Investigation of Taper Angle in Dry Micro Wire EDM

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Abstract**—Dry micro wire EDM have been introduced to fabricate complex micro parts with high accuracy. It is a process where gas is used instead of liquid as the dielectric fluid. However, in order to achieve high accuracy, taper angle remains as one of the critical issues. Hence, this paper investigates the effect of process parameters; gap voltage and wire tension; on taper angle in dry micro wire EDM on stainless steel using compressed air as dielectric fluid and tungsten as wire electrode. Empirical model using general factorial method was developed for the estimation of taper angle. Based on the ANOVA, gap voltage has major influence on taper angle. The optimum machining parameters for minimum taper angle were found to be 85 V gap voltage and 14 % wire tension.**[1]

Index Terms**—dry wire EDM, dry micro wire EDM, taper angle, accuracy**

I. INTRODUCTION

The increasing demands for miniaturized products especially in biomedical, electronics, and aerospace industry have obliged the manufacturers to fabricate complex micro parts with high accuracy and nano surface finish using electrical discharge machining (EDM) [1-2]. EDM is a non-traditional and non-contact machining operation where electrical energy is used to produce a series of discrete sparks between the tool electrode and the workpiece. Compared to the other traditional machining method, EDM offers a precise solution since the material removal does not affects the mechanical properties of the workpiece. The machining operation is performed in the presence of liquid dielectric fluids which are commonly mineral oil-based liquid or hydrocarbon liquids. The dielectrics act as a deionizing medium for the electrodes that ensures an optimal condition for sparks generation as well as flushes away the debris from machining gap [1-6].

However, these dielectric fluids have certain weaknesses where it can cause fire hazard, generate toxic and non-recyclable dielectric waste, generate toxic fumes, and pose a health hazard to the operators [4, 7-9]. Hence, researchers came up with a solution to apply green manufacturing method through EDM process where it is known as the dry EDM.

Dry EDM is a method where gas is used as the dielectric fluid instead of the liquid dielectric fluid [1-2, 4, 7, 10-11]. This dry technique is also applicable for micro fabrication applications for micro level machining process; dry wire EDM, micro dry EDM, and micro dry wire EDM [1-2, 7, 11-13]. Dry wire EDM also known as the wire EDM using dry dielectric fluid is a modification of the oil wire EDM operation where gas is used as dielectric fluid instead of liquid. The high pressure gas helps to eliminate the debris and avoids excessive heating between the wire and the workpiece at the discharge gap [1-4, 7, 14-18].

However, this machining method has several limitations such as low MRR, poor sharp cutting edge, and high debris deposition [8, 14]. Even though this type of machining operation has some limitation, but it also has quite a number of advantages. Lower tool wear, better surface quality, lower residual stresses, thinner white layer, as well as higher accuracy and precision in machining are some of the merits of this dry technique [3, 7, 14-18].

Micro dry wire EDM have the ability to produce finishing cut with high accuracy since the gap distance between the wire and the workpiece is narrow and the process reaction force during the machining operation is negligible compared to the conventional wire EDM [3, 14, 19]. Hence, some researchers suggested that dry wire EDM can be used for finish cut with high surface quality especially in manufacturing high precision dies and molds. This is because craters with smaller volumes are generated since the gases have low energy intensity [3, 18, 20].

Wire EDM and micro wire EDM are considered as a promising process for microfabrication of miniaturized products. However, one of the main concerns on this type of machining operation is the accuracy of the machined parts which can be affected by the taper angle. Taper angle occurs due to the wire deflection that happens during the machining operation. Wire deflection happens

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because of the straightness of the wire, distance between the guides, wire stiffness, and the geometry of the guide itself. However, these problems can be reduce by controlling the machining parameters [20-23]. Thus, the objective of this paper is to investigate the effect of the process parameters; gap voltage and wire tension; on taper angle in dry micro wire EDM on stainless steel using compressed air as dry dielectric fluid and tungsten as wire electrode.

II. Experiment and Measurement

General factorial of two factors with four levels (4^2) was used to design the experiments where the controlled parameters were the gap voltage and the wire tension. A total of 16 experiments were conducted on a stainless steel (13 mm × 30 mm × 0.25 mm) using micro wire EDM 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 for cooling purposes for electronic components [24-26]. Tungsten wire with 70 µm was used as the tool electrode since it has high tensile strength and load-carrying capability [27] while compressed air as the dielectric fluid. The experimental parameters are listed in Table I.

