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Optimization of Machining Parameters in Wire EDM of Copper Using Taguchi Analysis

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Abstract

WEDM is a one of the non-traditional machining processes used for machining complex shape components and hard materials like composites and inter-metallic materials. This paper presents the optimization of wire electrical discharge machining (WEDM) process parameters such as pulse on time (T_{on}), pulse off time (T_{off}) and wire tension (WT) to yield maximum material removal rate (MRR) and minimum surface roughness (Ra) of copper. The machining experiments were carried out according to the Taguchi parametric design (L_9) using 0.25 mm diameter brass wire as a cutting tool. Analysis of variance (ANOVA) was used to find the significance of each process parameter. Optimal results have been verified through confirmation experiments. In addition, the regression equations were also established between the process parameters and responses. The results indicate that pulse on time is the most significant factor influencing the MRR and Ra followed by pulse off time and wire tension.

Keywords

Wire EDM, Copper, Taguchi, Anova

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1. Introduction

Wire electrical discharge machining is one of the non-traditional machining processes used in the field of micro-machining to fabricate very complex micro products like forging dies, plastic moulds, punches and contour cutting etc. from hard materials that are difficult to machine. The process produces low residual stresses during cutting of material because it does not need higher cutting forces for material removal resulted a little change in mechanical properties of material after machining. In this process, the material is removed from the workpiece by a series of discrete spark discharges between a work and tool electrode immersed in a liquid dielectric medium. The developed spark discharges melt and vaporize minute amount of the work material. The removed material is ejected and flushed away by the dielectric.

In WEDM, the process variables that influence the performance measures material removal rate and work piece surface roughness are discharge current, discharge capacitance, pulse duration, pulse frequency, wire speed, wire tension, average working voltage etc. Many researchers have done work on WEDM to find the influence of variables on responses for various materials [1-4].

Huang et *al*. [1] applied Taguchi and Grey relational analyses to determine the optimal selection of machining parameters for the Wire Electrical Discharge Machining. They concluded that feed rate and T_{on} were the most influential factors on MRR, and Ton has a significant influence surface roughness. Mahapatra et *al*. [4] identified the significant machining parameters affecting the performance measures are as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow using Taguchi's parameter design and also established nonlinear regression equations between process parameters and performance measures. Saurav Datta [5] developed quadratic

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mathematical models to represent the process behaviour of wire electrical discharge machining (WEDM) operation. Hewidy et *al.* [6] established mathematical models correlating the various WEDM machining parameters (peak current, duty factor, wire tension and water pressure) with the metal removal rate, wear ratio and surface roughness using response surface methodology. Singh et *al*. [7] investigated the effect of various process parameters of WEDM like pulse on time (T_{on}), pulse off time (T_{off}), gap voltage (SV), peak current (IP), wire feed (WF) and wire tension (WT) to reveal their impact on the material removal rate of hot die steel (H-11) using one variable at a time approach. Durairaja et *al.* [8] used Grey relational theory and Taguchi optimization technique to optimize the cutting parameters in Wire EDM for SS304. They reported that pulse on time has a major influence on the surface roughness (µm) and kerf width (mm) in both the Taguchi optimization method and Grey relational analysis. Martowibowo et *al.* [9] conducted experiments to optimize the input parameters of Wire EDM machine, such as no load voltage, capacitor, on-time, off-time, and servo voltage, for machining medium carbon steel ASSAB 760. The results revealed that the MRR and the SR are greatly influenced by the on-time and the taper angle, respectively.

This present work describes the optimization of WEDM process parameters using Taguchi technique and also to determine the influence of process parameters on the responses using ANOVA analysis. In the present work, statistical analysis software MINITAB 15 was used for the design of experiments and to perform ANOVA analysis.

