamental study on the surface of EDMed single-crystal silicon using transmission electron microscopy (TEM) and laser- Raman spectroscopy to characterise the micro-structural changes as well as the presence of any contaminants and defects at the nano-scale. Daneshmand et al. studied the effects of electro discharge machining parameters such as voltage, discharge current, pulse on time and pulse off time on the rate of material removal, tool wear, relative electrode wear and surface roughness of NiTi alloy. Shabgard et al. developed a system based on fuzzy rule for better and user friendly selection of EDM and US/EDM processes machining parameters. They found that fuzzy modeling results of EDM and US/EDM are in good agreement with experimental findings demonstrating approximately 90% predictions. Jatti and Singh studied the effects of cryogenic treatments on the machinability of NiTi alloys in electro discharge machining. From the literature survey, it has been observed very few studies have being carried on cryogenic treatment of NiTi alloys, NiCu alloys and BeCu alloys in electrical discharge machining. The settings for new materials such as titanium alloys, aluminium alloys, special steels, advanced ceramics and binary alloys have to be optimized experimentally. When new and advanced materials appear in the field, it has not been possible to use existing models and hence experimental investigations are always required. Undertaking frequent tests or many experimental runs is also not economically justified. This study was based on investigating the effect of EDM process parameters on the tool wear rate during machining of NiTi alloys, NiCu alloys and BeCu alloys in electrical discharge machine. Taguchi L18 orthogonal array and analysis of variance was used to identify significant parameters at influence the tool wear rate. Taguchi single objective optimization method was employed to obtain optimal setting of EDM process parameters. Confirmation experiments were carried out to validate the optimal setting of process parameters for achieving minimum value of tool wear rate.

## 2 Material and Methods

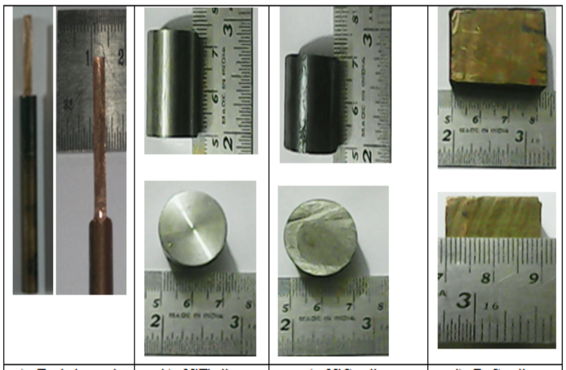
In the present study NiTi alloy, NiCu alloy and BeCu alloy were selected as workpiece materials. The NiTi alloy workpiece samples were cut into ϕ20 mm x 20 mm length which has density of 6.45 gm/cc. NiCu alloy workpiece samples were cut into ϕ20 mm x 20 mm length which has density of 8.8 gm/cc. BeCu alloy workpiece samples were cut into 30 mm x 20 mm x 20 mm size which has density of 8.25 gm/cc. Electrolytic copper of high thermal conductivity is selected as tool electrode for the present study. Tool electrode of size □3 mm x 90 mm length which has density of 8.94 gm/cc were used for the experiments. In the present study both workpiece and tool are cryo-treated at -185 °C. Cryogenic treatment process in this study consists of three main periods and soaking time as shown in figure 1. The thermal cycle for the cryogenic treatment was as follows: slow descend from room temperature to -185 °C in 9 hours, dwell at -185 °C for 24 hours (soaking stage), and slow ascend from -185 °C to room temperature in 9 hours. Linear ramp up to +150 °C in 1 hour, dwell at +150 °C for 4 hours and back to room temperature in 1 hour. The electrical conductivity of workpiece and tool electrode was obtained by using electrical resistivity testing system. In this study gap current, gap voltage, pulse on time and pulse off time were considered at three levels as input process parameters along with electrical conductivity of workpiece at two levels. The change in weight of workpiece was measured by digital weighing balance of model GR-300 with accuracy of 0.0001 gm. By using change in weight, density of workpiece and time of machining, and material removal rate is calculated for all experimental runs using equation 1.

$$TWR = \frac{(T_1 - T_2)\times 1000}{\rho \times t} \qquad (1)$$

where $T_1$ and $T_2$ is the weight of tool before and after machining respectively in grams, ρ is density of workpiece in gm/cc, t is machining time in minutes.

