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ORIGINAL ARTICLE

The parameters evaluation and optimization of polycrystalline diamond micro-electrodischarge machining assisted by electrode tool vibration

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Abstract The objective of this research is to evaluate and optimize machining parameter of tool electrode vibration on micro-electric discharge machining of polycrystalline diamond. The machining parameters evaluated are charge voltage, capacitance, and vibration of the tool electrode. An orthogonal array, signal-to-noise ratio, and analysis of variance are employed to analyze the effect of these machining parameters. The results show that by application of vibration on tool electrode in machining of polycrystalline diamond, it has significant effect up to 66.48% in increasing material removal rate without increasing surface roughness and tool electrode wear. Using Taguchi method for design of experiment, other significant effects on surface quality and tool electrode wear are also investigated. The results also show that surface roughness is mostly affected by the amount of capacitance (52.24%), and the tool electrode wear is also affected by the amount of capacitance (92.82%).

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Keywords Micro-EDM · Tool electrode vibration · Taguchi approach · Polycrystalline diamond · Material removal rate

1 Introduction

Polycrystalline diamond (PCD) is a superior material made by sintering diamond particle with binder metal of cobalt, under high pressure and temperature. The properties of PCD such as superior in hardness, toughness, good endurance against abrasion, and good wear resistance are expected as a good material for micro-dies, micro-mold, and micro-cutting tool. The use of PCD is limited by one of its properties, that is, it is very difficult to machine in conventional machining.

PCD has an electric conductivity caused by the existence of binder material of cobalt during sintering process, and it makes the PCD to have a good electrical conductivity. Thus, it is possible to perform micro-electrical discharge machining (EDM) to machine PCD since processing with micro-EDM depends on its thermal conductivity, melting point, and electrical resistivity [1–3]. The EDM process is based on the thermoelectric energy created between a workpiece and an electrode submerged in a dielectric fluid. When the workpiece and the electrode are separated by a specific small gap, a pulsed discharge occurs and removes material from the workpiece through melting and evaporation. The difference of micro-EDM and EDM is mainly in the amount of energy per discharge pulse. In the micro-EDM, the range of energy per discharge pulse is usually 0.025–19.965 μJ. However, in the EDM, the range is usually larger (40.5–144,000 μJ).

There have been many researches on the use of PCD as cutting tool in the conventional machining. Davim et al. [4]

study the thermal and mechanical behavior in machining of aluminum alloys (Al 7075-0) using PCD and K10 (cemented carbide) tools, and make a comparison between the performances of both tools. It was concluded that the polycrystalline tool has a superior performance in terms of cutting and feed forces and temperature when compared to the cemented carbide tool. Muthukrishnan et al. [5] study the machinability issues of aluminum–silicon carbide metal matrix composites in turning using different grades of PCD inserts. It was observed that the 1600 grade PCD inserts performed well from the surface finish and specific power consumption points of view closely followed by the 1500 grade.

However, there are relatively few researches on the manufacturing of PCD tools. Tso [6] presented the effect of manufacturing process on PCD grinding, and with proper parameters, the PCD will be less damaged and retain its superiorities as a cutting tool. In addition, this study presents a beginning for research on understandings of principles in cutting PCD. It may be useful for toolmakers to produce a high-quality and reusable PCD tools. Cassidy [7] presented PCD grinding optimization by means of PCD inserts. By observation of scanning electron microscope on the insert edge, the study compared the effect of working parameters like grinding wheel speed on feed rate and oscillation frequency. Cheng et al. [8] presented the fabrication of a cutter with complicated geometry, and a cutter made of ultra hard material is successfully demonstrated on a six-axis wire EDM. The cutter is made from PCD.

The main objective of the research is to investigate the vibration effect of tool electrode, with respect to the material removal rate, tool electrode wear, and surface roughness in micro-EDM of PCD using Taguchi approach.

2 Experimental setup and methods

The workpiece material used in this work was PCD with diameter of 1 mm. The thermal conductivity is 540 W/mK with the melting point of 1,530 K. Tungsten–silver (Ag–W) square plate with dimensions of 10×10×1.2 mm was used as the tool electrode. The reason of using tool electrode size of 10×10×1.2 mm is because the area size of the tool electrode holder of the piezoelectric transducer (PZT) is 9.5×9.5 mm; thus, the area size of the tool electrode which is 10×10 mm can be fitted well. And the thickness of the tool electrode of 1.2 mm is appropriate since the depth of machining is only 0.2 mm. The area of tool electrode is 100 mm^2, and this is also appropriate since the diameter of the workpiece is only 1 mm (the machining area is 0.785 mm^2). The machining process was performed using Panasonic MG-ED72 micro-electro discharge machine and use kerosene as dielectric fluid. The micro-EDM uses the resistor–capacitor circuit to produce the discharge pulse. A PZT was used to vibrate the tool electrode with a frequency of 1 kHz and an amplitude of 1.5 µm. The vibration of 1 kHz in frequency and 1.5 µm in amplitude is used because it is the maximum vibration that can be generated by our charge amplifier. The PZT was made by NEC Tokin (type AE1010D16). The experimental setup is shown in Fig. 1.

