Investigation of Kerf in Micro Wire Electro Discharge Machining

Mohammad Yeakub Ali*, Siti Nur Zalikha Khamarruzaman and Asfana Banu

Department of Manufacturing and Materials Engineering
International Islamic University Malaysia
PO Box 10, 50728 Kuala Lumpur, Malaysia
E-mail: mmyali@iium.edu.my

Abstract. Precision and accuracy are among those of the most important factors in the field of machining processes. Micro wire electro discharge machining (micro-WEDM) is used widely in the machining process to fabricate micro parts with high precision and accuracy. However, in micro-WEDM, minimal kerf remains as a critical issue. This paper investigates the kerf in micro-WEDM of stainless steel (S304). Experimental investigation is carried out with 70 μm diameter tungsten electrode wire with two varying parameters voltage and capacitance. The kerf data are analyzed and an empirical model is developed using Design Expert software. The optimum parameters for minimum kerf are found to be 10nF capacitance and 90V voltage.

1. Introduction

Wire electrical discharge machining (WEDM) is a non-traditional machining process that is widely used for machining delicate components. WEDM involves a series of process that is cooling and heating where the machining efficiency, accuracy and surface quality are influenced by the electrical discharge energy. The main challenges in this machining process are to control the kerf, accuracy and surface finishing. This is because WEDM relies heavily on the operators’ experiences and the tables of parameters provided by the builder of the machines. Furthermore, the discharges of the electrified current in a controlled manner by means of a thin wire, is guided alongside the desired cutting path. This heightened precision allows for complicated, three dimensional cuts, and produces highly accurate punches, dies, and stripper plates. The common machining parameters such as pulse-on and off, feed rate, current, polarity, voltage and vibration should be choose properly as it can affect the overall performance [1-4].

Kerf is a width of the machined slots which is one of the most vital characteristics of WEDM [5, 6]. The corner errors and kerf variation are usually caused by the wire tool deflection and vibration in the discharge gap. These are the main factors that affect the WEDM machining accuracy. However, the kerf variations have higher influences on dimensional accuracy in micro-WEDM compared to the conventional WEDM. This is because, the relative error found in miniature parts produce by the micro-WEDM are bigger than the corresponding values in conventional WEDM [7]. Besides that, a stable machining performance in micro-WEDM is related to the debris free machined kerf. It is evident from the debris tracking analysis that the most debris are left out from the kerf section under any constant fluid flow rate. More effectively, debris can be excluded and high micro-WEDM performance is obtainable with the improvement of jet flushing conditions of the working fluid from the nozzles [8].
machining micro structures, precision control of kerf is very important and it is related to machining processes, electrode wire diameter and also machining vibration. As such, it is difficult to control the minimum kerf. Therefore, the objective of this paper is to study the optimal parameters of voltage and capacitance for minimum kerf.

2. Experiment

Taguchi’s L9 orthogonal array statistical approach was used to design the experiment. Taguchi method was chosen because it requires minimum experimental cost thus minimizes the effect of the sources of variation [9]. Besides, it reduces the number of runs needed for the experiment compared to the full factorial approach [10]. A total of 9 experiments were conducted using micro-WEDM machine, DT-110 Mikrotools (Mikrotools Inc., Singapore) to complete the analysis of kerf. The experimental parameters are shown in Table 1 with controlled parameters; voltage and capacitance. The workpiece used was stainless steel (S304) with 70 μm diameter tungsten electrode wire. The wire-workpiece gap is thoroughly maintained by a computer controlled positioning system and the gap ranges around from 0.025mm to 0.075mm. The measurement of kerf is taken using scanning electron microscope (SEM) machine. Kerf will be measured by the width of the gap present. Then, the difference in gap will be compared to the tool width used that is 70µm. The example of the measured kerf at five different positions is shown in Figure 1. The results of average kerf are tabulated in Table 2. The results were analyzed using analysis of variance (ANOVA) approach.

3. Analysis and Discussions

Based on the results tabulated in Table 2, run 8 shows the smallest kerf with 90.00 µm when the capacitance is 10 nF and voltage is 90V. This is probably because when the capacitance decreases, small amount of energy is dissipated. Thus, it emits a weak sparks and leads to a smaller material erosion [11]. Therefore, with a smaller value of capacitance and voltage, the cutting width is to be reduced significantly.

Analysis of variance (ANOVA) of average kerf is shown in Table 3. The model was developed with 95% confidence level. The F-Value of 58.42 implies that the model is significant. There is only 0.08% chance that the F-Value could occur due to the noise. Values of Prob>F less than 0.05 indicates that the model terms, v (voltage), c (capacitance), v^2 and c^2 are found to be significant. Looking at the Prob>F, the factor c (capacitance) and c^2 is the most influential on kerf. The Prob>F for c and c^2 indicates that they have more than 99.00% confidence level. The Prob>F for v and v^2 has a confidence level of at least 95.00% thus showing that these factors have a very good influence on kerf itself. The analysis shows the effects of the relation of the process variables with each other either directly or indirectly. Statistically, F-Value providing confidence level as to whether the values are significantly different. For a large F-Value, it indicates that the performance characteristics are affected by the variation in process parameters [12].