Experiments were conducted on Electronic machine tool limited make of die sinking type of electrical discharge machine. Flushing pressure of 0.5 kg/cm2 was used with side wise flushing on electrode. A blind square hole of 5 mm depth was obtained on the workpiece for all experimental runs. Figure 1 shows the experimental setup and figure 2 shows all three types of workpiece and tool electrode. Experiments were designed using Taguchi $L_{18}$ ($2^1$ x $3^4$) mixed orthogonal array. Table 1 shows the process parameters and their levels.

Fig. 1 Experimental Setup



a) Tool electrode b) NiTi alloy c) NiCu alloy d) BeCu alloy

Fig. 2 Workpiece and tool materials

Table 1 Process parameters and its levels

| Factors | Levels | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Workpiece electrical conductivity (S/m) | untreated | treated | - |
| Gap current (A) | 8 | 12 | 16 |
| Gap voltage (V) | 40 | 55 | 70 |
| Pulse on time (µs) | 13 | 26 | 38 |
| Pulse off time (µs) | 5 | 7 | 9 |

The philosophy of Taguchi's method is to minimize the variations in product or systems characteristics. Taguchi's philosophy defines three approaches to minimize variations namely, parameter, tolerance and system design. Orthogonal arrays are used in these approaches which reduces the experimental runs. Taguchi's method has few benefits such as with fewer number of trials run an acceptable solution is achieved. It minimizes the variability around the target value with lesser experimental cost. The optimal setting of parameters obtained from analysis can also be used in real production environment. To determine the effect of each variable on the output, the signal-to-noise ratios, are calculated for each experiment [16]. For the case of minimizing the performance characteristic, the following definition of the SN ratio can be used:

$$SN_i = -10\log\left(\sum_{u=1}^{N_i}\frac{y_u^2}{N_i}\right) \qquad (2)$$

For the case of maximizing the performance characteristic, the following definition of the SN ratio can be used:

$$SN_i = -10\log\left[\frac{1}{N_i}\sum_{u=1}^{N_i}\frac{1}{y_u^2}\right] \qquad (3)$$

where, i = experiment number, u = trial number, y = observed value, Ni = number of trials for experiment i [16].

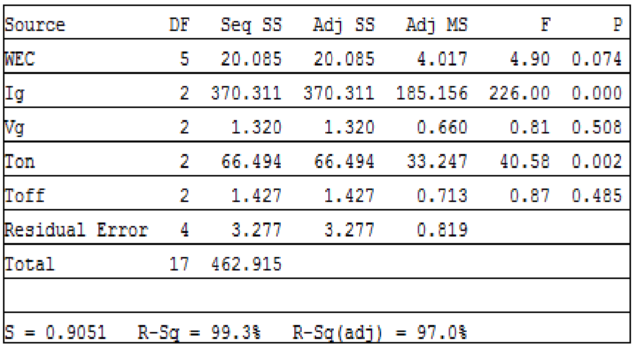
## 3 Results and Discussions

In order to see the effect of process parameters on tool wear rate, experiments were conducted using $L_{18}$ orthogonal array as shown in table 2. The average values of tool wear rate for each parameter at levels 1, 2 and 3 for S/N data are plotted in figure 3 and raw data is plotted in figure 4. Analysis of variance (ANOVA) was performed at a confidence level of 95% i.e. a significance level of 0.05. It was found that gap voltage and pulse off time are non-significant parameters for tool wear rate are given in tables 3 and 5 respectively. Pooled ANOVA of the S/N data and raw data was performed after eliminating non-significant parameter given in tables 4 and 6 respectively. And percentage contributions of most significant parameters were carried out. The response table show the average of each response characteristic for each level of each factor. The tables include ranks based on delta statistics, which compare the relative magnitude of effects. Table 7 and 9 shows the Taguchi response table for S/N data and raw data respectively. Table 8 and 10 shows Taguchi pooled response table for S/N data and raw data respectively. All the analysis was carried out using MINITAB 15 statistical software.