In order to perform the online monitoring system to monitor the effect of vibration of tool electrode on machining of PCD, the signals from discharge pulses were captured by using current probe sensor from Tektronix (type TCP202) and the feeding action of the table was measured by laser displacement sensor from Keyence (type LK-010) as shown in Fig. 1.

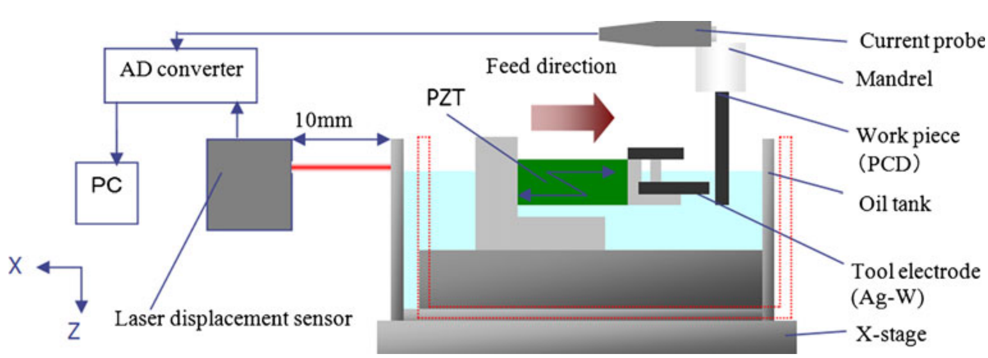
Figure 2 shows the machining dimension of the PCD using Ag–W as the tool electrode with the machining depth in *Z*-direction was 200 µm and the machining depth in *X*-direction was 200 µm. The Ag–W was vibrated during machining process with a frequency of 1 kHz and an amplitude of 1.5 µm.

3 Configurations of the parameters and their level

3.1 Design factor selected

The charge voltage (A), capacitance (B), and vibration of tool electrode (C) are selected as the input parameter. The various process parameters in micro-EDM are charge

Fig. 1 Experimental setup



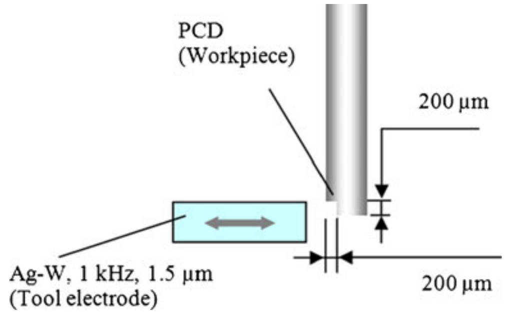


Fig. 2 The machining characteristics

voltage, capacitance, and feed speed during machining, and the reasons of using the charge voltage, capacitance as the parameters, are because they are widely used in micro-EDM processes. By changing these parameters, the kind of machining can be determined (rough, semi-finish, or finish machining). And about the vibration, it is as the new parameter outside the micro-EDM system. We add the vibration because we would like to increase the material removal rate by reducing adhesion, cavitations, and short-circuiting. The explanation about the effect of vibration will be discussed in the Section 4.1.

3.2 Response variables selection

The responses variable selected are material removal rate (MRR), tool electrode wear (TEW), and surface roughness (SR).

Material removal rate is expressed as the ratio of the difference of volume of the workpiece before and after machining to its machining time. After machining, the workpiece dimension was measured by laser microscope from Lasertech (type 1LM21D).

Tool electrode wear is expressed as the worn-out area of the tool electrode after machining. It was measured using surface roughness machine from Tokyo Seimitsu (type Surfcom) as shown in Fig. 3, and then the area of tool electrode wear was calculated by image processing using MATLAB.

Surface roughness parameter selected is Rz parameter. Rz is the average of the height of five highest peaks plus the depth of five deepest valleys over the evaluation length.

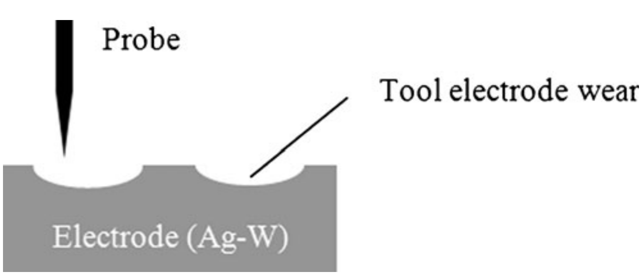


Fig. 3 Measurement method of tool electrode wear

It was measured using laser microscope from Lasertech (type 1LM21D). The laser microscope determines the value of highest five peaks and the depth of five deepest valleys from the PCD surface after machined, and then it was used to calculate the Rz.

