

Water-in-sunflower seed oil emulsion as a dielectric fluid for micro electrical discharge machining (μ EDM)

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ABSTRACT

Dielectric fluid is an important component in machining using Electrical Discharge Machining (EDM). Conventional dielectric fluids have disadvantages such as emit carbon dioxide and carbon mono oxide gases to the environment. Vegetable-based dielectrics are biodegradable, environment-friendly, and emit less harmful gases. This study focuses on water-in-sunflower seed oil as a replacement for conventional dielectric fluid. The quality of the performance is evaluated through selected machining responses such as material removal rate (MRR), tool wear ratio (TWR), circularity, taper conicity, and overcut of the hole. The experimental design of the project is designed based on the Taguchi L_9 orthogonal array which results in 9 sets of experiments with different combinations of electrode diameter, dielectric fluids, feed rate, and capacitance. Water-in-sunflower seed oil provides the highest MRR. Besides that, it also performs well in the overcut which shows a steady spark throughout the whole fabrication.

Keywords: Electrical discharge machining; Dielectric fluid; Green machining; Water-in-sunflower seed oil.

1. INTRODUCTION

A non-conventional machining process, Electrical Discharge Machining (EDM) is the most popular technique in manufacturing processes for brittle and very hard materials. EDM machining is suitable for the manufacture of moulds, tools, and die [1–5]. The principle of EDM is based on thermoelectric energy that occurs between the workpiece and electrode with the presence of dielectric [6]. The process creates high-frequency discrete electric sparks that cause dielectric fluid to undergo thermoelectric decomposition. These phenomena initiate a large amount of heat causing workpiece material to melt and vaporize at a rapid rate. The pulse discharge from the thermoelectric process corrodes workpiece material with continuous-discrete electrical sparks while being flushed by dielectric fluid pressure [7].

The process of EDM modified the characteristics and structure of the recast layer through melting and vaporizing. The recast layer is the consequence of the melted material which did not overrun and harden on the material's surface during the EDM machining [8, 9]. High energies emit during the process lead to an increasing number of by-products in the form of gases resulting in serious occupational and environmental problems. Also, environmental issues are caused by the release of a volatile agent, hazardous and toxic fumes, odour, and toxic solids of micro/nanoparticles [10–13]. In addition, waste generated during the process has an intent argument related to reuse, recycling, and non-degradability [7, 14]. These issues are devoted to the poor sustainability of EDM machining due to the use of hydrocarbon-based dielectric fluids in the EDM process.

In EDM, the dielectric medium takes the main role in affecting the surface quality, material removal rate, and electrode wear during machining. The function of the dielectric fluid is a flushing medium, accelerating the energy density of the plasma channel, an insulator and cooling the electrodes [15, 16]. In addition, dielectric fluid is an influential factor in the cost, productivity, and quality of the machined parts. Kerosene is commonly used as a dielectric medium in EDM due to its good dielectric strength and low viscosity [17]. Kerosene has a higher insulation strength, good fluidity, and dissipation ionization [9]. Nonetheless, kerosene has high volatility which gives a negative impact on the environmental [18]. Kerosene is degraded during long-term machining which leads to air pollution. Furthermore, carbon elements tend to attach to the electrode surface due to their high discharge temperature [16, 19]. In addition, kerosene is flammable which can cause irritation to the human skin and respiratory system during processing [20]. KANG and KIM [21] highlighted the role played by kerosene as the dielectric in the EDM process.

Some researchers suggest water as an alternative to hydrocarbon dielectric. Using water as the machining medium in EDM can create zero fire hazards and a safe working place. Furthermore, using water as a dielectric reduces the operation cost. EKMEKCI *et al.* [22] found the intensity of microcracks was reduced when machining with de-ionized water. CHEN *et al.* [23] found a higher material removal rate with a lower relative electrode wear ratio achieved when machining Ti-6Al-4V alloy with distilled water. CHUNG *et al.* [24] raised that by using deionized water the electrode wear can be minimized and the machining rate improved. Also, CHOW *et al.* [25] improved water dielectric by adding additives. The results revealed additional SiC powder boosts the electrical conductivity of the dielectric fluid, increasing the material removal rate, extending the discharge gap between workpiece and electrode, and also improving the removal of debris. KONIG and SIEBERS [26] reveal that erosion in water dielectric acquires higher thermal stability and higher power input achieved under critical conditions, which produce a higher removal rate.