2. Methodology

2.1. Taguchi Method

Taguchi technique is a powerful statistical technique used for analyzing and optimizing the process parameters. The Taguchi analysis uses orthogonal arrays from design of experiments theory to study the influence of a large number of variables on responses with a small number of experiments. In this method, the experimental results are transformed into a signal-to-Noise (S/N) ratio. It uses the S/N ratio as a measure of quality characteristics deviating from or nearing to the desired values [8]. Taguchi classified the quality characteristics into three categories such as Lower the better, Higher the better and Normal the better. The formula used for calculating S/N ratio is as follows.

$$\text{Lower the better: S/N ratio } (\eta) = -10 \log_{10} \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

Where y_i = observed response value, n= number of replications.

Normal the better: It is used where the nominal or target value and variation about that value is minimized.

$$\text{S/N ratio } (\eta) = -10 \log 10 \frac{\mu^2}{\sigma^2} \quad (2)$$

Where µ =mean and σ = variance

Higher the better: It is used where the larger value is desired.

$$\text{S/N ratio } (\eta) = -10 \log 10 \frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2} \quad (3)$$

Where, y_i = observed response value, n= number of replications

2.2. Selection of Process Parameters

In this investigation, WEDM parameters such as T_{on}, T_{off} and WT were considered. According to Taguchi's design of experiments, for three parameters and three levels L_9 Taguchi orthogonal array [9] was selected. The number of factors and their corresponding levels are shown in the Table 1 and the basic Taguchi L9 (3^4) orthogonal array used for this work is shown in Table 2. Here, A, B, C and D are Control factors.

Table 1. Selected variable levels for WEDM.

Code	Variable	Level 1	Level 2	Level 3
1	T_{on}	120	125	130
2	T_{off}	60	58	56
3	WT	6	8	10

Table 2. The basic Taguchi L9 (3^4) orthogonal array.

Expt. No	Control factors and their levels			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

2.3. Experimental Set up

Table 3. Chemical Composition of copper.

Element	Cu	Zn	Pb	Fe	Bi	Cr	Zr	Mg
% (weight)	99.86	0.111	<0.05	<0.010	<0.002	0.001	0.027	0.001

Figure 1. Experimental setup.

The experiments were carried out on a CNC wire-cut EDM machine and experimental setup is shown in Fig. 1. In this work, 0.25 mm diameter brass wire used as a cutting tool. 100 x 95 x 8.5 mm size copper plate was mounted on the WEDM machine tool and 20 x 20 x 10 mm square specimens were cut. Chemical composition of copper material was tested and the percentage of elements is shown in Table 3.

2.4. Calculation of Material Removal Rate (MRR) and Surface Roughness

To optimize the machining process parameters, the most important outcomes of WEDM such as Material Removal Rate (MRR) and Surface Roughness (Ra) were considered in this investigation. The Material Removal rate was calculated as

$$MRR = W/T \text{ (gm/sec)}$$

Where, W is the Weight of Material Removed after Machining.

T is the Time in which material is removed

$$W = I - (R + w)$$

I = Initial weight of metal Specimen.

R = Remaining weight of metal specimen after Machining

w = Weight of piece which is cut from the specimen

After machining the work piece, the surface roughness values were measured using a Surtronic 3 + Taylor Hobson Talysurf surface profilo meter.

3. Results and Discussion

3.1. Influence of Process Parameters on MRR

Leading statistical analysis software MINITAB 15 was used for the design and analysis of experiments to perform the Taguchi and ANOVA analysis and to establish regression models. The optimization of process parameters using Taguchi method provides the evaluation of the effect of individual independent parameters on the identified quality characteristics. The statistical analysis of variance (ANOVA) was carried out. Based on the ANOVA, the contribution of each parameter in influencing the variation in quality characteristic was evaluated. The ANOVA also provides an indication of which process parameters are statistically significant. The results table for MRR and Ra is shown in Table 4 along with the input factors.

Table 4. Response table.