3.3 Statistical methods

The three factors and two levels are selected, and the orthogonal array selected is L_8. The Taguchi method is a powerful design of experiments tool, which provides a simple, efficient, and systematic approach to determine optimal parameters [9]. The machining factors and their levels are listed in Table 1. The reason of using very selective range and levels of process parameters is because we would like to provide simplicity to find the basic knowledge and effect of how many percent the process parameters especially the vibration affects the response variable.

The experimental layout for the experiments is tabulated in Table 2. It was decided to select the trials at random and complete all of three successive replications. A number of readings at different surfaces are taken to measure the respective response parameters.

4 Results and discussions

Taguchi uses a coefficient of variation to define its signal-to-noise (S/N) ratio [10, 11]. In this study, to analyze the material removal rate, the data are transformed into S/N higher better (HB) characteristic, while for surface roughness and tool electrode wear, the data are transformed into S/N lower better (LB) characteristic. The averages of the results from three replications are described in Table 3.

Figures 4, 5, and 6 describe the main effect plot results for material removal rate, surface roughness, and tool electrode wear, and Tables 4, 5, and 6 describe the ANOVA analysis of material removal rate, surface roughness, and tool electrode wear, respectively.

4.1 Analysis on material removal rate

The main effect of material removal rate is shown in Fig. 4; the gradient of the multiple linear graphs of vibration of

Table 1 Machining factors and their levels

Machining parameter	Symbol	Unit	Level 1	Level 2
Charge voltage	A	Volt	80	110
Capacitance	B	pF	220	3,300
Vibration	C	1 kHz, 1.5 μm	Off	On

Fixed factors: feed rate of 5 μm/s

Table 2 Experimental layout using L_8 orthogonal array

Test no.	Machining parameter		
	Charge voltage (A)	Capacitance (B)	Vibration (C)
1	1	1	1
2	1	1	2
3	1	2	1
4	1	2	2
5	2	1	1
6	2	1	2
7	2	2	1
8	2	2	2

tool electrode between their levels is highest compare to the others. The effect of vibration of tool electrode has a greatest impact to the material removal rate, followed by capacitance and voltage. Table 4 presents the ANOVA of material removal rate, as detailed by the Percentage Contribution Error (PCR) values. The PCR is the total percentage that each factor contributes to the total variation of the result and is a measure of how much the performance could be altered if the factor was controlled. The effect of vibration of tool electrode is 66.48% highest among the others and significant in confidence interval of 99%.

PCD is a difficult-to-machine material in micro-EDM processes because it consists of diamond which is not a conductive material. In the PCD machining by using micro-EDM, the machining time is very long because sometimes the diamond particles cover the spark. PCD become conductor because of its bonding material (cobalt), and the material removal rate is not constant. It is not constant because the workpiece is cylindrical and the flat surfaced electrode is fed radially to the workpiece, but because there are some disturbances from the short-circuiting, cavitations, and adhesion, hence it is necessary to find a method to make it become an easy-to-machine material in micro-EDM processes. One of the methods is using vibration-assisted

Table 3 Experimental results (average from three replications)

Test no.	Material removal rate (mm^3/min)	Surface roughness [Rz] (µm)	Tool electrode wear (μm^2)
1	1.28e−4	6.11	6,239.93
2	1.89e−3	9.67	6,395.23
3	6.83e−4	14.30	9,004.33
4	1.00e−2	14.11	10,119.23
5	3.71e−4	12.27	5,864.97
6	5.15e−3	14.11	5,647.83
7	2.13e−3	20.18	9,964.80
8	1.92e−2	20.69	11,277.33

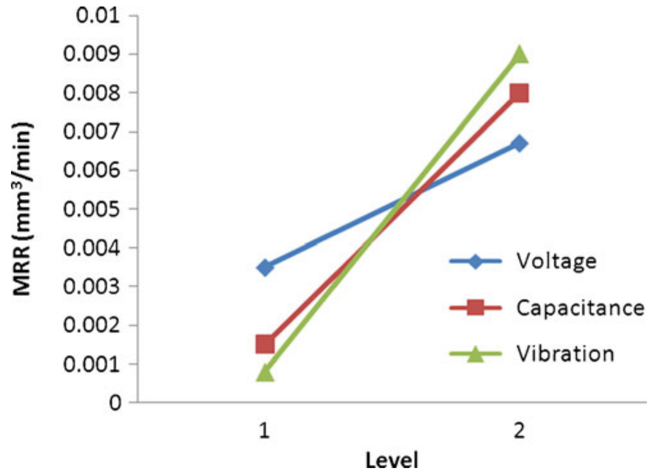


Fig. 4 The main effect plot for material removal rate

micro-EDM. It can be explained that the vibration of tool electrode with a frequency of 1 kHz and an amplitude of 1.5 µm removes adhesion from the melting material attached to the workpiece and reduces the feeding back action of the machining table. The effect of vibration is also similar to sawing machine which fasten the machining time. Hence, the material removal rate is increase significantly.

