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Analysis of Corner Radius in Dry Micro WEDM

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***Abstract*— Dry micro WEDM is a machining process where gas is used as the dielectric medium instead of liquid. This process favored for its environmental friendly nature and its ability in machining complex intricate shapes with great precision. Regardless of its high precision, the machining precision of cutting sharp corners cannot be satisfied. Therefore, the purpose of this paper is to analyze the process parameters; gap voltage, wire tension, and air dielectric pressure to find the optimal parameters to minimize the radius during the sharp corner cutting of stainless steel workpiece. Compressed air was used as the dielectric fluid, whereas the electrode was a 70 micrometer tungsten wire. The experiments were design using full factorial method while the data were analyzed using analysis of variance (ANOVA). Based on ANOVA, gap voltage and wire tension had a major influence on the corner radius. The optimum parameters for minimum corner radius were found to be 85 V gap voltage, 0.16 N wire tension, and 0 MPa dielectric pressure.**

***Index Terms*—Corner radius, dry WEDM, dry micro WEDM**

I. Introduction

As the demand microscopic products and parts have increased across various fields, micromachining technology has become a key issue in the production of micro-components. Among micromachining technologies, micro electrical machining technologies such as electrical discharge machining (EDM) (Fig. 1) has been investigated by numerous researchers worldwide because of their exclusive advantages. Due to capability of producing high precision and good surface quality parts, EDM is potentially an important process for the fabrication of micro-tools, micro-components and parts with micro-features. EDM has a high capability of machining the accurate cavities of dies and molds. As EDM is based on a contactless process between the tool electrode and the workpiece, only a small amount of force is exerted on both the tool and the workpiece [1-4]. This prevents the problem of tool deformation or breakage, making it appropriate for micromachining where tools of very small sizes are used. It also possesses the ability to machine hard materials, which is a difficult task to perform when using traditional machining technologies [1].

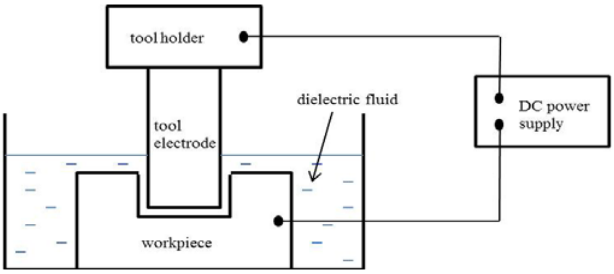

Figure 1. Schematic diagram of EDM [4].

Micro EDM is similar to the principle of macro EDM where the mechanism of the process is based upon an electro-thermal process relying on a discharge through a dielectric in order to supply heat to the surface of the workpiece [4]. However, micro EDM is particularly developed to manufacture components of less than 1 mm. Other alternative of micro EDM would be the micro wire EDM (micro WEDM) where wire is used as the tool in cutting the work material. The wire diameter is usually less than 0.1 mm. The wire moves between two guides, which execute on it the requirements of verticality [5].

Micro WEDM operates using a very small diameter electrode (Ø 20-70 μm) to cut a fine width of cut in the work material. The wire is extracted through the workpiece from a supply roll onto a receiving mechanism. Material is eroded from the work material by a sequence of discrete sparks that happens between the work material and the wire separated by a stream of dielectric [2-3]. Even though the material removal mechanism of micro WEDM may be similar to that of micro EDM, their functional features are quite different. Micro WEDM uses an exceptionally thin wire that constantly feeds through the workpiece by the functions of microprocessor. This allows for parts of complex shapes to be machined with excellent high accuracy [2].

WEDM disregards the need for elaborate pre-shaped electrodes, which are commonly used in conventional EDM for performing finishing operations. In WEDM, the wire has to make several machining passes along the profile to be machined to attain the desired dimensional accuracy and surface finish. The wire path is programmed by the user and controlled by the numerical control (NC) of the machine. The most significant control parameters are discharge current, wire tension, pulse duration, pulse frequency, discharge voltage, wire speed, discharge capacitance, and dielectric flushing condition [4].

