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Micro Wire Electro Discharge Grinding: Optimization of Material Removal Rate and Surface Roughness

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Abstract. This paper presents the analysis and modelling of material removal rate (MRR) and surface roughness (R_a) by micro wire electro discharge grinding (micro-WEDG) with control parameter of gap voltage, feed rate, and spindle speed. The data were analyzed and empirical models are developed. The optimized values of MRR and R_a are 0.051 mm^3/min and 0.25 µm respectively with 110 V gap voltage, 38 µm/s feed rate, and 1315 rpm spindle speed. The analysis showed that gap voltage has significant effect on material removal rate while spindle speed has significant effect on surface roughness.

1. Introduction

Micro manufacturing field continuously improved from few decades before due to encouragement by increase in demand on micro scale products. Thus, scaling down the traditional macro-manufacturing process to micro- manufacturing is continuously developing in order to improve its efficiency as well as accuracy [1].There are various techniques in order to produce multiple types of micro- products. Micro- electromechanicals systems (MEMS) particularly comprises of techniques such as photolithography, LIGA, laser fabrications, etc. while non-MEMS based manufacturing techniques involves mechanical machining, EDM, laser cutting, and etc. Micro wire electro discharge grinding (micro-WEDG) is one of the non-MEMS based manufacturing [1]. In micro-WEDG the uses of grinding wheel is replaced with micro wire which acts as an electrode. When fine rod need to be ground, it acts as a workpiece and allowed to be rotated while the electrode (micro wire) is held stationary. This process utilizes the electrical sparks or thermal energy produced to remove the unwanted materials from the workpiece in order to make the desired shape. The electrode is fixed on the table, and the table is controlled to give the feed. This process is broadly used for forming very thin rods with high-aspect ratio, which can be used as tool electrodes for micro-EDM drilling or milling (micro-tools) as well as micro- parts [2]. Comparing the usage of grinding wheel with WEDM, WEDM is more flexible.

In order to enhance the performance of WEDG particularly in accuracy and repeatability, special wire guide mechanism need to be applied. Usage of wire guide was introduce where machining accuracy is not sufficient enough for aiming size of rod around Ø50 µm. This due to wire vibration amplitude which range 10 µm and more also due to wire deviation produced by original curl or by machining force [2].The concept of wire guide is there is no vibration and wire deviation at point where the wire contacts with the wire guide. Besides that, suitable tension of wire is required in order to keep contact with the wire guide. However, excessive high tension applied is not necessary as long as the middle part of the wire is fix by the tension applied. High material removal rate (MRR) is achieved at maximum during rough-cut stage. This is due to increasing in energy in each discharge produce, which depends on the energy stored by the capacitor, this theory is based on Eq.1. Meanwhile, during finish cut, lower voltage is used in order to produce good surface finish [3].

$$\boldsymbol{E = \frac{1}{2}\, CV^2} \tag{1}$$

where, E = diacharge energy, C = capacitance, and V = voltage

Mefuz et al. (2008) investigated in the influence of feed rate, capacitance, and voltage on five response variables, which are surface roughness, maximum peak-to valley roughness height, tool wear ratio, and material removal rate. Based on the research, capacitance and voltage are the most influential factor on surface roughness; meanwhile, for MRR it was found that feed rate, capacitance, and voltage carries significant effect in order to increase MRR [4]. The same results also obtain by Periyanan et al. (2011), by using Taguchi method as design of experiment found that feed rate, capacitance, and voltage have significant effects on MRR in micro-WEDG [5]. Thus, the objective of this paper is to investigate the MRR and R_a with three varying parameters, gap voltage, feed rate, and spindle speed.

2. Experiment

Taguchi's L9 orthogonal array statistical approach was used to design the experiment with a total of 9 experiments. The experiments were conducted using micro-WEDG machine, DT-110 Mikrotools (Mikrotools Inc., Singapore) to complete the analysis of MRR and R_a. The experimental parameters are shown in Table 1 with controlled parameters; gap voltage, feed rate, and spindle speed. The workpiece used was tungsten rod with 1.00 mm diameter and copper wire as the electrode wire. Before an experiment is started, tungsten rod is cut into length of approximately 20 mm. After that, the weight of the workpiece is measured using electronic balance in order to obtain its initial weight. Then, air gun was used to dry the workpiece after the experiment is done to obtain its final weight. These steps were repeated for all the remaining experiments. Alicona Infinite Focus (Alicona Imaging, Austria) was used to determine the R_a value of the machined area. The coaxial white light produce by light source which then delivered through a beam splitter to a series of selectable, infinity-corrected objectives contained in a six-place turret. Fine light produced is then used to focus on workpiece. After that, the workpiece reflects the light back and projected through the beam splitter on colour digital sensor, thus resulting image which similar to conventional light microscope. All the data are tabulated in Table 2. The results were analyzed using analysis of variance (ANOVA) approach. Analysis of variance (ANOVA) approach was used to check the adequacy of the model. The analysis mainly intended to shows the interaction effects of the process variables on the responses. Main effect was the direct effect of independent variables while interaction effect was the join effect of two independent variables of the responses.