Adhesion occurs when the melted component of the workpiece becomes attached to the tool electrode, causing the discharge pulse to become unstable as a result of short-circuiting between the workpiece and tool electrode, and inhibiting the insulation recovery of the EDM machine [12, 13]. Adhesion causes the machining time to lengthen because of the feedback of the table required to remove the melted debris from the electrode as shown in Fig. 7.

Figure 8a shows the online monitoring results, during machining of PCD with charge voltage of 110 V, capacitance of 220 pF, and without vibration of tool electrode (test no. 5), and Figure 8b shows the same machining conditions but with vibration of tool electrode (test no. 6). The blue

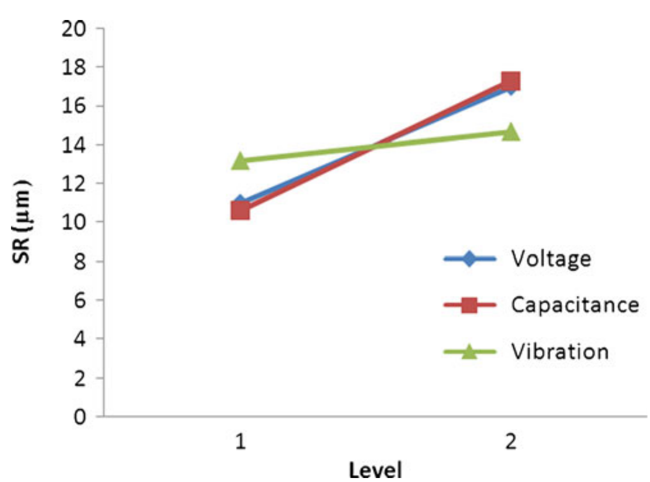


Fig. 5 The main effect plot for surface roughness

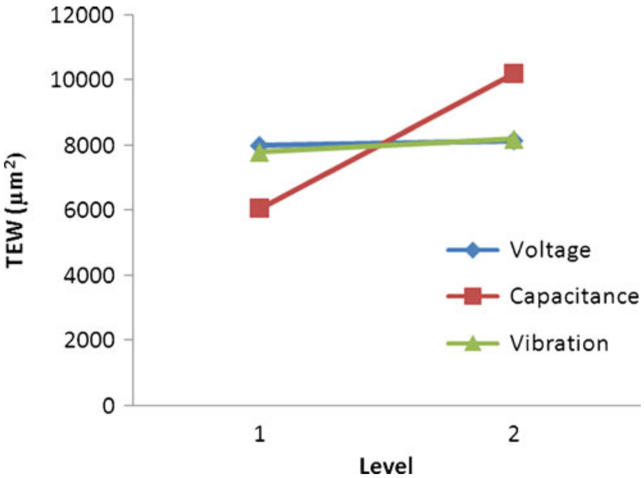


Fig. 6 The main effect plot for tool electrode wear

line represents the signals from the laser displacement sensor, which measure the feed in *X*-direction, and the pink line represents the current signals from discharge pulses. It can be seen from Fig. 8a, b that the effect of vibration of tool electrode can reduce the machining time effectively. As shown in Fig. 8a, when the machining time was reaching at 30 s, without vibration of tool electrode, the machining feed was only 3 μm. However, from Fig. 8b when the machining time was reaching at 30 s, with vibration of tool electrode, the machining feed was high (20 μm) since adhesion was removed by vibration of the tool electrode.

The increase of capacitance also has a significant impact to the material removal rate (23.90%). It is attributed to the increase of discharge pulse energy when increasing capacitance, described by the equation as follow:

$$E = \frac{1}{2} C V^2 \tag{1}$$

The energy of discharge pulse (E) is proportional to the second power of the charge voltage (V) and proportional to the capacitance (C). The effect of charge voltage is 8.97%, and the pooled error is only 0.65%. In addition, there was no evidence of significant interaction between each factor.

Table 5 ANOVA of surface roughness

Factor	dof	Sum of square	Variance	*F*-ratio	PCR (%)
A	1	25.07	25.07	11.19	28.31[a]
B	1	44.37	44.37	19.80	52.24[b]
Pooled error	5	11.20	2.24		19.45
Total	7	80.64			100.00

dof degree of freedom

[a] At least 95% confidence

[b] At least 99% confidence

The higher the response the better characteristic is used because maximum material removal rate is desirable. The equation for the higher the response the better characteristic is as follow:

$$S/N_{HB} = -10 \log \left(\frac{1}{r} \sum_{i=1}^{r} \frac{1}{y_i^2} \right) \tag{2}$$

where S/N_{HB} is the signal-to-noise ratio for higher better characteristic, r is the number of observation, and y_i is the experimental value.