There are previous research reports that vegetable oil has the capability to replace commercial hydrocarbon-based dielectric. Vegetable oils are suggested as alternative dielectrics for EDM because of their non-toxic, easy bio-degradability, higher flash point, higher breakdown voltage and lower volatility [27]. DAS *et al.* introduced transesterified neem as green dielectric fluid for EDM [28]. Further analysis shows that transesterified neem as a dielectric fluid certified 6.2% to 15.6% more removal rate and 12.25% to 15.45% lower surface roughness than kerosene [29]. Researchers also used recycled palm oil and its blends as an alternative for dielectric medium for EDM [27, 30, 31, 32].

Another possible alternative for EDM fluid is a water-in-oil (W/O) emulsion-based dielectric. Water-in-oil dielectric has good insulation, safety, and is environmentally friendly. This statement is supported by LIU *et al.* [16]. The findings of this study show that emulsion-1 and emulsion-2 show higher MRR, lower SR, and higher discharge gaps when compared with kerosene. There is some evidence to suggest that the high viscosity of water-in-oil emulsion creates high pressure which increases material removal rate efficiency [33]. Due to poor stability and high viscosity, water-in-oil nanoemulsion is initiated to compete for the machining performance of EDM using kerosene [34–36]. The finding shows a better material removal rate with a lower relative electrode wear ratio when using water-in-oil nanoemulsion. Overall, there are other researchers [9, 20, 34–36] that strengthen the idea that water-in-oil emulsion can be used as an alternative to the hydrocarbon-based EDM process.

Existing research recognizes the critical role played by water-in-oil emulsion as a dielectric medium. It was found that a single discharge, material removal characteristics is significantly affected by the dielectric medium. However, current research suffers from a paucity of dielectric properties that act alike kerosene to create sustainable electrical discharge machining. In this paper, a study was attempted to conduct an experimental investigation on the micro EDM process with concentrated water-in-sunflower seed oil as dielectric fluid compared with water and hydrocarbon-based dielectric fluid.

2. MATERIALS AND METHODS

Based on the objectives, the research methodology starts with machine parameters, workpiece, electrode and dielectric fluid selection. Follow by an experimental setup where Taguchi Method is used and lastly run the experiments. Data and results are collected and analyzed. An FEA simulation will be conducted to compare with experimental results.

2.1. Preparation of water-in-sunflower seed oil emulsion

The water-in-oil emulsion is a mixture of water and sunflower seed oil with the existence of an emulsifier. The emulsifier uses in this study is Tween 80 (Polysorbate 80, polyoxyethylene sorbitan monooleate), which is a hydrophilic emulsifying agent. The formulated water base dielectric fluid consists of 80% sunflower seed oil + 20% Tween 80 + 95% Deionise water. The properties of distilled water, kerosene and water-in-sunflower seed oil are shown in Table 1. Thermal conductivity & volumetric heat capacity is measure using KD2Pro. Viscosity is measured using programmable rheometer. Thermal diffusivity is the ratio of the thermal conductivity to the heat capacity. Properties of kerosene are used as a control parameter. Firstly, the emulsifier is dissolved in the

Table 1: Properties of distilled water, kerosene and sunflower oil (water-based).

PROPERTIES	DISTILLED WATER	KEROSENE	WATER-IN-SUNFLOWER SEED OIL
Thermal Conductivity (W/m.K)	0.487	0.114	0.414
Volumetric Heat Capacity (MJ/m ³ .K)	4.056	0.777	2.233
Viscosity (cP)	1.060	3.280	1.330
Thermal diffusivity (m ² s ⁻¹)	0.120	0.147	0.185



Figure 1: Portable Electric Discharge Machine (PEDM).