3. Analysis and Discussions

3.1 Material removal rate (MRR)

The developed model is shown in Eq. 2. Based on ANOVA, the model was developed based on 95% level of confidence and the model shows F-value of 8.77 indicates the model is significant. There is small influence, 2.93% of noise on the model developed. Furthermore, F-value and Prob> F proves that factor v and interaction effects of fn are the most influential factors on MRR by indicating the Prob>F value less than 1%. The Prob> F value of interaction effects of fn shows the above 95% level of confidence which express this interaction brings great impact on MRR. For MRR, inverse transformation was used for developing the model as shown in Eq. 2.

$$1/\mathrm{MRR} = 365.33 - 4.61v + 6.31f + 0.15n - 5.57 \times 10^{-3}fn \quad (2)$$

where, MRR = material removal rate (mm^3/min), v = voltage (V) and f = feed rate (μm/s)

Furthermore, as mentioned above, voltage have great influence on MRR because when higher energy spark strikes, larger amount of material was removed by melting and evaporation [6]. Figure 1a shows the sugar colour graph of machined area obtain by using Alicona surface roughness machine when 110 V gap voltage, 30 μm/s feed rate, and 500 rpm spindle speed were used. The graph helps to shows the levels of the peaks presence on the surface of the workpiece by different colour labels. Figure 1b shows the contour graph of 1/MRR against the feed rate and spindle speed. With the increase in feed rate from 20 µm to 30 µm and increase in spindle speed 500 rpm to 1000 rpm causes reduction in MRR value, but as the feed rate further increase to 40 µm and spindle speed increase to 1500 rpm, the value of MRR increase. This is because as increase in speed of rotating workpiece, the amount of eroded volume per crater also increases [7]. Besides that, when more speed is applied, the discharge energy is better and melts more material.

Table1. Experimental parameters

Control Parameters	Factor	Unit	Level I	Level II	Level III
Gap voltage	*v*	V	100	105	110
Feed rate	*f*	µm/sec	20	30	40
Spindle speed	*n*	rpm	500	1000	1500
Fixed Parameters:					
Workpiece material		Tungsten (Ø 1.00 mm)			
Wire electrode		Copper wire			
Capacitance (µF)		0.4			
Polarity		Workpiece positive			
Dielectric fluid		EDM-3			
Threshold (%)		25			

Table 2. Experimental results

Expt	Parameters: Gap voltage, *v* (V)	Feed rate, *f* (µm/s)	Spindle speed, *n* (rpm)	Response: Time taken , t (min)	Δ Weight, w (g)	MRR (mm^3/ min)	R_a (µm)	MRR S/N value	R_a S/N value
1	110	20	1500	8.70	0.004	0.0230	0.4107	-32.7654	9.7144
2	110	30	500	27.5	0.0134	0.0257	1.285	-31.8013	-2.1794
3	110	40	1000	21.9	0.009	0.0222	0.3268	-33.0729	7.7295
4	100	20	1000	23.11	0.0106	0.0238	0.5638	-32.4685	-5.0885
5	100	30	1500	22.02	0.0103	0.0242	0.3933	-32.3237	8.1055
6	100	40	500	51.72	0.0112	0.0111	1.7965	-39.0935	4.9775
7	105	20	500	27.86	0.0112	0.0207	1.1877	-33.6806	11.6108
8	105	30	1000	51.97	0.0110	0.0110	0.2957	-39.1721	10.5830
9	105	40	1500	22.68	0.0103	0.0232	0.2627	-32.6902	11.6108

