Micro Dry Wire EDM: Kerf Investigation using Response Surface Methodology

Mohammad Yeakub Ali¹ *, Asfana Banu², Mohamed Abdul Rahman², Muataz Hazza Al Hazza³ and Ahmed Ghalib Khan Chowdhury²

¹ Mechanical Engineering Programme Area, Faculty of Engineering, Universiti Teknologi Brunei, Tungku Highway, Gadong BE1410, Brunei Darussalam
² Department of Manufacturing and Materials Engineering, Faculty of Engineering, International Islamic University Malaysia, P.O. Box 10, 50728 Kuala Lumpur, Malaysia
³ Mechanical and Industrial Engineering Department, School of Engineering, American University of Ras Al Khaimah, PO Box 10021, United Arab Emirates

*Contact E-mail: yeakub.ali@utb.edu.bn

Abstract. Dry electrical discharge machining (DEDM) is an environmentally friendly and green machining process where it uses gas as the dielectric fluid instead of liquid. It is an alternative to the conventional electrical discharge machining (EDM) process. However, kerf variation remains as a critical issue in micro dry wire EDM (µDWEDM) process. Therefore, the objective of this research is to investigate kerf in µDWEDM using response surface methodology (RSM). The experimental investigation was perform using an integrated multi process machine tool, DT 110 (Mikrotools Inc., Singapore). Stainless steel (SS304), tungsten wire, and compressed air were used as the workpiece, electrode, and dielectric fluid respectively. Central composite design (CCD), a type of RSM, was used to design the experiment using two controlled parameters which were capacitance and gap voltage. Analysis of variance (ANOVA) was used to analyse the results and to evaluate the adequacy of the developed model. The results were obtained by measuring the kerf using scanning electron microscope (SEM) (JEOL JSM-5600, Japan). An empirical model has been developed, and it was found that both parameters; capacitance and gap voltage have high influence on kerf. The optimum parameters for minimum kerf were found to be 0.1 nF capacitance and 91 V gap voltage. The developed model was found to be adequate since the percentage error was relatively small (≈ 2%).

1. Introduction

Dry electrical discharge machining (DEDM) is a type of green electrical discharge machining (EDM) process where gas is used as the dielectric fluid instead of liquid [1-3]. This process was introduced as an alternative to reduce fire hazard, health hazard to the operators, and environmental problems [3,4-5]. In DEDM, the gas is supplied through a pipe electrode where sparks are generated between the workpiece and the electrode [6]. This machining technique is also applicable in micro level such as micro dry EDM (µDEDM) and micro dry wire EDM (µDWEDM) [1-3, 6]. µDWEDM is able to produce high accuracy finishing cut since it has the ability to generate craters with small volumes. This situation happens due to the limited gap distance between the wire and the workpiece and negligible process reaction force during the machining operation [7].

Due to the non-contact in nature, µDWEDM is considered as a promising process for
microfabrication of miniaturized products. However, one of the main concerns on this type of machining is the dimensional accuracy of the machined parts [8-9] which is related to kerf; width of the machined slots [10-11]. 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 causes a lack of precision at the machined area which affects the dimensional accuracy. It frequently happens during rough cuts when high discharge energy is used [8-9, 12]. However, the wire behaviour during the machining operation is still unclear due to their unsteady and very high-speed phenomenon in narrow machined kerf [13]. Therefore, the main objective of this research is to investigate kerf in µDWEDM using response surface methodology.

2. Methodology
The workpiece and the electrode used were stainless steel (SS304) plate (30 mm × 20 mm × 0.5 mm (t)) and tungsten (W) wire (Ø 70 µm) respectively. Stainless steel is desirable to fabricate micro-fins for electronic components [1] while tungsten wire is desirable due to its ability in fabricating high tolerance small features with high accuracy [1]. Central composite design (CCD); a second-order design of response surface methodology (RSM); was utilized to investigate the kerf in µDWEDM using capacitance and gap voltage as the controlled parameters as shown in Table 1. The total number of experiments were 13 (Table 2) with four factorial points (2² = 4), four axial points (2k = 2(2) = 4), and five centre points.

| Controlled Parameters | Symbol | Coded Levels |
|-----------------------|--------|--------------|
|                       |        | -1 | 0 | +1 |
| Capacitance (nF)      | c      | 0.1 | 1.0 | 10.0 |
| Gap voltage (V)       | v      | 80 | 95 | 110 |

Table 1. µDWEDM experimental parameters using CCD

| Fixed Parameters |
|------------------|
| Workpiece, thickness (µm) | Stainless steel (SS304), 500 |
| Wire electrode material, diameter (µm) | Tungsten, 70 |
| Machining length (µm) | 300 |
| Dielectric fluid | Compressed air |
| Dielectric fluid pressure (MPa) | 0.0345 |
| Workpiece polarity | +ve |
| Threshold voltage (%) | 24 |
| Wire tension (N) | 0.0809 |
| Wire feed rate (µm/sec) | 0.2 |
| Wire speed (rpm) | 0.6 |