Run	T_{on}	T_{off}	WT	MRR	Ra
1	120	60	6	0.00176	1.65525
2	120	58	8	0.00235	1.83150
3	120	56	10	0.00214	1.67850
4	125	60	8	0.00231	1.85350
5	125	58	10	0.00250	2.11275
6	125	56	6	0.00273	1.70875
7	130	60	10	0.00300	2.09500
8	130	58	6	0.00300	2.21325
9	130	56	8	0.00333	2.01575

In this investigation, the S/N ratio was chosen according to the criterion, the "larger-the-better" in order to maximize MRR. The S/N ratio for the "larger-the-better" target for all the responses was calculated using e.q. (3).

Table 5. S/N ratio for MRR.

Level	T_{on}	T_{off}	WT
1	0.002083	0.002732	0.002496
2	0.002511	0.002617	0.002662
3	0.003110	0.002356	0.002547
Delta	0.001027	0.000377	0.000167
Rank	1	2	3

In the present study, MRR of WEDM was analyzed to determine the effect of WEDM process parameters on MRR and Ra. The experimental results were transformed into a signal-to-noise (S/N) ratio using the Minitab statistical software. Main effects at all the levels of the chosen parameters are calculated and listed in Table 5. The main effect for mean and S/N ratio is plotted in Figure 2 and 3 respectively. It is observed from Figure 2 and 3 that the MRR is highest at the level 3 of T_{on}, at the level 1 of T_{off} and at the level 2 of the WT. It is clear that the highest S/N ratio is the optimal level of each process parameter. Therefore, both mean effect and S/N ratio values indicate that the MRR is at maximum when T_{on} at level 3, T_{off} at level1 and WT at level 2, i.e. T_{on} at 130, T_{off} at 56 and WT at 8.

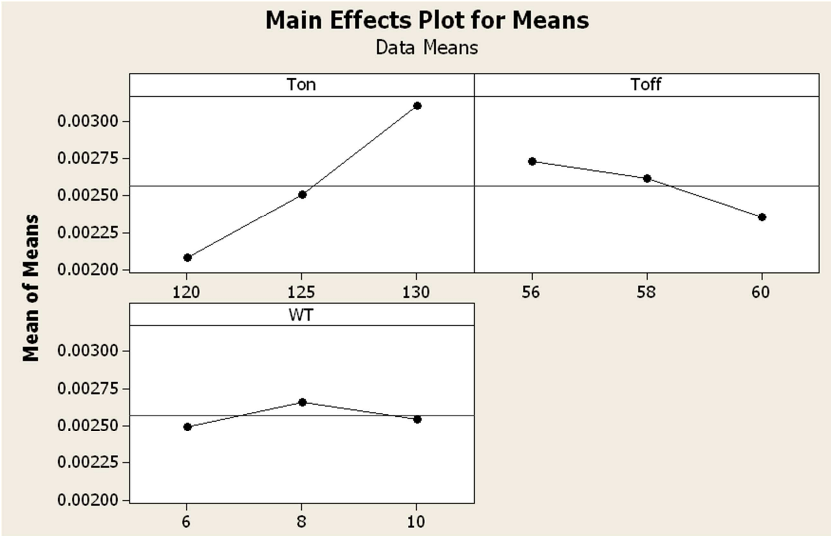

Figure 2. Main effects plots for mean of MRR.

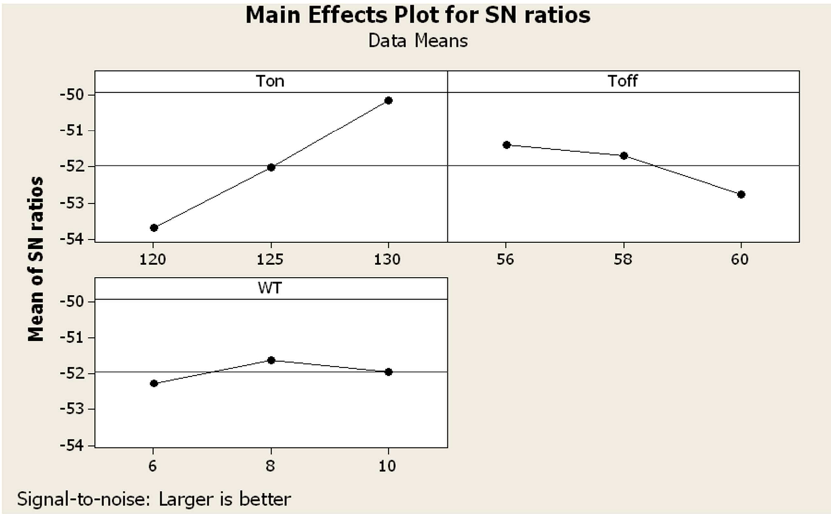

Figure 3. Main effects plots for S/N ratio of MRR.