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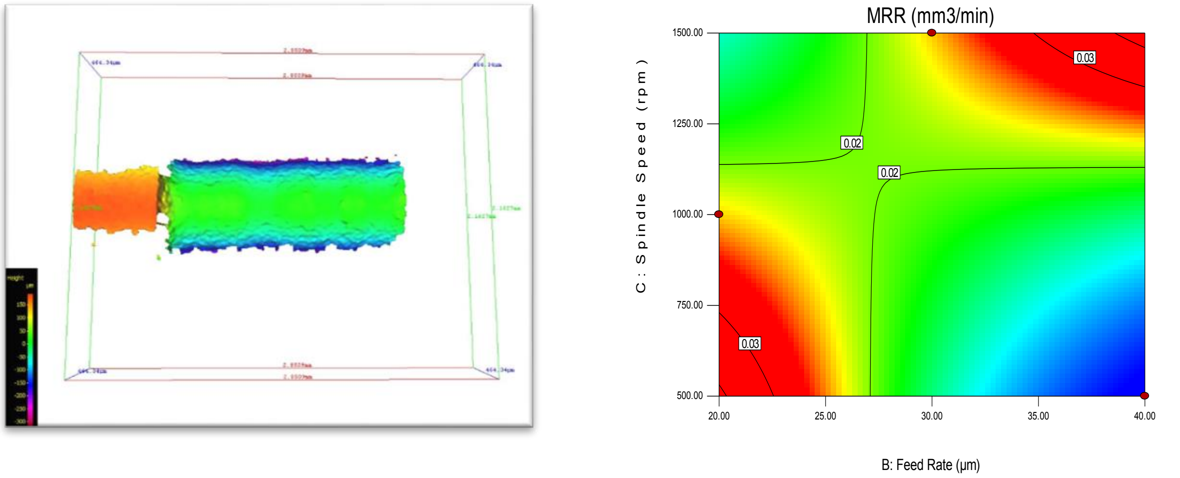

Figure 1. (a) Sugar colour graph of workpiece produce by Alicona when 110 V gap voltage, 30 μm/s feed rate, and 500 rpm spindle speed (b) countour graph of 1/MRR vs. feed rate and spindle speed.

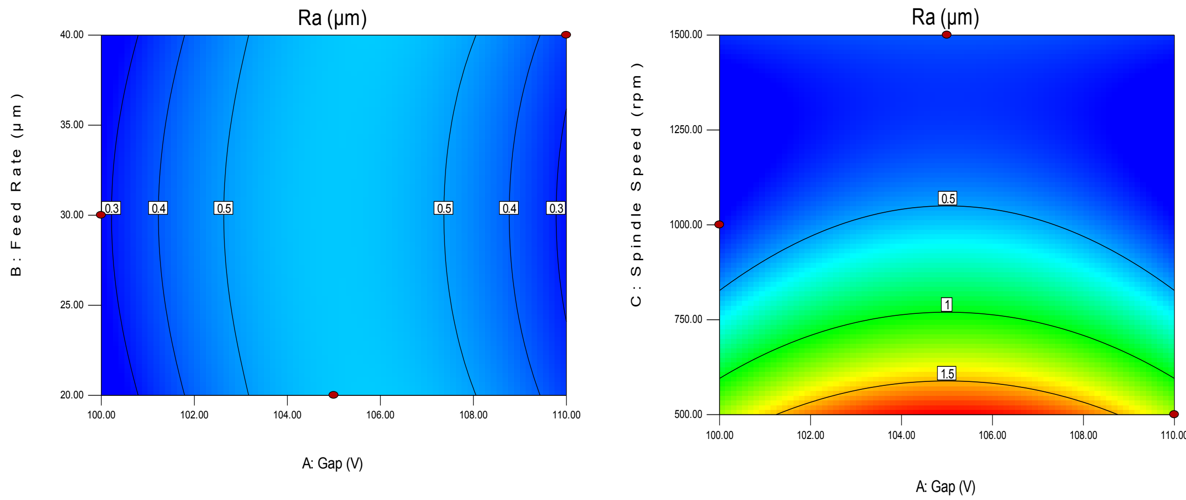

Figure 2. Countour graph of (a) R_a vs. gap voltage and feed rate, (b) R_a vs. gap voltage and spindle speed.