Table 2 Trail conditions with observed values

| Work electrical conductivity (S/m) | Gap current (A) | Gap voltage (V) | Pulse on time (μs) | Pulse off time (μs) | TWR ($mm^3$/min) |
|---|---|---|---|---|---|
| 3268 | 8 | 40 | 13 | 5 | 0.071 |
| 3268 | 12 | 55 | 26 | 7 | 0.112 |
| 3268 | 16 | 70 | 38 | 9 | 0.149 |
| 4219 | 8 | 40 | 26 | 7 | 0.052 |
| 4219 | 12 | 55 | 38 | 9 | 0.084 |
| 4219 | 16 | 70 | 13 | 5 | 0.236 |
| 5515 | 8 | 55 | 13 | 9 | 0.096 |
| 5515 | 12 | 70 | 26 | 5 | 0.155 |
| 5515 | 16 | 40 | 38 | 7 | 0.201 |
| 5625 | 8 | 70 | 38 | 7 | 0.040 |
| 5625 | 12 | 40 | 13 | 9 | 0.176 |
| 5625 | 16 | 55 | 26 | 5 | 0.224 |
| 5645 | 8 | 55 | 38 | 5 | 0.041 |
| 5645 | 12 | 70 | 13 | 7 | 0.172 |
| 5645 | 16 | 40 | 26 | 9 | 0.210 |
| 5902 | 8 | 70 | 26 | 9 | 0.075 |
| 5902 | 12 | 40 | 38 | 5 | 0.119 |
| 5902 | 16 | 55 | 13 | 7 | 0.256 |

Table 3 ANOVA table for tool wear rate (S/N data)



| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| WEC | 5 | 20.085 | 20.085 | 4.017 | 4.90 | 0.074 |
| Ig | 2 | 370.311 | 370.311 | 185.156 | 226.00 | 0.000 |
| Vg | 2 | 1.320 | 1.320 | 0.660 | 0.81 | 0.508 |
| Ton | 2 | 66.494 | 66.494 | 33.247 | 40.58 | 0.002 |
| Toff | 2 | 1.427 | 1.427 | 0.713 | 0.87 | 0.485 |
| Residual Error | 4 | 3.277 | 3.277 | 0.819 | | |
| Total | 17 | 462.915 | | | | |

S = 0.9051 R-Sq = 99.3% R-Sq(adj) = 97.0%

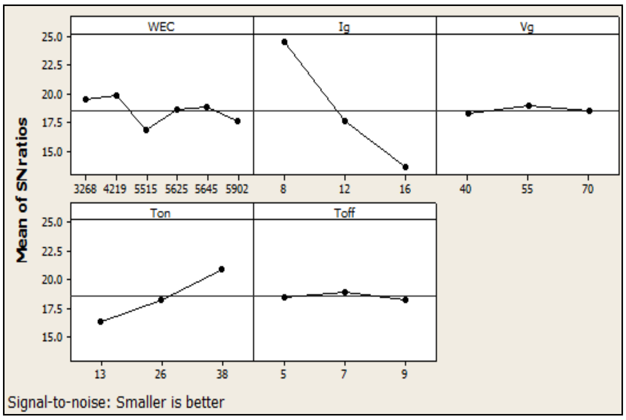


Fig. 3 Effect of input parameters on tool wear rate (S/N data)