Table 2: Properties of brass and nickel.

PROPERTY	BRASS	NICKEL
Elastic Modulus (N/mm ²)	100000	210000
Poisson's Ratio	0.33	0.31
Shear Modulus (N/mm ²)	37000	79000
Mass Density (kg/m ³)	8500	8500
Tensile Strength (N/mm ²)	478.413	317
Yield Strength (N/mm ²)	239.689	59
Thermal Expansion Coefficient (K)	1.8e-05	1.7e-05
Thermal Conductivity (W/(m·K))	110	43
Specific Heat (J/(kg·K))	390	460
Melting Point (°C)	900–940	1465

sunflower seed oil and stirred at 600 rpm for 60 minutes at 65°C. Then, the distilled water is titrated slowly into emulsified oil at 65°C. After that, the mixture is stirred at 600 rpm for 30 minutes by maintaining the same temperature using a stirrer. After that, water-in-sunflower seed oil emulsion is poured into a vial for further observation. KD2Pro apparatus is used to measure thermal conductivity and viscosity is measured using a rheometer.

2.2. Machine and material selection

Portable Electric Discharge Machine (PEDM) as shown in Figure 1 selected for this study. The first step is to clamp the workpiece on the table and the electrode on the tool holder. Next, choose the capacitance for the experiment and start the process. The process will take a few minutes depending on the parameters chosen for the experiment. The tool and workpiece materials selected for this study are brass and nickel respectively. Their properties are shown in Table 2. The size for electrode was 0.5, 0.6 and 0.8 mm. The selections for dielectric fluids were water, kerosene, and water-in-sunflower seed oil.

2.3. Performance parameters

To evaluate the quality of machining holes, a few parameters have been identified to measure the performance of each machining setup. The parameters which are used are material removal rate (MRR), tool wear ratio (TWR) and circularity of the hole. Each parameter is calculated in a different method using different equipment.

The MRR value usually indicates how fast the tools can machine the workpiece completely. Many elements involve effects the value of MRR of an EDM process such as material properties of the electrode and workpiece, dielectric fluid addition, debris removal and spark produced. Generally, MRR can be calculated by

$$MRR = \frac{W_b - W_a}{t_m} \text{ g/min} \quad (1)$$

Where,

W_b = Weight of workpiece after the machining (g)

W_a = Weight of workpiece before the machining (g)

t_m = Machining time (min)

Tool Wear Ratio (TWR) can also be called electrode wear ratio (EWR) as our tool for the EDM process is an electrode. This value provides the ratio of the weight of the electrode used and the workpiece drilled after the machining process in percentage.

$$TWR = \frac{W_e}{W_w} \times 100\% \quad (2)$$

Where,

W_e = Weight of electrode used (g)

W_w = Weight of workpiece drilled (g)

The circularity of the hole defined the accuracy of the hole drilled into the workpiece by the EDM process. A good EDM process will have a closer value of circularity with the diameter of the electrode [34, 35]. The circularity of the hole can be calculated using equation (3):

$$Circularity = 4\pi \frac{\text{Area of through hole}}{\text{Perimeter of through hole}(P)^2} \quad (3)$$