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In conventional EDM, machining operations are performed in the presence of liquid dielectric fluids. The liquid dielectric commonly used in conventional EDM is hydrocarbon oil, which gives rise to fumes that can be hazardous to health when it is decomposed [4-7]. One of the effective ways of reducing harmful or hazardous effects on the environment is by replacing oil based liquids with gas as coolants or working media during the process of machining also known as dry EDM (Fig. 2) [8]. The gases commonly in use are nitrogen, oxygen, air etc. During the use of high velocity air, the high speed air runs in between the gaps, removing debris faster and in a more efficient manner. This high speed air not only allows for quick removal of debris from the gap, but also minimizes the excessive heating of the electrode. A quick recovery of the dielectric strength between the gaps can be ensured since the plasma created by the previous discharge can be blown off by the help of compressed air being flown through the gaps [6].

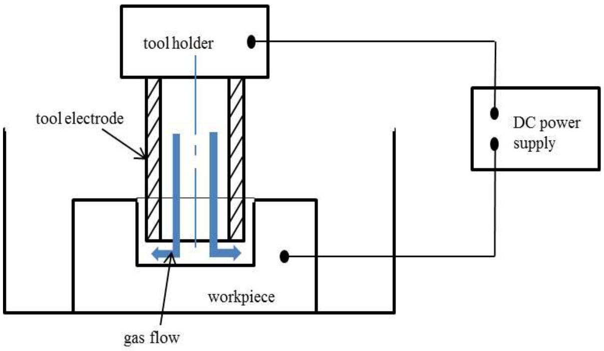


Figure 2. Schematic diagram of dry EDM [4].

Even though micro WEDM is a promising process for microfabrication with high precision, however, cutting sharp corners is a concern under micro WEDM technology. Micro WEDM has the tendency to produce a radius along the corner when trying to machine sharp 90 ° cut. Unbalance of external load, wire deflection, and discharge concentration are the three main causes of corner radius inaccuracy that have been tested and analysed. In WEDM process, the wire electrode suffers various forces of different nature and directions such as discharge spark force and hydraulic forces. Hydraulic forces push the wire electrode back of the machining path due to flushing, gas spreading, and bursting the discharge spark force is the resultant force of material removing force and discharge pressure, and its value depends on the characteristic of material and the process parameters. In addition, the discharge spark force is the major cause of wire electrode deflection and vibration [9].

Even though the wire electrode may be tiny and flexible, it is also with some rigidity under weak discharge spark force in fact. In the actual machining process, the wire centre always is pulled back of the machining path; the wire lag has insignificant impact on straight path machining precision, while deflection and vibration are the major causes of the corner error. These problems can be reduce by controlling the machining parameters [10]. Hence, the objective of this paper is to analyse the effect of the process parameters; gap voltage, wire tension and air dielectric pressure; and find the optimal setting of parameters to minimize the radius during the sharp corner cutting of stainless steel workpiece.

II. METHODOLOGY

Full factorial method was used to design the experiment where there was three factors were involved. One factor involved two levels and the other two factors involved three levels, producing a total of 18 (3x3x2) experimental runs. The controlled parameters were gap voltage, wire tension, and air dielectric pressure. Both gap voltage and wire tension involved three levels, whereas air dielectric pressure involved only two levels. The experiments were conducted on a stainless steel (13 mm × 30 mm × 0.25 mm) using micro WEDM with multi-process micro machine tools, DT-110 (Mikrotools Inc., Singapore). Stainless steel is usually used in most of the industrial application including miniaturize products such as micropillars [11-12]. Tungsten wire with 70 µm was used as the tool electrode. Tungsten has a high tensile strength and load-carrying capability [11, 13]. The experimental parameters are listed in Table 1.

After machining was performed, an ultrasonic cleaning machine was used to clean the workpiece under ethanol for 5 minutes. The specimen was magnified x350 under the scanning electron microscope (SEM) to allow for more accurate measurement. The above process was repeated for each machining performed thereafter. Fig. 3 shows the method of measurement of the corner radius. The radius of the corner was measured using the circle tool in the SEM. Two tangent lines were drawn along the edges of the part that was machined to determine the two tangent points from which the curve was starting. The tangent points were used to pinpoint the center of the radius, from which a circle could be drawn up to the edge of the curve. The SEM only displays the diameter value, so it had to be divided by two to obtain the radius. The measured and calculated results for the corner radius are tabulated in Table II.