3.2 Surface roughness (R_a)

The developed model is shown in Eq. 3. Based on ANOVA, the model was developed based on 95% level of confidence and the model shows F-value of 1266.95 indicates the model is significant. There is small influence, 99.00% of noise on the model developed. Furthermore, F-value and Prob> F proves that factor n, v^2, n^2, and interaction effects of v^2n and vf^2 are influential factors on R_a by indicating the Prob>F value less than 1% which shows very influential influence.No power transmission was used for modelling R_a.

$$R_a = 4.23 - 6.33 \times 10^{-3}n - 8.13 \times 10^{-5}v^2 + 1.98 \times 10^{-6}n^2 + 1.18 \times 10^{-7}v^2n + 1.09 \times 10^{-6}\, vf^2 \quad (3)$$

where, R_a = material removal rate (mm^3/min), v = voltage (V) and f = feed rate (μm/s)

Figure 2a shows the contour graph of R_a vs. gap voltage and feed rate. Gap voltage has a strong influence on R_a. R_a increase as voltage increase from 100 V to 103 V, then R_a value reduce as the voltage increase to 110 V. In the first phase, higher discharge energy reduces the ability to produce good surface roughness [8]. High discharge energy produce stronger spark, stronger spark erodes high amount of debris from workpiece causes uneven crater to be produce. When debris is produced, it will be trap in between plasma channel and yield unwanted spark. Consequently, high amount of energy discharge is engaged to spark with debris, whereas only small portion of discharge energy is available to removed material from the workpiece. Meanwhile, in second phase, further increase in gap voltage, reduces the R_a, this may be due to different theories which stated that discharge energy strongly effect the discharge crater geometry. It must be assumed that the plasma channel able to breaks down with increasing circumferential speed. This affects the discharge crater becomes smaller in relation to crater area and volume, thus lower R_a is obtained. Besides that, Figure 2b shows the contour graph of R_a vs. gap voltage and spindle speed. R_a decreased as spindle speed increase. This condition happens due to the effect of the rotational movement on the position and expansion of the plasma channel of a single discharge [9].

3.3 Signal to noise (S/N) ratio for MRR

Signal to noise is vital in Taguchi experimental design and proposed to maximize the performance of the objectives. Table 2 shows the S/N value for MRR and Ra. Based on Taguchi method, S/N ratio is defined as signal to ratio where signal signifies the desirable value and noise represents the undesirable value. S/N value calculated for MRR as shown on Table 2 above is achieved by calculation using Eq. 4. Since the objective is to maximize as much as possible the value of MRR, equation of 'Larger-the–better' is used for S/N ratio calculation. Figure 3 shows the effect of three control parameters which are gap voltage, feed rate and spindle speed graphically. The analysis was done with the helps from MINITAB 14 software. The software facilitate in producing S/N ratio response table, which used to further analyze the results. Based on Figure 3, factors at 110 V, 20 μm/s, and 1500 rpm gives the maximum MRR. Gap voltage and spindle speed is observed which provide significant effect on MRR. Even though, feed rate do not show significant influence but it still cannot be neglected.

$$\text{Larger-the-better:} \qquad S/N = -10 \log \frac{1}{n}\left(\sum \frac{1}{y^2}\right) \quad (4)$$

3.4 Signal to noise (S/N) ratio for R_a

Taguchi method helps in reducing fluctuation causes by noise and aim to achieve consistent performance, thus for R_a which target to smallest value as possible. Due to that signal to noise value for R_a is calculated by using Eq. 5 and show in Table 2, which used for 'Smaller-the-better' [12]. Factors level at 105 V, 30 μm/s, and 1500 rpm are recommended for minimization of R_a value as shown in Figure 4. Feed rate provide least influence on R_a, while spindle speed give highest influence followed by gap voltage.

$$\text{Smaller-the-better:} \qquad S/N = -10 \log \frac{1}{n} \sum y^2 \quad (5)$$