The rate of removal of metal at varying hole lengths is taper conicity, or also can be termed a gap resistivity [28, 29]. The taper conicity represents the drilled hole accuracy from start to the end, which is

$$Taper\ conicity = \frac{D_{entry} - D_{exit}}{2H} \quad (4)$$

Where,

D_{entry} = Diameter of the hole at the entry

D_{exit} = Diameter of the hole at the exit

H = Thickness of the workpiece

For EDM, it is a non-contact process which means there is no mechanical cutting involved while machining. It only uses electrical sparks which then react with a workpiece to slowly erode the material while the electrode moves through. Therefore, the diameter of the hole will always be bigger than the diameter of the electrode, which is called overcut [28, 29]. The overcut value can be obtained from the diameter of the hole at the entry and the diameter of the tool, as:

$$Overcut = D_{entry} - D_{tool} \quad (5)$$

Where,

D_{entry} = Diameter of the hole at the entry

D_{tool} = Diameter of tool

2.4. Experimental design

The experimental design for this study is based on the Taguchi method, which is to identify the conditions which optimise the performance of the process or product. To achieve the best set of conditions, Taguchi implements the use of the signal-to-noise ratio (SNR). The value is used as the output response of the experiment, which represents the measure of variation when uncontrolled noise factors are present in the system. Taguchi has developed and defined over 60 different SNRs for engineering applications of parameter design. There are three

Table 3: Experimental condition using L_9 orthogonal array.

NO	WORK-PIECE	ELECTRODE	ELECTRODE DIAMETER (MM)	FEED RATE (MM/MIN)	CAPACITANCE (μ F)	DIELECTRIC FLUID
1	Nickel	Brass	0.5	3	100	Water
2	Nickel	Brass	0.5	5	470	Kerosene
3	Nickel	Brass	0.5	8	1000	water-in-sunflower seed oil
4	Nickel	Brass	0.6	3	470	water-in-sunflower seed oil
5	Nickel	Brass	0.6	5	1000	Water
6	Nickel	Brass	0.6	8	100	Kerosene
7	Nickel	Brass	0.8	3	1000	Kerosene
8	Nickel	Brass	0.8	5	100	water-in-sunflower seed oil
9	Nickel	Brass	0.8	8	470	Water

categories in determining the SNR performance characteristics: which are Larger the Better; Nominal the better; and Smaller the better.

L_9 orthogonal array method with 4 factors and 3 levels has been chosen to run the experiment. For the L_9 array, there are four independent factors which have 3 different levels each. Factors selected are the diameter of the electrode, feed rate, capacitance and dielectric fluids. All the factor selected has three different level. The parameters used to evaluate the performance are material removal rate (MRR), tool wear ratio (TWR) and circularity of the machining hole. Using the Taguchi L_9 orthogonal array, 9 sets of experiments are created to fulfil the project objective. Table 3 show the sets of experiment design for this study.

2.5. Steps in design of experiment

The procedures of performing an experiment according to the following few steps:

- i. Problem statement
- ii. Selection of performance parameters
- iii. Identifying control factors
- iv. Selection of factor levels and possible interactions
- v. Design of orthogonal array
- vi. Experiment set up
- vii. Run experiment and data collection
- viii. Result statistical analysis and interpretation

2.6. Finite Element Analysis (FEA)

FEA can be described by considering an object is going through any stress or force such as a component under load or temperatures subject to heat input through computer simulation. The design components of FEA simulation consist of elements, nodes and mesh. For this study, FEA simulation was conducted to simulate the mechanism of heat transfer during the EDM process. The simulation is done which duplicates the heat produced by the sparks as the heat source and transfers it into the workpiece. Then using FEA, a mesh was created to calculate the heat distribution on the workpiece.

3. RESULTS

3.1. Material Removal Rate (MRR)

The weight of the workpiece and electrode were measured three times and averaged. All sets of experiments are also repeated five times and the average was recorded. Figure 2 shows an example of measured circles after each experiment.

From the graph of MRR for each conducted experiment as shown in Figure 3, it shows that experiment 3 which is a combination of 0.5 mm electrode, 8 mm/min feed rate, 1000 μ F capacitance and using water-in-sunflower seed oil as the dielectric fluid has the best MRR performance. The value of high capacitance and feed rate does



Figure 2: Example of measurement taken after conducted experiment.