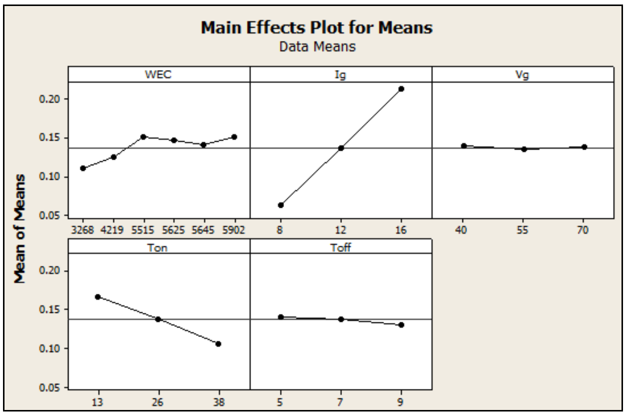
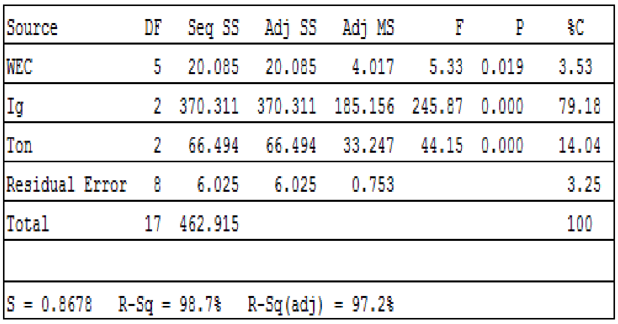


Fig. 4 Effect of input parameters on tool wear rate (raw data)

Table 4 Pooled ANOVA table for tool wear rate (S/N data)

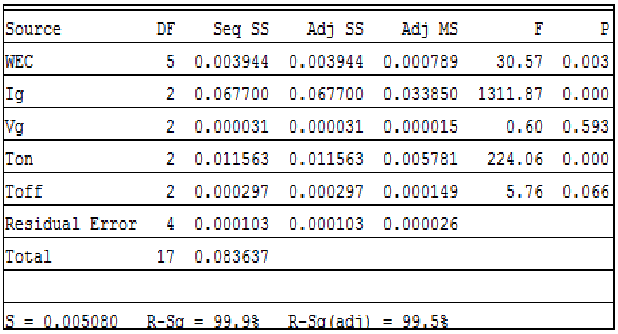


| Source | DF | Seq SS | Adj SS | Adj MS | F | P | %C |
|---|---|---|---|---|---|---|---|
| WEC | 5 | 20.085 | 20.085 | 4.017 | 5.33 | 0.019 | 3.53 |
| Ig | 2 | 370.311 | 370.311 | 185.156 | 245.87 | 0.000 | 79.18 |
| Ton | 2 | 66.494 | 66.494 | 33.247 | 44.15 | 0.000 | 14.04 |
| Residual Error | 8 | 6.025 | 6.025 | 0.753 | | | 3.25 |
| Total | 17 | 462.915 | | | | | 100 |
| | | | | | | | |
| S = 0.8678   R-Sq = 98.7%   R-Sq(adj) = 97.2% | | | | | | | |

Where, DF= degrees of freedom, SS= sum of squares, MS= mean square, F= fisher distribution, p=probability value, %C= percentage contribution

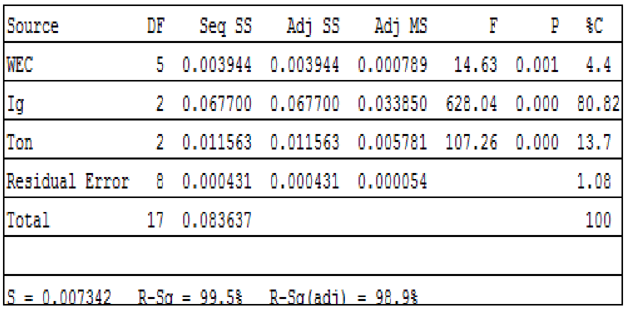
As tool wear rate is the smaller-the-better type of quality characteristics, from figure 3 and 4 it can be seen that first level of work electrical conductivity ($A_1$), first level of gap current ($B_1$) and third level of pulse on time (D3) provides minimum value of tool wear rate.