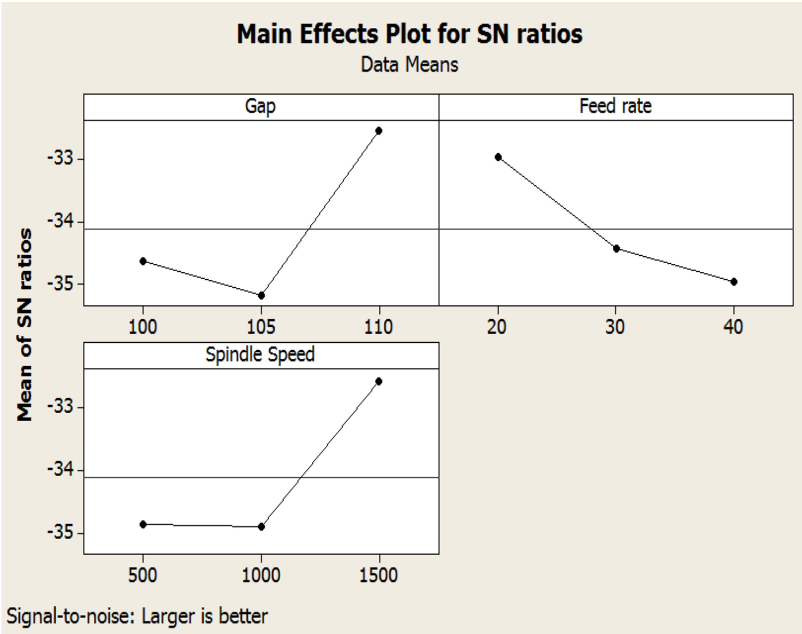

Figure 3. S/N ratio curves of gap voltage, feed rate, and spindle speed for (a) MRR and (b) R_a

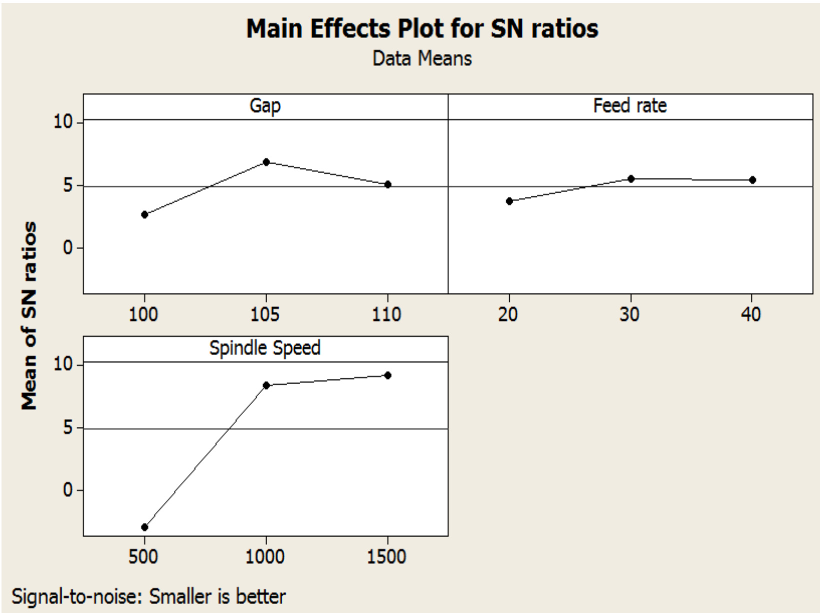

Figure 4. S/N ratio curves of gap voltage, feed rate, and spindle speed for (a) MRR and (b) R_a

4. Optimization and Verification

Multi-responses optimization is done to obtain optimum set of parameters for micro-WEDG process. The optimization was done by selecting the gap voltage, feed rate, and spindle speed to be in range with maximum MRR and minimum R_a. The optimized result for maximum MRR was 0.05863 mm^3/min and minimum R_a was 0.255 µm with 110 V gap voltage,38 µm/s feed rate, and 1315 rpm spindle speed. Experiment was conducted for verification using results obtained from the optimization.

The actual values obtained from the experiments were compared with the optimize results. The percentage error for MRR is 14.76 %. The percentage error for MRR is quite big. Electronic weighing balance might be the factor, which contribute to the error since due to its low resolution. To reduce this error, increase the amount of material remove and using higher resolution electronic weighing balance may give positive impact on the results.

5. Conclusions

The purpose of this paper is to study the effect of machining parameters, which are gap voltage, feed rate, and spindle speed on MRR and R_a of micro-WEDG. In order to analyse the results of the experiment, ANOVA has been used as method of analysis and empirical equations for both response were developed. This study shows that:

1. Based on ANOVA, it is observed that gap voltage provides significant influence on MRR where further increase in gap voltage, MRR increase. Meanwhile, spindle speed provides highest influence on R_a where further increase in spindle speed, reduce the R_a.
2. The maximum MRR is found to be 0.05863 mm^3/min meanwhile, Ra is found to be 0.255 µm. The optimum parameters obtained are 110 V gap voltage, 38 µm/s feed rate, and 1315 rpm spindle speed.

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