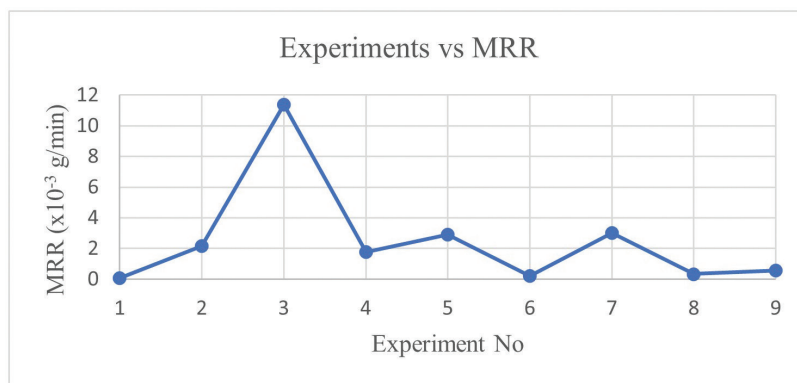


Figure 3: Experiments vs MRR.

impact the MRR substantially. This finding is consistent with the analysis of μ EDM drilling on of Ti-6Al-4V alloy, according to this analysis capacitance is found to be most significant parameters for MRR rather than effect of other parameters like pulse on time, voltage and tool rotation speed [37]. This finding was also reported by ABIDI *et al.* [38], capacitance is indicated as the most dominant factor for Ra, TWR, and MRR and is followed by electrode material and discharge voltage. An increase in the capacitance and voltage resulted in an increase in discharge energy, and this leads to higher MRR [38]. The lowest MRR value is recorded in experiments 1,6 and 8. The low capacitance again gives the biggest impact, while kerosene as a dielectric fluid in experiment 8 makes it worse due to its properties where it generates smaller sparks compared to water-in-sunflower seed oil dielectric fluids.

Then, the larger the better statistical analysis is done to find the main effects plot for means and signal-to-noise (SN) ratio. From Figure 4(a), the means value for each parameter shows that 0.5 mm electrode, 8 mm/min feed rate, 1000 μ F capacitance and water-in-sunflower seed oil dielectric fluids give the highest means value for MRR. As mentioned in the literature review, W/O emulsion could be used as the dielectric fluid of sinking EDM could lead to obtaining higher MRR than kerosene [39]. This also accords with earlier finding, which showed that using W/O nanoemulsion as a dielectric in sinking EDM, a nearly 34 times higher MRR obtained in rough machining, and a better machined surface with no recast layer is attained in finishing machining [40]. Figure 5(b) shows the effect of the parameter on the MRR performance. The capacitance gives the biggest impact followed by the diameter of the electrode, feed rate and dielectric fluids. The higher capacitance will produce bigger sparks, hence eroding more workpieces for every penetration. Moreover, the larger the diameter means the bigger the surface area for sparks to happen. For feed rate, the higher the value means the faster the

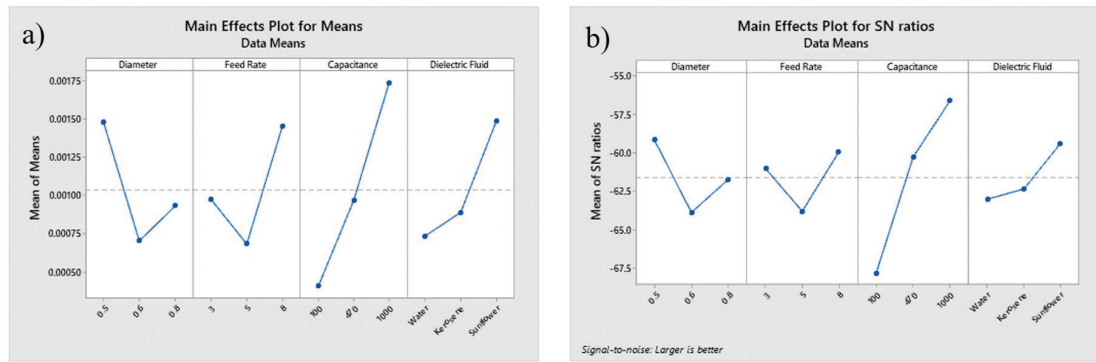


Figure 4: Taguchi analysis on MRR for (a) means and (b) SN ratios.