4.2 Analysis on surface roughness

Figure 5 shows the multiple graph of main effect and their variation of each levels of surface roughness. The relative gradient from the graph shows that capacitance has biggest effect to the surface roughness. Table 5 describes the result of ANOVA for surface roughness analysis, which shows that the impact of capacitance to the surface roughness is 52.24%, followed by voltage (28.31%). It can be explained that in micro-EDM, increasing capacitance generally will increase surface roughness, caused by higher spark energy, and will produce larger diameter of crater on the PCD. As stated by Eq. 1, the spark energy is proportional to the charge voltage square (in this case: $110^2/80^2=1.9$ times) and the amount of capacitance (in this case: 3,300/220=15 times).

Table 4 ANOVA of material removal rate

Factor	dof	Sum of square	Variance	*F*-ratio	PCR (%)
A	1	138.64	138.64	97.18	8.97[a]
B	1	366.95	366.95	257.20	23.90[a]
C	1	1,018.40	1,018.40	713.81	66.48[a]
Pooled error	4	5.71	1.43		0.65
Total	7	1,529.70			100.00

dof degree of freedom

[a] At least 99% confidence

Table 6 ANOVA of tool electrode wear

Factor	dof	Sum of square	Variance	*F*-ratio	PCR (%)
B	1	38.92	38.92	107.37	92.82[a]
A×B	1	1.53	1.53	4.22	2.81[b]
Pooled error	5	1.09	0.36		4.37
Total	7	41.54			100.00

dof degree of freedom

[a] At least 99% confidence

[b] At least 90% confidence

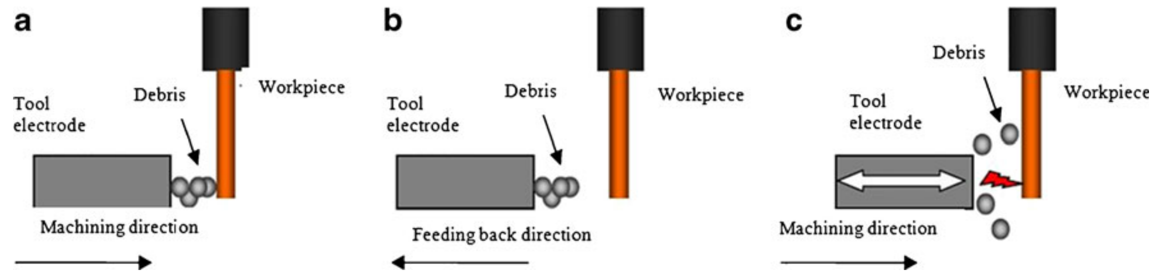


Fig. 7 The effect of vibration to the adhesion process: **a** without vibration of tool electrode, **b** feeding back action of the machining table, and **c** with vibration of tool electrode

That is why the surface roughness and also tool electrode wear are more influenced by capacitance (15 times) than by charge voltage (1.9 times). The surface roughness is not affected by the adhesion, cavitations, and short-circuiting. That is why the vibration is only having significant effect for material removal rate but not for surface roughness. PCR for tool electrode vibration is only taking about 2.31% (included in the pooled error).

Thus, it can be concluded that vibration of tool electrode with a frequency of 1 kHz and an amplitude of 1.5 μm is very effective to increase material removal rate without increasing surface roughness. The ANOVA also describes that there are no significant effect of interaction between each factor. Figure 9a, b shows that the vibration of tool electrode has no significant effect in increasing surface roughness (20.18 and 20.69 μm), and Figure 9c, d shows the surface roughness profile and its values. Since minimum surface roughness is needed, the smaller better characteristic is applied in this analysis. The equation for the smaller better characteristic is as follow:

$$S/N_{LB} = -10\log\left(\frac{1}{r}\sum_{i=1}^{r} y_i^2\right) \tag{3}$$

where S/N_{LB} is the signal-to-noise ratio for smaller better characteristic, r is the number of observation, and y_i is the experimental value.

The pooled error of surface roughness is 19.45%, and it is not because the selection of process parameters and their ranges is not good, since the value is still under 50% [10]. Thus, it is still considered that the selection of process parameters and their ranges is good.