The analysis of variances of the factors is shown in Table 6 which clearly shows that the WT is not an important factor that influences MRR and Ton (84.21%) is the most influencing factor for MRR followed by T_{off} (10.53%).

Table 6. Analysis of Variance for S/N ratios for MRR.

Source	DF	Seq SS	Percentage of contribution
Ton	2	0.0000016	84.21
Tof	2	0.0000002	10.53
WT	2	0.0000000	0.00
Error	2	0.0000001	5.26
Total	8	0.0000019	100

3.2. Influence of Process Parameters on Surface Roughness

In this investigation, the S/N ratio was chosen according to the criterion, the "smaller-the-better" in order to minimize surface roughness. The S/N ratio for the "smaller -the-better" target for all the responses was calculated using e.q. (1)

Table 7. S/N for Ra.

Level	T_{on}	T_{off}	WT
1	1.722	1.801	1.859
2	1.892	2.053	1.900
3	2.108	1.868	1.962
Delta	0.386	0.252	0.103
Rank	1	2	3

In the present study, surface roughness of WEDM was analyzed to determine the effect of WEDM process parameters. Main effects at all the levels of the chosen parameters are calculated and listed in Table 7. The main effect for mean and S/N ratio is plotted in Figure 4 and 5 respectively. It is observed from Figure 4 and 5 that the Ra is lowest at the level 3 of T_{on}, at the level 2 of T_{off} and at the level 3 of the WT. It is clear that the highest S/N ratio is the optimal level of each process parameter. Therefore, both mean effect and S/N ratio values indicate that the Ra is at minimum when T_{on} at level 3, T_{off} at level 2 and WT at level 3, i.e. T_{on} at 130, T_{off} at 58 and WT at 10.

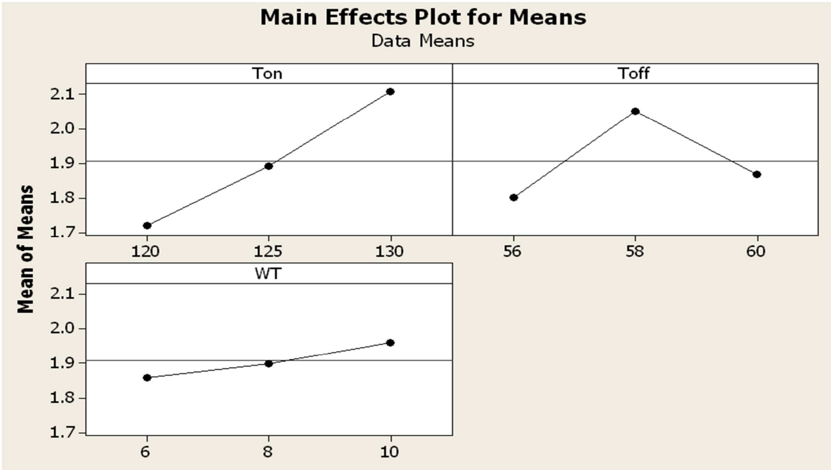

Figure 4. Main effects plots for mean of Ra.