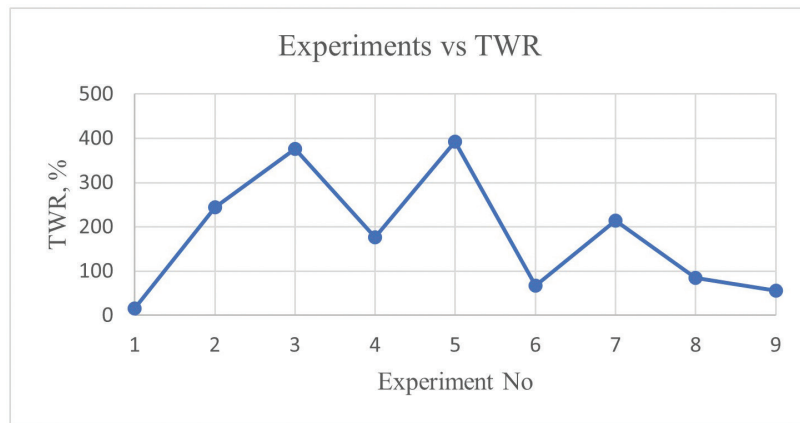


Figure 5: Experiments vs TWR.

penetration is made. The best combination for good MRR performances is 0.5 mm electrode, 5 mm/min feed rate, 1000 μ F capacitance and water-in-sunflower seed oil dielectric fluids. SINGH *et al.* [41] found increase in capacitance will increase MRR. This is because an increase in discharge energy will erode more material from the workpiece. The hole diameter is increased due to an increased material removal as well as increased average overcut [41]. These findings also concurrent with CYRIL *et al.* [42]. Their research highlights that as capacitance and voltage increase, the discharge energy also increases, which causes more heat generation. Thus, higher MRR is observed for higher levels of voltage and capacitance [42].

3.2. Tool Wear Ratio (TWR)

From Figure 5, the best TWR performances were obtained from experiment 1. The TWR is only 15.57% due to the low feed rate and capacitance. As compared to the very low performance of the MRR in experiment 1, this eventually helps to preserve the tools from wearing too fast. Besides that, it also used water as a dielectric fluid which has been proven to be better in reducing the TWR of the electrode. The lowest performance can be observed in experiments 3 and 5. The main influence can be seen from the high value of capacitance and feed rate. This simply increases the power and damage absorbed by the electrode for each spark created, hence the tool tends to wear faster than the workpiece being removed.

The analysis of mean and SN ratios for TWR is shown in Figure 6. The best performance based on the means is obtained at 0.8 mm electrode, 3 mm/min feed rate, 100 μ F capacitance and water as dielectric fluid. From Figure 6(a), the importance of parameters can be observed where the most affecting parameters are capacitance followed by dielectric fluid, feed rate and lastly diameter of the electrode. This is due to the higher the capacitance used means the bigger and more powerful the sparks will be generated. Hence, the electrode will conduct a larger heat transfer which contributes to higher mass from the tools' experience of deformation. This finding is consistent with that ABIDI *et al.* [38] who found an increase in the capacitance and voltage resulted in an increase in discharge energy, and this leads to higher TWR [38]. In accordance with the present results, previous studies have demonstrated that the most influencing parameters for TWR were found to be capacitance