After machining, the workpiece was cleaned in ethanol for 5 min using an ultrasonic cleaning machine. Scanning electron microscope (SEM) was used to estimate the width of the machined slot. Fig. 1 shows the front view of the workpiece and the wire electrode and Fig. 2 shows the position of the measured width and taper angle while (1) is the equation use to calculate the taper angle. The measured and calculated results for slot width and taper angle are tabulated in Table II. Analysis of variance (ANOVA) approach was used to check the sufficiency of the model.

$$Taper\ Angle, \alpha = \tan\frac{(\frac{D-d}{2})}{t} \qquad (1)$$

where, D = width of the bottom machined slot, d = width of the top machined slot, and t = thickness of the workpiece.

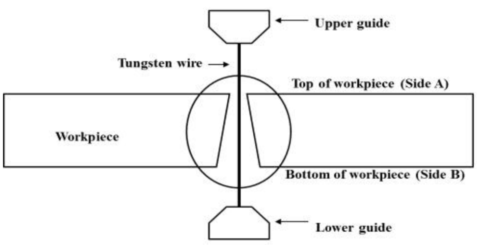

Figure 1. Front view of the workpiece and the wire electrode.

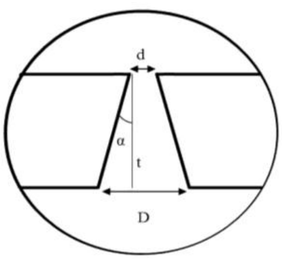

Figure 2. Position of the measured width and the taper angle.

TABLE I. Experimental Parameters

Control Parameters	Factors	Level I	Level II	Level III	Level IV
Gap voltage (V)	*v*	85	90	95	100
Wire tension (%)	*t*	10	12	14	16
Fixed Parameters:					
Workpiece material	Stainless steel S304				
Tool electrode	Tungsten wire (Ø 70 µm)				
Machining length (mm)	0.3				
Dielectric fluid	Compressed air				
Dielectric pressure (MPa)	0.0345				
Capacitance (µF)	0.4				
Threshold (%)	24				
Wire speed (rpm)	0.6				
Wire feed (µm/s)	0.2				

TABLE II. Experimental Results for Measured Width and Calculated Taper Angle

Expt.	Parameters: Gap voltage (V)	Parameters: Wire tension (%)	Response: Width (µm) Side A (d)	Side B (D)	Differences	Taper angle (°)
1	85	10	101.5	98.0	-3.5	-0.40
2	90	10	104.0	102.0	-2.0	-0.23
3	95	10	110.5	115.5	5.0	0.57
4	100	10	105.5	107.5	2.0	0.23
5	85	12	110.0	112.5	2.5	0.29
6	90	12	99.5	103.5	4.0	0.46
7	95	12	107.0	112.0	5.0	0.57
8	100	12	99.5	102.5	3.0	0.34
9	85	14	108.0	107.5	-0.5	-0.06
10	90	14	99.5	101.5	2.0	0.23
11	95	14	107.5	104.0	-3.5	-0.40
12	100	14	105.5	107.0	1.5	0.17
13	85	16	108.0	106.5	-1.5	-0.17
14	90	16	99.0	100.5	1.5	0.17
15	95	16	110.0	103.5	-6.5	-0.86
16	100	16	102.5	105.5	3.0	0.34

TABLE III. ANOVA for Taper Angle

Source	Sum of squares	DF	Mean Square	F value	Prob > F
Model	0.50	7	0.071	5.49	0.0143
v	0.21	1	0.21	16.39	0.0037
t	0.081	1	0.081	6.23	0.0371
v^2	0.14	1	0.14	10.71	0.0113
t^2	0.013	1	0.013	0.98	0.3518
vt	0.047	1	0.047	3.65	0.0923
v^3	0.18	1	0.18	13.72	0.0060
t^3	0.079	1	0.079	6.08	0.0390
Residual	0.10	8	0.013		
Cor Total	0.60	15			

Standard deviation	0.11	R^2	0.8278
Mean	0.34	Adjusted R^2	0.6771
Coefficient of variation	33.17	Predicted R^2	0.3515
Predicted residual error of sum of square (PRESS)	0.39	Adequate precision	7.522