The workpiece was grounded manually using 320, 400, 600, and 800 grades of sand papers respectively for sample preparation. Then, the workpiece was cleaned using ultrasonic cleaning machine (BRANSON 2510, Virginia) for 5 minutes with ethanol as the cleaning media. After the completion of the sample preparation, µDWEDM process was conducted using an integrated multi process machine tool DT-110 (Mikrotools Inc., Singapore). Figure 1a shows the image of the machining setup during the machining process. The workpiece was cleaned once again in ethanol for 5 minutes using ultrasonic cleaning machine after the µDWEDM process was completed. The kerfs were measured at five different places along the microchannels (Figure 1b) using SEM (JEOL JSM-5600, Japan). The averages of the kerfs are tabulated in Table 2. The data analyses were carried out using ANOVA approach at 5% significance level [14].
Table 2. CCD for 13 runs of experiments

| Expt. No. | Parameters | Responses |
|-----------|------------|-----------|
|           | c: Capacitance (nF) | v: Gap Voltage (V) | Average Kerf (µm) |
| 1         | 1          | 95        | 83.20 |
| 2         | 1          | 110       | 96.74 |
| 3         | 0.1        | 80        | 86.04 |
| 4         | 0.1        | 95        | 82.34 |
| 5         | 1          | 95        | 85.32 |
| 6         | 1          | 95        | 86.64 |
| 7         | 10         | 110       | 103.60 |
| 8         | 10         | 80        | 92.46 |
| 9         | 10         | 95        | 91.86 |
| 10        | 1          | 95        | 88.38 |
| 11        | 0.1        | 110       | 87.12 |
| 12        | 1          | 95        | 87.34 |
| 13        | 1          | 80        | 87.54 |

Figure 1. (a) Machining setup during μDWEDM and (b) kerf measurement

3. Results and Analysis
The adequacy of the developed statistical model was check using ANOVA. Eqn. 1 was developed based on the response surface quadratic model which was considered statistically significant; Prob > F equals to 0.0082 and F-value equals to 16.55. The adequacy and the validity of the model is determined as significant when the model terms with Prob > F is less than 0.05 [15]. Therefore, factors $c$ (capacitance), $v$ (gap voltage), $c^2$ (capacitance), and $v^2$ (gap voltage) are the significant model terms. In addition, the $R^2$ value of 0.922 indicates that the model is sufficient in explaining most of the variability in the experiment results. This is because the $R^2$ value is more than 0.75 [8, 15]. The Predicted $R^2$ is in reasonable agreement with the Adjusted $R^2$ since the difference is within 0.1851 which is less than 0.2 [15]. The adequate precision of 15.298 indicates that the signal-to-noise ratio is adequate since the value
is greater than 4 [8, 10]. Hence, the model seems to be adequate to predict the behaviour of the kerf within the experimental constraints [8].

\[ Kerf = 290.867 + 3.719c - 4.574v + 0.023cv - 0.477c^2 + 0.025v^2 \]  

(1)

where, \( c \) = capacitance (nF) and \( v \) = gap voltage.

**Figure 2.** Diagnostic test for kerf based on (a) normal probability of residuals plot, (b) residuals vs. predicted plot; and (c) contour plot of kerf vs. gap voltage and capacitance.
Diagnostic test such as the analyses of the residuals were used to ascertain the adequacy of the developed model. Normally, adequate model shows the residual of the data is normally distributed and unstructured with constant variance [8]. Therefore, Figure 2a and Figure 2b shows the normal probability of residual plot and residual versus predicted plot respectively. In Figure 2a, the residual of the data is within the straight-line pattern where it shows the normality condition is satisfying. In addition, Figure 2b is considered adequate because the fitted values are dispersed randomly. Thus, it is anticipated that the variances of the original observations are constant for all the values [8].

Figure 2c shows the contour plot of kerf with gap voltage and capacitance. The figure shows, kerf is at the peak when the gap voltage is more than 104 V. It is due to the wire vibration [8, 10]. Usually, when higher discharge energy is employed, wire vibration will increase, and the kerf also increases causing poor accuracy [8-9]. Wire vibration occurs due to the forces acting during the machining process such as the hydrodynamic forces from the flushing system, the electrostatic forces that act on the wire, and the electromagnetic forces from the spark generation [1, 9]. Therefore, generally, in µDWEDM, the wire vibration is considered minimum compared to the conventional µWEDM [8].

The relationship between the controlled parameters; capacitance and gap voltage; together with the kerf were analysed for the optimal condition using Eqn. 1. The optimal condition suggested that minimum kerf, 81.20 µm is obtainable at 0.1 nF capacitance and 91 V gap voltage with the desirability of 97.8%. The model was verified by conducting the experiment based on the optimized parameters. From the experiment, the actual value of kerf (82.84 µm) is higher compared to the optimized kerf with maximum error of 2.02%. The percentage error is relatively small which indicates that the developed model is significant [8].

4. Conclusions
This research investigate kerf in µDWEDM using RSM. CCD, a type of RSM, was used to design the experiments using capacitance and gap voltage as the controlled parameters. An empirical model was developed. The parameters obtained from the optimization were also verified by another set of experiments. This investigation showed:
1. Capacitance and gap voltage have strong influence on kerf. Discharge energy is one of the reasons that causes the wire to vibrate and affect the accuracy of the kerf.
2. It was found that the optimum values of process parameters for minimum kerf are 0.1 nF capacitance and 91 V gap voltage.
3. The percentage error for the predicted value and the experimental value for kerf was found to be relatively small (≈ 2.02%). Therefore, the developed model is satisfactory.

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