TABLE I. EXPERIMENTAL PARAMETERS

Controlled Parameters	**Factor**	**Level**		
		I	**II**	**III**
Gap voltage (V)	v	85	100	115
Wire tension (N)	t	0.08	0.12	0.16
Air dielectric pressure (MPa)	p	0	0.04	-
Fixed Parameters				
Workpiece material	Stainless steel 304			
Tool electrode	Tungsten			
Dielectric fluid	Compressed air			
Capacitance (µF)	0.4			
Threshold (%)	24			
Wire speed (rpm)	0.7			
Wire feed (µm/s)	0.2			

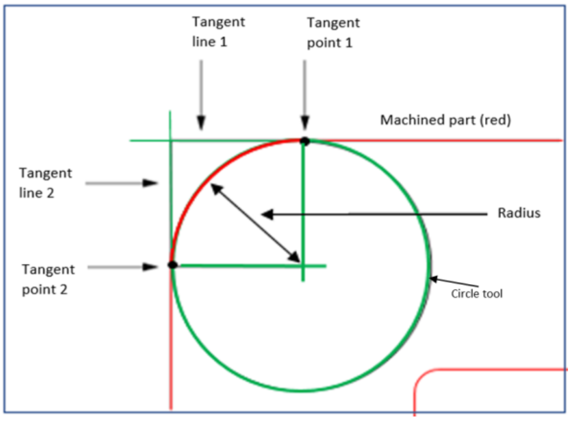


Figure 3. Corner radius measurement.

TABLE II. EXPERIMENTAL RESULTS FOR CORNER RADIUS

Exp.	Controlled parameters			Response
	Gap voltage (V)	Wire tension (N)	Air dielectric pressure (MPa)	Corner radius (μm)
1	85	0.08	0.00	43.145
2	100	0.08	0.00	51.430
3	115	0.08	0.00	58.570
4	85	0.12	0.00	42.000
5	100	0.12	0.00	43.710
6	115	0.12	0.00	48.090
7	85	0.16	0.00	38.100
8	100	0.16	0.00	40.000
9	115	0.16	0.00	46.000
10	85	0.08	0.04	42.000
11	100	0.08	0.04	46.060
12	115	0.08	0.04	56.290
13	85	0.12	0.04	39.350
14	100	0.12	0.04	42.290
15	115	0.12	0.04	48.850
16	85	0.16	0.04	39.143
17	100	0.16	0.04	45.950
18	115	0.16	0.04	46.570

III. ANALYSIS AND DISCUSSIONS

Analysis of variance (ANOVA) approach was used to check the sufficiency of the model as shown in Table III. The model was developed with 95% confidence level. The F-value of 19.19 implies that the model is significant. There is only 0.01% chance that the F-value could occur due to noise. Values of Prob>F less than 0.05 indicate that the model terms *v* (gap voltage), *t* (wire tension), *vt* (gap voltage and wire tension), and *tp* (wire tension and air dielectric pressure) are found to be significant [11]. Values greater than 0.1000 indicate the model terms are not significant. Looking at the Prob>F, the factor *v* (gap voltage) and factor *t* (wire tension) are the most influential on corner radius. The Prob>F for *v* (gap voltage) and *t* (wire tension) indicate that they have more than 99% confidence level.

The Prob>F for *vt* (gap voltage and wire tension) and *tp* (gap voltage and air dielectric pressure) has a confidence level of at least 96% thus showing these factors have a very good influence on the corner radius as well. Based on ANOVA, the insignificant factors are *p* (air dielectric pressure) and *vp* (gap voltage and air dielectric pressure) with values of 0.6079 and 0.8077 respectively. The "Pred R-Squared" of 0.7589 is in reasonable agreement with the "Adj R-Squared" of 0.8653. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 14.981 indicates an adequate signal. This model can be used to navigate the design space [14]. The mathematical model in terms of actual factors is expressed in Eq. (1).

TABLE III. ANOVA FOR CORNER RADIUS

Source	Sum of Squares	Degrees of Fredom	Mean Square	F-Value	Prob>F
Model	501.08	6	83.51	19.19	< 0.0001
v - Gap voltage	306.35	1	306.35	70.41	< 0.0001
t - Wire tension	145.13	1	145.13	33.36	0.0001
p - Air dielectric pressure	1.15	1	1.15	0.26	0.6179
vt	25.88	1	25.88	5.95	0.0329
vp	0.27	1	0.27	0.062	0.8077
tp	22.30	1	22.30	5.12	0.0448
Residual	47.86	11	4.35		
Cor Total	548.94	17			

Std. Dev.	2.09	R-Squared	0.9128
Mean	45.42	Adj R-Squared	0.8653
C.V.	4.59	Pred R-Squared	0.7589
PRESS	132.34	Adeq Precision	14.981

$$CR = -8.459 + 0.687v + 178.729t - 267.147p - 2.998vt + 0.501vp + 1703.958tp \quad (1)$$

where, *CR* = corner radius (μm), *v* = voltage (V), *t* = wire tension (N), and *p* = air dielectric pressure (MPa).