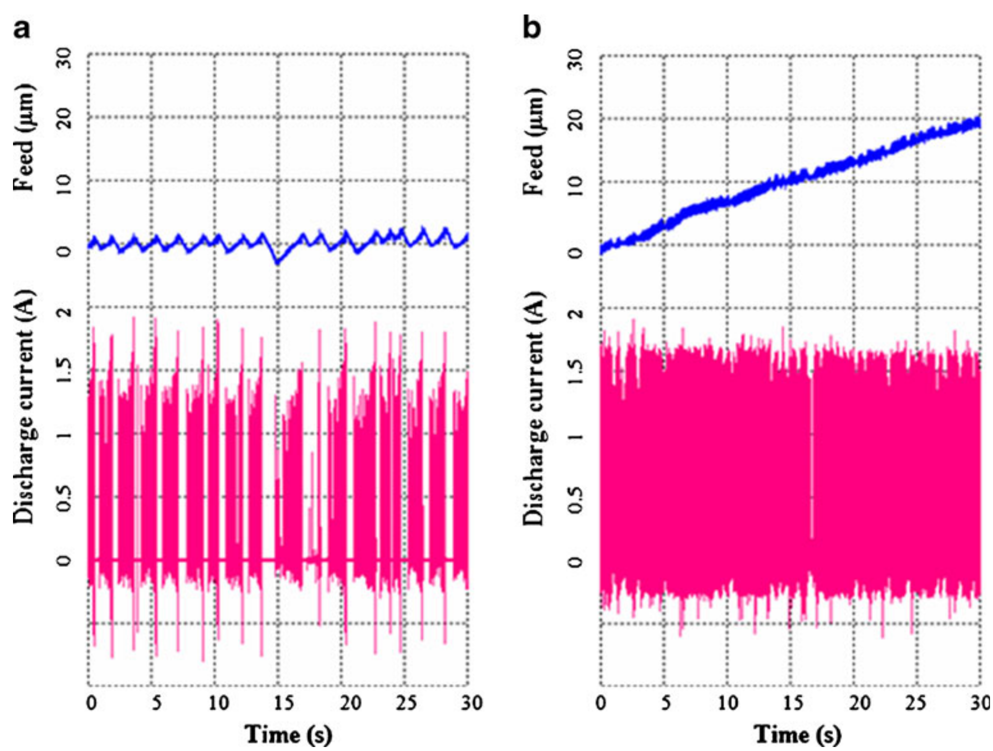


Fig. 8 The machining characteristics: **a** test no. 5; 110 V, 220 pF, without vibration of tool electrode, and **b** test no. 6; 110 V, 220 pF, with vibration of tool electrode

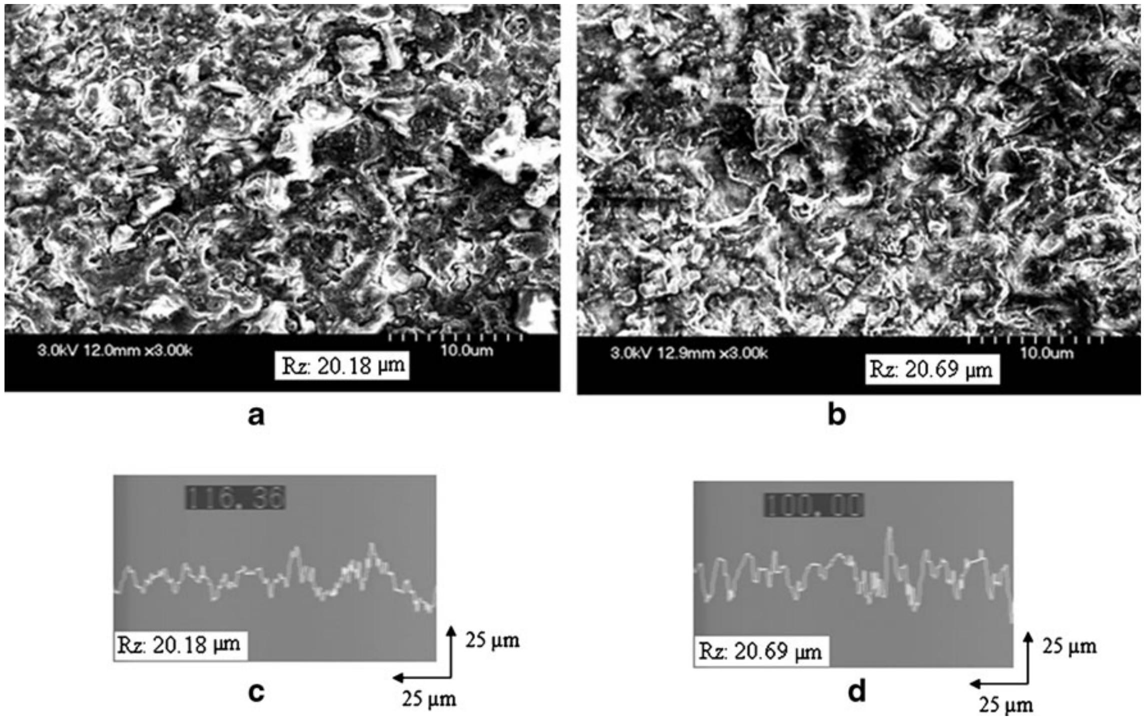


Fig. 9 The surface roughness characteristics: **a** test no. 7; 110 V, 3300 pF, without vibration of tool electrode, and **b** test no. 8; 110 V, 3300 pF, with vibration of tool electrode. **c** The surface roughness profile and value of **a** and **d**. The surface roughness profile and value of **b**