Therefore, the final equation for this statistical model in terms of the actual factors is expressed by Eq. 1. This equation can be used to make predictions about the response for each given levels for each factors. However, the equation should not be used to get the relative impacts of each factor. This is because the coefficients are scaled to accommodate the units of each factors and the intercept is not at the centre of the design space. Furthermore, regression model has helped generating an equation to trace the statistical connections between the process’s parameters and the response variable [13].

\[
Kerf = 294.62 - 4.28v + 0.13c + 0.02v^2 - 2.4 \times 10^{-4}c^2
\]  
(1)

where, \( v \) = voltage (V) and \( c \) = capacitance (nF).
### Table 1. Experimental parameters

| Control Parameters | Factor | Unit | Level | | |
|--------------------|--------|------|-------|---|---|---|
| Voltage            | $v$    | V    | I     | 90 | 100 | 110 |
| Capacitance        | $c$    | nF   | II    | 400| 100 | 10  |

**Fixed Parameters:**
- Workpiece material: Stainless steel (S304)
- Wire electrode: Tungsten (Ø 70 µm)

### Table 2. Taguchi’s L9 orthogonal array experimental design and measured kerf values

| Expt. | Voltage, $v$ (V) | Capacitance, $c$ (nF) | Kerf at different point (µm) | Average Kerf (µm) |
|-------|------------------|------------------------|------------------------------|-------------------|
|       |                  |                        | A & B | C | D | E | | |
| 1     | 90               | 400                    | 107.00 | 103.00 | 109.00 | 102.00 | 96.00 | 103.40 |
| 2     | 100              | 100                    | 92.70 | 98.70 | 98.70 | 99.30 | 101.00 | 98.08 |
| 3     | 90               | 100                    | 95.30 | 95.30 | 97.30 | 107.00 | 98.70 | 98.72 |
| 4     | 100              | 400                    | 105.00 | 102.00 | 100.00 | 103.00 | 98.00 | 101.60 |
| 5     | 110              | 100                    | 109.00 | 103.00 | 103.00 | 100.00 | 103.00 | 103.60 |
| 6     | 100              | 10                     | 90.70 | 88.70 | 90.00 | 94.70 | 86.70 | 90.16 |
| 7     | 110              | 400                    | 109.00 | 103.00 | 107.00 | 101.00 | 104.00 | 104.80 |
| 8     | 90               | 10                     | 90.70 | 88.70 | 87.30 | 91.30 | 92.00 | 90.00 |
| 9     | 110              | 10                     | 96.00 | 94.40 | 92.00 | 91.30 | 88.40 | 92.42 |

**Figure 1.** Five different points taken for calculating average kerf (From top - point A, B, C, D and E)
Table 3. ANOVA of average kerf

| Source | Sum of Squares | Degree of Freedom (DF) | Mean Square | F-Value | Prob>F |
|--------|----------------|------------------------|-------------|---------|--------|
| Model  | 272.12         | 4                      | 68.03       | 58.42   | 0.0008 |
| $v$    | 12.61          | 1                      | 12.61       | 10.83   | 0.0302 |
| $c$    | 230.89         | 1                      | 230.89      | 198.27  | 0.0001 |
| $v^2$  | 9.77           | 1                      | 9.77        | 8.39    | 0.0443 |
| $c^2$  | 74.94          | 1                      | 74.94       | 64.35   | 0.0013 |
| Residual | 4.66       | 4                      | 1.16        |         |        |
| Cor Total | 276.78   | 8                      |             |         |        |

Figure 2. Contour plot of average kerf vs. capacitance and voltage

Figure 3. S/N ratio curves of voltage and capacitance for average kerf
Figure 2 shows the contour plot capacitance and voltage on kerf at constant wire tension and speed. Capacitance has a strong influence on kerf. The kerf increases with the increase of capacitance and voltage. Along with the increase of capacitance, a stronger sparks was emitted thus dissipating a large energy [11]. Therefore, this condition leads to a very large kerf to be produced. With increasing capacitance during the process, the cutting width get larger as it was affected by a high spark energy.