Fig. 4a shows the model for the predicted vs actual chart is very accurate, there's a strong correlation between the model's predictions and its actual results. In Fig. 4b, each point is one run, where the prediction made by the model is on the x-axis, and the accuracy of the prediction is on the y-axis. The distance from the line at 0 represents the inaccuracy of the prediction for that particular value [15]. Positive values for the residual (on the y-axis) mean the prediction was too low, and negative values mean the prediction was too high; 0 means the guess was exactly correct. It can be said that the plot in Fig. 4b is quite ideal because the points are pretty much evenly distributed. They're clustered around the lower single digits of the y-axis and there aren't any clear patterns within the plot [16].

Fig. 5a is a graph that displays the relationship between the air dielectric pressure and gap voltage. The graph shows virtually no interaction between the two parameters. The gap voltage happens to be the main effect because the value of corner radius is significantly reduced as gap voltage is reduced. The effect of air dielectric flow remains pretty much constant throughout. The reason why a bigger gap voltage causes larger radius is because bigger sparks are produced which causes more material erosion, thus increasing the width of the cut. This causes the corner edge to be further away from the electrode [7].

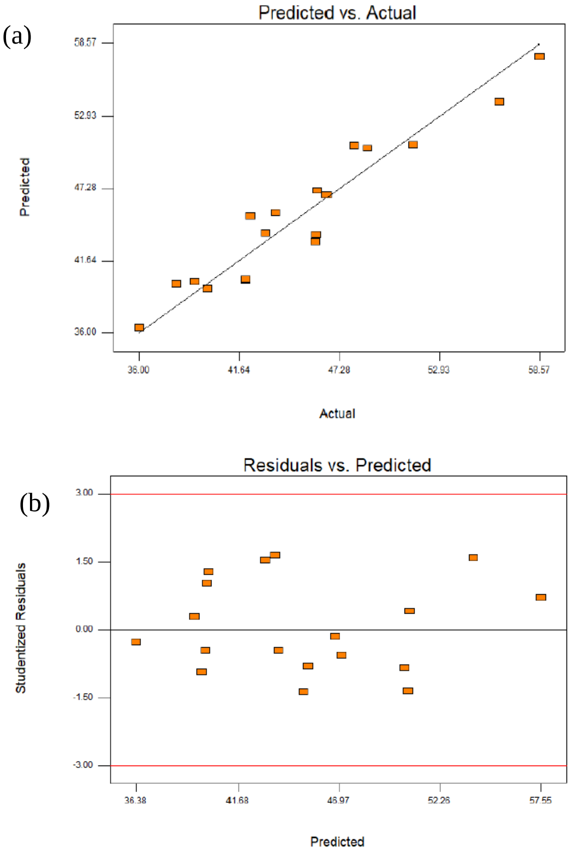
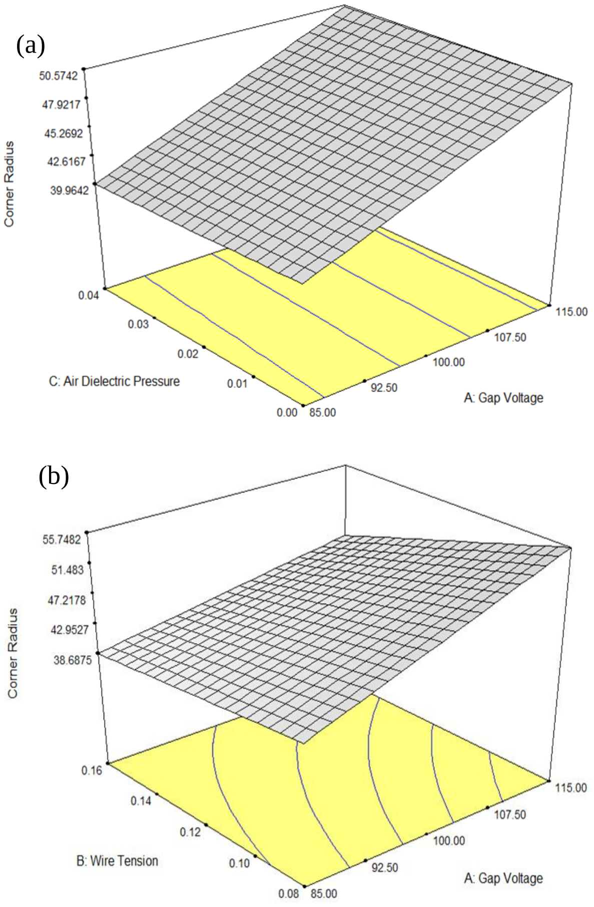