4.3 Analysis on tool electrode wear

The area of tool electrode wear of Ag–W was also affected by the amount of capacitance. Figure 6 shows that the slope of capacitance is the greatest. It is evident that capacitance has the greatest impact to the tool electrode wear because higher discharge energy not only machines the workpiece but also machines the tool electrode and produces higher tool electrode wear. A 92.82% of PCR contribution given in the Table 6 from capacitance, followed by the interaction of voltage and capacitance at PCR of 2.81%, is significant in increasing tool electrode wear. Increasing capacitance will produce higher spark energy; thus, the tool electrode is easier to get worn-out. The total error pooled from Table 6 is 4.37%; it shows that all important factors and interactions have been considered and the performance of measurement is completed with high accuracy.

Although the contribution of voltage is not significant with the PCR of 0.87% (included in the pooled error), the interaction between voltage and capacitance shows relatively a contribution, with the value of PCR at 2.81%, which was statistically significant at the confidence interval of 90%.

The vibration of tool electrode with a frequency of 1 kHz and an amplitude of 1.5 μm is not significant at all in increasing tool electrode wear but is effectively increasing

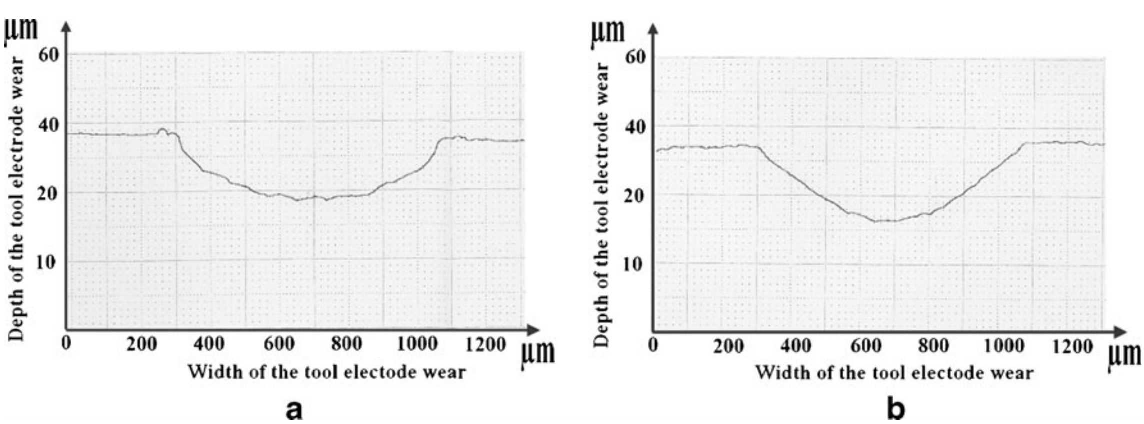


Fig. 10 The tool electrodes wear characteristics: **a** test no. 3; 80 V, 3300 pF, without vibration of tool electrode, and **b** test no. 4; 80 V, 3300 pF, with vibration of tool electrode

Table 7 Summary of ANOVA analysis

Factor	Level at which the factor has an optimum output condition		
	Charge voltage (A)	Capacitance (B)	Vibration (C)
MRR	2	2	2
SR	1	1	1
TEW	1	1	1

material removal rate as mentioned in Section 4.1. The PCR of tool electrode vibration in the tool electrode wear analysis is only 0.33% (included in the pooled error). As shown in Fig. 10a, b, the effect of tool electrode vibration to the tool electrode wear is not significant at all. The smaller better characteristic is applied in this analysis because minimum tool electrode wear is needed. The equation for smaller better characteristic is described in Eq. 3.

4.4 Optimum conditions

Table 7 describes the summary of ANOVA analysis which discusses about the level at which the responses to be set for optimizing the output. The table shows that to optimize the material removal rate, the level of machining condition need to be set as level 2 for every factor. It can be determined from Fig. 4 that higher material removal rate can be obtained when the level is set at level 2. For surface roughness and tool electrode wear, in order to have minimum surface roughness and tool electrode wear, the level of factors should be at the level 1, and it can be determined from Figs. 5 and 6 that when the level is set as 1, the surface roughness and tool electrode wear are minimum.

The steps of statistical analysis are divided into three phases. First phase is concern about ANOVA analysis and on determining the effect of each factor and interactions. Second phase is finding out the correlation of every factor on their respective level to determine the optimum condition in each factor related to the optimum output. The first and second phases are already explained in the previous discussion. Third phase is doing confirmation experiment (CE) of the results. Confirmation experiments were conducted based on the results from Taguchi analysis related to the highest material removal rate, lowest surface roughness, and lowest electrode wear (denoted as CE 1, CE 2, and CE 3) as shown in the Table 8.