Table 5 ANOVA table for tool wear rate (raw data)



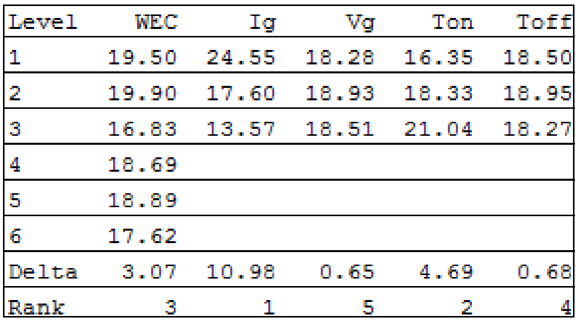
| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| WEC | 5 | 0.003944 | 0.003944 | 0.000789 | 30.57 | 0.003 |
| Ig | 2 | 0.067700 | 0.067700 | 0.033850 | 1311.87 | 0.000 |
| Vg | 2 | 0.000031 | 0.000031 | 0.000015 | 0.60 | 0.593 |
| Ton | 2 | 0.011563 | 0.011563 | 0.005781 | 224.06 | 0.000 |
| Toff | 2 | 0.000297 | 0.000297 | 0.000149 | 5.76 | 0.066 |
| Residual Error | 4 | 0.000103 | 0.000103 | 0.000026 | | |
| Total | 17 | 0.083637 | | | | |
| | | | | | | |
| S = 0.005080   R-Sq = 99.9%   R-Sq(adj) = 99.5% | | | | | | |

Table 6 Pooled ANOVA table for tool wear rate (raw data)



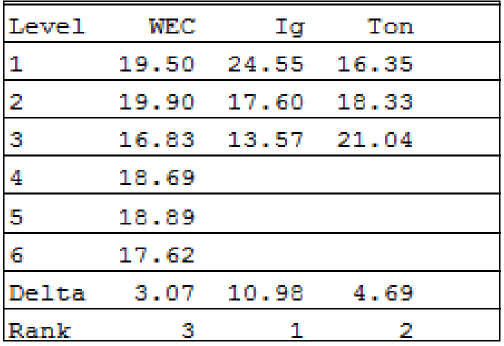
| Source | DF | Seq SS | Adj SS | Adj MS | F | P | %C |
|---|---|---|---|---|---|---|---|
| WEC | 5 | 0.003944 | 0.003944 | 0.000789 | 14.63 | 0.001 | 4.4 |
| Ig | 2 | 0.067700 | 0.067700 | 0.033850 | 628.04 | 0.000 | 80.82 |
| Ton | 2 | 0.011563 | 0.011563 | 0.005781 | 107.26 | 0.000 | 13.7 |
| Residual Error | 8 | 0.000431 | 0.000431 | 0.000054 | | | 1.08 |
| Total | 17 | 0.083637 | | | | | 100 |
| | | | | | | | |
| S = 0.007342   R-Sq = 99.5%   R-Sq(adj) = 98.9% | | | | | | | |

Table 7 Response table for tool wear rate (S/N ratio data, smaller-the-better)



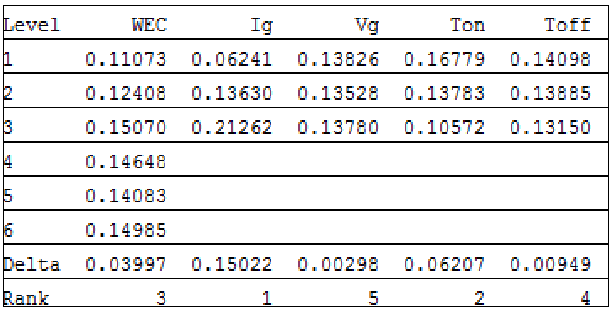
| Level | WEC | Ig | Vg | Ton | Toff |
|---|---|---|---|---|---|
| 1 | 19.50 | 24.55 | 18.28 | 16.35 | 18.50 |
| 2 | 19.90 | 17.60 | 18.93 | 18.33 | 18.95 |
| 3 | 16.83 | 13.57 | 18.51 | 21.04 | 18.27 |
| 4 | 18.69 | | | | |
| 5 | 18.89 | | | | |
| 6 | 17.62 | | | | |
| Delta | 3.07 | 10.98 | 0.65 | 4.69 | 0.68 |
| Rank | 3 | 1 | 5 | 2 | 4 |