Figure 4. (a) Predicted vs. actual plot and (b) residual vs predicted plot.



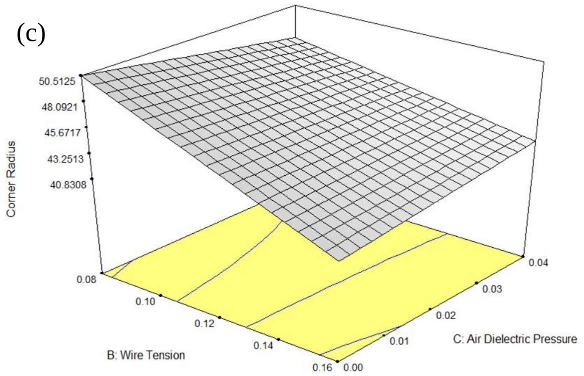


Figure 5. Three dimensional plot of corner radius with (a) air dielectric pressure and gap voltage, (b) wire tension and gap voltage, and (c) wire tension and air dielectric pressure.

Fig. 5b shows the relationship between wire tension and gap voltage. It can be seen that when wire tension is increased and gap voltage is at its lowest, there is a very minimal reduction in the value of the corner radius, there isn't much change. The corner radius value is at its highest when the wire tension is at its lowest and gap voltage is highest. It can be observed that as wire tension increases, corner radius reduces; and as voltage increases, corner radius also increase. But the effect of gap voltage is observed to have a more significant effect than wire tension. There is a study shows that wire amplitude and vibration is a major cause of dimensional inaccuracy as more material erosion is involved. It has been shown that increase in voltage increases wire vibration [10]. Besides that, when the wire tension is higher, the lesser the wire lag and wire vibration. This helps by not removing excess material from the workpiece and the distance from the wire to the cutting edge remains small. Therefore, a higher wire tension is suitable in machining sharp corners [9].

Fig. 5c reveals relationship between wire tension and air dielectric pressure. As wire tension increases, it shows significant drop in corner radius value regardless of the air dielectric pressure value. But the value of corner radius does increase slightly with the increase of air dielectric pressure. The amount of dielectric pressure can be a significant cause of wire vibration [17]. From the above analysis, it can be concluded that the major cause of larger radius is due mainly to wire vibration and that gap voltage and wire tensions are the factors which play the most significant roles.

IV. OPTIMIZATION AND VERIFICATION

The ANOVA-based optimization for minimum corner radius was 38.05 µm with 85.25 V gap voltage, 0.16 N wire tension, and 0.01 MPa air dielectric pressure. Experiment was conducted three times for verification using results from the optimization. The actual values obtained from the experiments were compared with the optimized results. The average minimum corner radius has increased from 38.05 µm to 38.636 µm with an error percentage of 1.55%. The percentage error of the corner radius is relatively small so the empirical model is significant.

V. CONCLUSION

The purpose of this study is to analyse the process parameters; gap voltage, wire tension, and air dielectric pressure to find the optimal parameters to minimize the radius during the sharp corner cutting of stainless steel workpiece. ANOVA approach was used for analysis of minimum corner radius and a mathematical equation was developed. To conclude, this study shows that:

1. Based on the experiment, the minimum corner radius was found to be 38 µm with 85 V voltage, 0.16 N wire tension and 0 MPa air dielectric pressure.
2. Based on the ANOVA, corner radius was strongly influenced by voltage and wire tension.
3. The model predicts minimum radius (38.05 µm) for 85 V voltage, 0.16 N wire tension and 0 MPa air dielectric pressure. The predicted value and experimental corner radius is within 1.5%.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Ahmed Ghalib did the experimental and analytical works with the guidance of Asfana Banu. They together wrote the paper. The whole work was supervised by Mohammad Yeakub Ali. All authors had approved the final version.

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