The confidence interval of 90% was used to predict the upper and lower limit of the response variables. The 90% confidence interval is used because, in micro-EDM, the process is highly un-linear, for example the machining time for machining same condition is different [12]. The upper and lower limit was calculated from the respective response variables. The results from the CE 1, CE 2, and CE 3 were found within the boundaries of its upper and lower limit.

5 Conclusions

In order to increase the material removal rate, the effect of tool electrode vibration for machining of PCD in micro-EDM was investigated. The results obtained from the experiments are summarized as follows:

1. The vibration of the tool electrode has a high significant effect in increasing material removal rate compared to the other factors. The PCR is 66.48%, and the tool electrode vibration has no significant effect in increasing surface roughness and tool electrode wear.
2. The vibration of tool electrode with a frequency of 1 kHz and an amplitude of 1.5 μm removes adhesion from the melting material attached to the workpiece and reduces the feeding back action of the machining table. Hence, the material removal rate is increase significantly.
3. Surface roughness is mostly affected by the amount of capacitance (52.24%), and the tool electrode wear is also affected by the amount of capacitance (92.82%), because higher capacitance produces high spark energy to create greater crater.
4. In micro-EDM machining, the material removal rate is affected by adhesion, cavitations, and short-circuiting. Adhesion happens when the debris is attached to the tool electrode and causing short-circuiting. By the application of vibration, it can be used to remove the adhesion, cavitations, and short-circuiting, hence increasing the material removal rate. However, the tool electrode wear and surface roughness are not affected by the adhesion, cavitations, and short-circuiting. That is why the vibration is having significant effect for material removal rate but not for tool electrode wear and surface roughness.

Table 8 Confirmation experiment

CE 1[a]	Actual MRR 1.97e–2 mm^2/min	Predicted MRR 1.61e–2 to ~2.26e–2 mm^3/min
CE 2[b]	Actual SR 5.56 μm	Predicted SR 4.77 to ~7.13 μm
CE 3[b]	Actual TEW 5936.2 μm^2	Predicted TEW 5,726.4 to ~6,728.6 μm^2

[a] Test 8: the optimum condition for MRR (the process parameters and levels are described in Table 7)

[b] Test 1: the optimum condition for SR and TEW (the process parameters and levels are described in Table 7)

5. The spark energy is proportional to the charge voltage square (in this case: $110^2/80^2=1.9$ times) and the amount of capacitance (in this case: 3,300/220=15 times). That is why the surface roughness and also tool electrode wear are more influenced by capacitance (15 times) than by charge voltage (1.9 times).

References

1. Mahardika M, Tsujimoto T, Mitsui K (2008) A new approach on the determination of ease of machining by EDM processes. Int J Mach Tool Manuf 48:746–760
2. Abbas NM, Solomon DG, Bahari MF (2007) A review on current research trends in electrical discharge machining (EDM). Int J Mach Tool Manuf 47:1214–1228
3. Prihandana GS, Mahardika M, Hamdi M, Wong YS, Mitsui K (2009) Effect of micro-powder suspension and ultrasonic vibration of dielectric fluid in micro-EDM processes—Taguchi approach. Int J Mach Tool Manuf 49:1035–1041
4. Davim JP, Maranhao C, Jackson MJ et al (2008) FEM analysis in high speed machining of aluminium alloy (Al7075-0) using polycrystalline diamond (PCD) and cemented carbide (K10) cutting tools. Int J Adv Manuf Technol 39:1093–1100
5. Muthukrishnan N, Murugan M, Rao KP (2008) An investigation on the machinability of Al-SiC metal matrix composites using PCD inserts. Int J Adv Manuf Technol 38:447–454
6. Tso PL (2002) Study on PCD machining. Int J Mach Tool Manuf 42:331–334
7. Cassidy R (2000) PCD grinding optimization. INTERTECH 2000, Staffordshire, United Kingdom
8. Cheng X, Wang ZG, Kobayashi S, Nakamoto K, Yamazaki K (2008) Development of a six-axis wire electrical discharge machine for the fabrication of micro end mills. Proc IMechE Part B: J Engineering Manufacture 223:121–131
9. Palanikumar K (2008) Application of Taguchi and response surface methodologies for surface roughness in machining glass fiber reinforced plastics by PCD tooling. Int J Adv Manuf Technol 36:19–27
10. Ross PJ (1989) Taguchi techniques for quality engineering. McGraw-Hill, New York
11. Wu FC, Chyu CC (2002) A comparative study on Taguchi's SN ratio, minimising MSD and variance for nominal-the-best characteristic experiment. Int J Adv Manuf Technol 20:655–659
12. Mahardika M, Mitsui K (2008) A new method for monitoring micro-electric discharge machining processes. Int J Mach Tool Manuf 48:446–458
13. Endo T, Tsujimoto T, Mitsui K (2008) Study of vibration-assisted micro-EDM—the effect of vibration on machining time and stability of discharge. Precis Eng 32:269–277