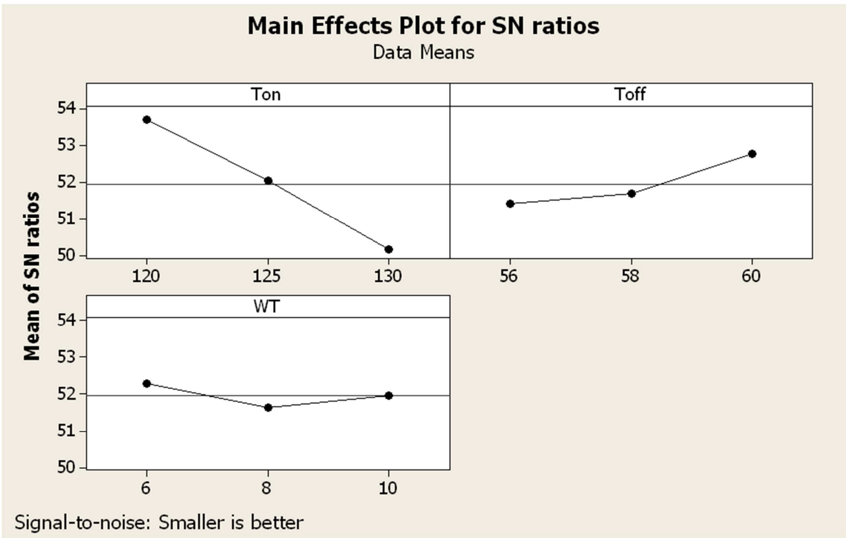

Figure 5. Main effects plots for S/N ratio of Ra.

The analysis of variances of the factors is shown in Table 8 which clearly indicates that T_{on} (64.86%) is the major factor affecting Ra of followed by T_{off} (9.35%) and WT (4.65 %).

Table 8. Analysis of Variance for S/N ratios for Ra.

Source	DF	Seq SS	Percentage of contribution
T_{on}	2	0.224861	64.86
T_{of}	2	0.101801	29.35
WT	2	0.016127	4.65
Error	2	0.003959	51.14
Total	8	0.346748	100

3.3. Regression Equations

Regression analysis is a statistical technique used to determine relationships between process parameters and outcomes for the purpose of predicting the results at intermediate values within the range of the level. During this investigation, the regression equations were established between the process parameters and responses. Nonlinear regression models were developed based on the experimental values to predict MRR and Ra. It is found that a second order polynomial curve fits the experimental results as well.

The equations obtained are as follows

$$\text{Material Removal Rate (MRR)} = -7.50667E\text{-}04T_{on} + 0.00201317T_{off} + 0.000577417\ WT + 3.41333E - 06T_{on}^2 - 1.81667E - 05T_{off}^2 - 3.52917E - 05WT^2 - 0.0148578,$$

$$R2 = 96.24\% \quad (4)$$

$$\text{Surface Roughness (Ra)} = -0.193458T_{on} + 6.33994T_{off} - 0.0155833WT + 0.000928333T_{on}^2 - 0.0545104T_{off}^2 + 0.00258333WT^2 - 172.677,\ R^2 = 98.86\% \quad (5)$$

3.4. Validation

Confirmation experiments were carried out at the optimum process condition to validate the optimum results estimated by the statistical analysis. The comparison of predicted MRR and R_a with experimental results at optimal levels is presented in Table 9.

Table 9. Results of Confirmation Test.

Ton	Toff	WT	MRR Predicted	Exp.	Ra Predicted	Exp
3	1	2	0.003136	0.003456		
3	2	3			2.309	2.315

4. Conclusion

In the present study, the effect of WEDM process parameters like pulse on time (T_{on}), pulse off time (T_{off}) and wire tension (WT) on machining responses MRR and Ra of copper has been investigated using Taguchi Technique. The optimum process parameters for maximization of MRR are T_{on} at level 3 (130), T_{off} at level 1 (56) and WT at level 2 (8). Similarly, the factors T_{on} at level 3 (130), T_{off} at level 2 (58) and WT at level 3(10) is recommended for minimization Ra. The ANOVA results indicate that T_{on} is the major factor affecting MRR (84.21%) and Ra (64.86%) followed by T_{off} and WT. The regression equations were established between the process parameters and responses for predicting the results at intermediate values within the range of the level.

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