Table 8 Pooled Response table for tool wear rate (S/N ratio data, smaller-the-better)



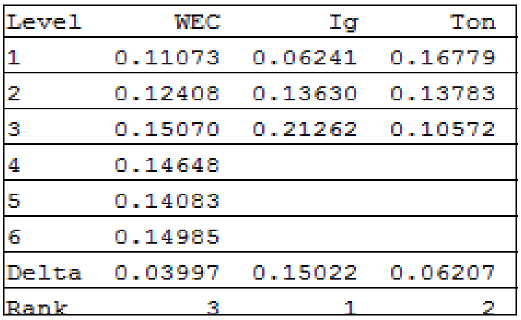
| Level | WEC | Ig | Ton |
|---|---|---|---|
| 1 | 19.50 | 24.55 | 16.35 |
| 2 | 19.90 | 17.60 | 18.33 |
| 3 | 16.83 | 13.57 | 21.04 |
| 4 | 18.69 | | |
| 5 | 18.89 | | |
| 6 | 17.62 | | |
| Delta | 3.07 | 10.98 | 4.69 |
| Rank | 3 | 1 | 2 |

Table 9 Response table for tool wear rate (raw data)



| Level | WEC | Ig | Vg | Ton | Toff |
|---|---|---|---|---|---|
| 1 | 0.11073 | 0.06241 | 0.13826 | 0.16779 | 0.14098 |
| 2 | 0.12408 | 0.13630 | 0.13528 | 0.13783 | 0.13885 |
| 3 | 0.15070 | 0.21262 | 0.13780 | 0.10572 | 0.13150 |
| 4 | 0.14648 | | | | |
| 5 | 0.14083 | | | | |
| 6 | 0.14985 | | | | |
| Delta | 0.03997 | 0.15022 | 0.00298 | 0.06207 | 0.00949 |
| Rank | 3 | 1 | 5 | 2 | 4 |

Table 10 Pooled Response table for tool wear rate (raw data)



| Level | WEC | Ig | Ton |
|---|---|---|---|
| 1 | 0.11073 | 0.06241 | 0.16779 |
| 2 | 0.12408 | 0.13630 | 0.13783 |
| 3 | 0.15070 | 0.21262 | 0.10572 |
| 4 | 0.14648 | | |
| 5 | 0.14083 | | |
| 6 | 0.14985 | | |
| Delta | 0.03997 | 0.15022 | 0.06207 |
| Rank | 3 | 1 | 2 |

## 4 Estimation of Optimum Tool Wear Rate and Conformation Experiments

In this section, the optimal values tool wear rate along with confidence interval has been predicted. To validate the optimal results confirmation experiments are also conducted. The average value of the tool wear rate obtained through the confirmation experiments must lie within the 95% confidence interval, $CI_{CE}$ and $CI_{POP}$. The predicted mean value of tool wear rate is calculated based on equation 4.

$$\mu_{TWR} = \overline{A_1} + \overline{B_1} + \overline{D_3} - 2\overline{T} \qquad (4)$$

$\overline{T}$ = overall mean of TWR = 0.1370 mm$^3$/min

$\overline{A_1}$ = average value of TWR at first level of workpiece electrical conductivity = 0.11073 mm$^3$/min

$\overline{B_1}$ = average value of TWR at first level of gap current = 0.06241 mm$^3$/min

$\overline{D_3}$ = average value of TWR at second level of pulse on time = 0.10572 mm$^3$/min