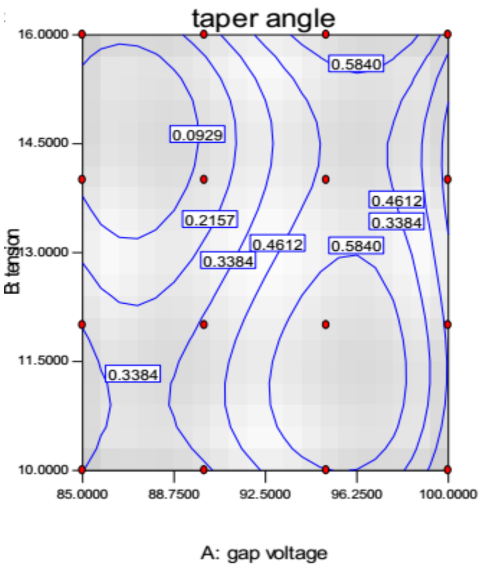

Figure 3. Contour graph of relationship between taper angle vs. wire tension and gap voltage.

III. Analysis and Discussions

Equation (2) is the developed model. ANOVA was used to check the adequacy of the developed statistical model. Based on Table III, the model F-value of 5.49 implies that the model is significant. This is due to less than 1.43 % chances of noise could occur in the model of F-value. Larger differences of the variation of the parameters or factors on the performance characteristics occur when the F-value is higher. Based on the F-values, factor *v* has the most influence on the taper angle with highest value of 16.39, followed by factor v^3, v^2, *t*, and t^3. The factors are significant when the values in the column Prob > F are less than 0.05 while values greater than 0.10 implies the factors are insignificant. Thus, based on ANOVA, the insignificant factors are *vt* and t^2 with values of 0.0923 and 0.3518 respectively. The Predicted R^2 of 0.3515 is in reasonable agreement with the Adjusted R^2 of 0.6771. Adequate precision measures the S/N ratio, where the ratio greater than 4 is preferable. The ratio of 7.522 designates that the signal is tolerable. As a result, this model can be used to navigate the design space.

$$\text{Taper angle} = 935.528 - 31.551v + 5.93t + 0.345v^2 - 0.503t^2 + 4.35\times10^{-3}vt - 1.257\times10^{-3}v^3 + 0.013t^3 \quad (2)$$

where, *v* = gap voltage and *t* = wire tension.

Fig. 3 shows the contour graph of wire tension and gap voltage on taper angle. Based on the figure, the taper angle is at the highest when the gap voltage is between 92.5 V to 100 V while the wire tension is between 10 to 13 % and 16 %. As a result, the accuracy of the machined slot is low. This situation is caused by the wire vibration and wire deflection. Generally, these problems happen due to the various forces acting on the wire during the machining operation. The forces are reaction forces from the pressure of the gas bubbles during the erosion mechanism, hydrodynamic forces because of the flushing system, the electrostatic forces that act on the wire, and the electromagnetic forces from the spark generation [20, 23, 28-30]. Moreover, when higher gap voltage is used, the discharge energy tends to be high. Hence, this may lead to the increment of wire vibration that will deteriorate the accuracy of the machined slot [20, 22-23]. However, wire vibration in dry wire EDM is still considered minimum since the process reaction force is negligible compared to the conventional wire EDM [18]. The accuracy is better when high tension with low gap voltage is used since the lowest taper angle value (0.0929 °) is possible to be attained.

IV. Optimization and Verification

The ANOVA-based optimization was done in order to get optimum values of the parameters for minimum taper angle. The minimum taper angle was 0.0246 ° with 85 V gap voltage and 14 % wire tension. The model was verify by conducting experiment based on the optimized parameters. Based on the experiment, the actual taper angle (0.0229 °) were higher compared to the optimize taper angle with maximum error of 7.42 %. The percentage error of minimum taper angle are relatively small which shows the empirical equation is valid.

V. Conclusions

The dry micro wire EDM was successfully performed in this study, and open opportunities in machining miniaturize products with higher accuracy. ANOVA was used to analyzed the influences of the two parameters, gap voltage and wire tension on taper angle. The following conclusions are drawn from the experimental study:

1. Based on the ANOVA, the taper angle is strongly influence by the gap voltage. The taper angle is at lowest when low gap voltage is used. This is because wire deflection is less during the machining operation.
2. The model predicts minimum taper angle (0.0229 °) when 85 V gap voltage and 14 % wire tension are used. The predicted value and experimental taper angle value is within 7.42 % error.

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