According to Taguchi method, the S/N ratio is the ratio of signal to noise where signal can be regarded as the preferable value while noise can be regarded as the value that was not preferred. The result of kerf was used to calculate the Signal to Noise ratio (S/N) using Eq. 2. Kerf is desired to be at minimum ratio, therefore the lower the better characteristic is used for S/N ratio calculation. The most favourable setting will be the one which could achieve the lowest S/N ratio [10].

\[
S/N_{LB} = -10 \times \log \left( \frac{1}{r} \sum y^2 \right)
\]

where \( S/N_{LB} \) = Signal to Noise ratio for the Lower the Better, \( y \) = output characteristic (Kerf) and \( r \) = number of trials

The S/N ratio for the two control factors for the experiment which is voltage and capacitance are shown respectively in Figure 3. The analysis was done using Minitab 17 software as a predictor to measures the performances and the interaction in between the factors. Analysis of the results leads to the decision that voltage at level 2 and capacitance at level 1 gives minimum kerf. Although the other factors at other level did not show any significant effect, but they still cannot be neglected. From Figure 3, capacitance seems the most important factor that affects the response as a whole.

4. Optimization and Verification
The optimized result for minimum average kerf was 89.61 µm with 93 V voltage and 10 nF capacitance. Experiment was conducted for verification using results obtained from the optimization. The actual values obtained from the experiments were compared with the optimize results. Average kerf had been increased from 89.48 µm to 89.61 µm with an error of 0.145%. The percentage error of average kerf is relatively small shows that the empirical model is significant.

5. Conclusion
The purpose of this paper is to investigate minimum kerf of micro-WEDM on stainless steel voltage and capacitance as the controlled parameters. ANOVA approach was used for analysis of minimum kerf and an empirical equation was developed. This study shows that:

1. Based on the experiments, the minimum average of kerf is found to be 90.00 µm with 90 V voltage and 10 nF capacitance.
2. Based on ANOVA analysis, kerf is strongly influenced by the capacitance. At a lower capacitance value, a low energy is dissipated when a weak sparks was emitted. Thus causes a smaller kerf.
3. The model predicts minimum kerf (89.61 µm) when 93 V voltage and 10 nF capacitance are used. The predicted value and experimental kerf value is within 0.145%. As such, the result developed an empirical model that is significant to represent the relationship of the parameters. Therefore, it is also useful to use it to predict the performance characteristics of machining stainless steel by micro-WEDM process.

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References

[1] Liao Y S, Huang J T, and Su H C 1997 A study on the machining-parameters optimization of wire electrical discharge machining J. Mater. Process. Tech. vol 71 pp 487-493

[2] Patil P A and Waghmare C A 2014 A review on advances in wire electrical discharge machining P. Int. Conf. Research and Innovation in Mechanical Engineering, Springer, India, pp 179-189

[3] Tosun N and Cogun C 2003 An investigation on wire wear in WEDM J. Mater. Process. Tech. vol 134 pp 273-278

[4] Debroy A and Chakraborty S 2013 Non-conventional optimization techniques in optimizing non-traditional machining processes: a review Manage. Sci. Letters. vol 3 pp 23-38

[5] Hoang K T and Yang S H 2015 Kerf analysis and control in dry micro-wire electrical discharge machining Int. J. Adv. Manuf. Technol. vol 78 pp 1803-1812

[6] Ghodsiyeh D, Golshan A, and Shirvanehdeh J A 2013 Review on current research trends in wire electrical discharge machining (WEDM) Indian J. Sci. Technol. vol 6 pp 4128-4140

[7] Di S, Chu X, Wei D, Wang Z, Chi G, and Liu Y 2009 Analysis of kerf width in micro-WEDM Int. J. Mach. Tool. Manu. vol 49 pp 788-792

[8] Okada A, Uno Y, Onoda S, and Habib S 2009 Computational fluid dynamics analysis of working fluid flow and debris movement in wire EDMed kerf CIRP Ann. Manuf. Techn. vol 58 pp 209-212

[9] Mahapatra S S and Patnaik A 2006 Parametric optimization of wire electrical discharge machining (WEDM) process using Taguchi method J. Barz. Soc. Mech. Sci. & Eng. vol 28 pp 422-429

[10] Durairaj M, Sudharsun D, and Swamynathan N 2013 Analysis of process parameters in wire EDM with stainless steel using single objective Taguchi method and multi objective grey relational grade Procedia Eng. vol 64 pp 868-877

[11] Somashekhar K P, Ramachandran N, and Mathew J 2010 Material removal characteristics of microslot (kerf) geometry in μ-WEDM on aluminum Int. J. Adv. Manuf. Tech. vol 51 pp 611-626

[12] Tosun N, Cogun C, and Tosun G 2004 A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method J. Mater. Process. Tech. vol 152 pp 316-322

[13] Pandaa A K and Singh R K 2013 Optimization of process parameters by Taguchi method: catalytic degradation of polypropylene to liquid fuel Int. J. of Multidisciplinary and Current Research pp 50-54.