$\mu_{TWR}$ = 0.00486 mm$^3$/min

The 95% confidence intervals of confirmation experiments ($CI_{CE}$) and population ($CI_{pop}$) are calculated by using formulae;

$$CI_{CE} = \sqrt{F_\alpha(1, f_e)V_e\left(\frac{1}{n_{eff}} + \frac{1}{R}\right)} \qquad (5)$$

$$CI_{pop} = \sqrt{\frac{F_\alpha(1, f_e)V_e}{n_{eff}}} \qquad (6)$$

Where,

$F_\alpha(1, f_e)$ = The F ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom $f_e$.

$$n_{eff} = \frac{N}{1 + [DOF \text{associated in the estimate of mean response}]}$$

$n_{eff} = 18 / (1+9) = 1.8$
N = Total number of results = 18
R = Sample size for confirmation experiments = 3
$V_e$ = Error variance = 0.000026
$f_e$ = Error DOF = 4
$F_\alpha(1, f_e) = 7.71$

$CI_{CE} = \pm 0.01335$
$CI_{pop} = \pm 0.01055$

The predicted confidence interval for confirmation experiments is:

$$\text{Mean } \mu_{TWR} - CI_{CE} < \mu_{TWR} < \text{Mean } \mu_{TWR} + CI_{CE}$$

$$-0.00849 < \mu_{TWR} < 0.01821$$

The 95% confidence interval of the population is:

$$\text{Mean } \mu_{TWR} - CI_{pop} < \mu_{TWR} < \text{Mean } \mu_{TWR} + CI_{pop}$$

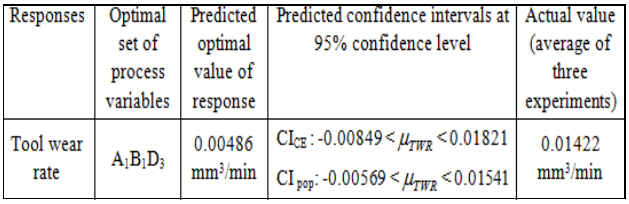
$$-0.00569 < \mu_{TWR} < 0.01541$$

The optimal values of process variables at their selected levels are as follows:

First level of Work EC ($A_1$): 3268 S/m
First level of gap current ($B_1$): 8 A
Third level of pulse on time ($D_3$): 38 µs

To validate the obtained optimal set of process parameter for minimization of tool wear rate confirmatory experiments were carried out (Table 11). Based on the confirmatory experimental results it was found that the actual value of tool wear rate lie within the confidence intervals at 95% confidence level. This confirms that the obtained optimal set of process parameter for achieving minimum tool wear rate values is acceptable.

Table 11 Validation experiments



| Responses | Optimal set of process variables | Predicted optimal value of response | Predicted confidence intervals at 95% confidence level | Actual value (average of three experiments) |
|---|---|---|---|---|
| Tool wear rate | $A_1B_1D_3$ | 0.00486 $mm^3/min$ | $CI_{CE}$: $-0.00849 < \mu_{TWR} < 0.01821$<br>$CI_{pop}$: $-0.00569 < \mu_{TWR} < 0.01541$ | 0.01422 $mm^3/min$ |

## 5 Conclusions

This study was focused on investigating the optimal set of process parameters for minimizing tool wear rate during machining of NiTi alloy, NiCu alloy and BeCu alloy in electrical discharge machining by using the parametric approach of the Taguchi's method. Based on the experimental results it was found that work electrical conductivity, gap current and pulse on time are significant process parameters that influence tool wear rate. Confirmation experiments were carried out to validate the obtained optimal set of parameters from Taguchi method. It was found that the actual value of tool wear rate lie within the confidence intervals at 95% confidence level. Hence by proper selection of process parameters will lead to optimal utilization of EDM machine. Based on the experimental results it can be concluded that Taguchi method helps to find out optimal setting of process parameters for newly developed material at minimum number of experimental runs. This in turn reduces the cost and time of experimentation and allows the shop floor operator to set the process parameters as per the requirement. This establishes the reliability of Taguchi's method as one of the most accurate optimization approaches.

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