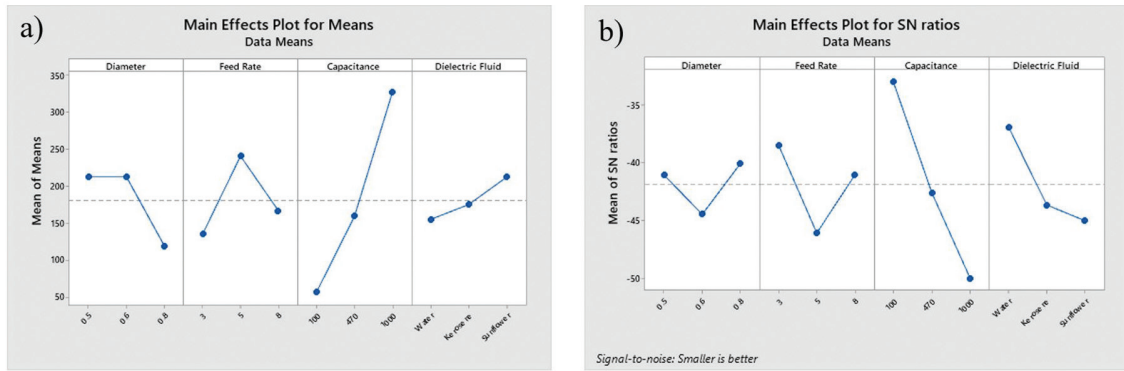


Figure 6: Taguchi analysis on TWR for (a) means and (b) SN ratios.

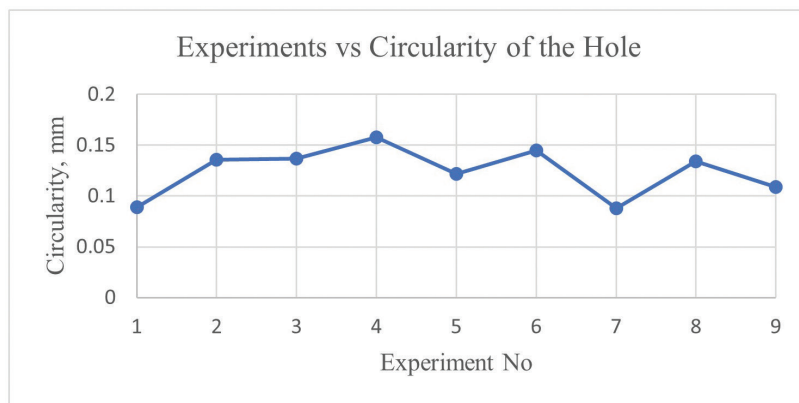


Figure 7: Experiments vs circularity of the hole.

and feed rate [43]. Comparison of the findings with those of other studies confirms that the discharge energy is high when the values of capacitance and voltage are high, resulting high TWR due to a large amount of heat generated. Therefore, as the level of voltage and capacitance increases the TWR also increases [42]. Besides that, the best combination for good TWR performances based on the SN ratios are 0.8 mm electrode, 3 mm/min feed rate, 100 μ F capacitance and water as dielectric fluid as shown in Figure 6(b).

3.3. Circularity of the hole

The circularity of the hole for each experiment is shown in Figure 7. The best circularity of the hole was observed in experiments 1 and 7. From both experiments, the feed rate used is only 3 mm/min. This contributes to the good performance when machining the hole. The slow feed rate avoids any extra force exerted on the workpiece for each penetration done. Each penetration was also much controlled when compared to the 8 mm/min feed rate which tends to create vibration in the electrode. This can cause the circularity of the hole to be large and uneven. The capacitance shows not much impact where set one uses 100 μ F capacitance while experiment 7 uses 1000 μ F. The power of sparks generated did not really impact the circularity as long the electrode was steadily moved for every penetration.

Figure 8 shows the mean and SN ratios for the circularity of the hole. From Figure 8 (a), the means value shows the best circularity can be obtained when using a 0.8 mm tool electrode, 3 mm/min feed rate, 1000 μ F capacitance and water as dielectric fluid. Dielectric fluid is ranked as the most influential followed by diameter of the electrode, feed rate and lastly capacitance. These results reflect those of TIWARY *et al.* [44] who also found that better circularity when using pure deionized water [44]. For the diameter of the electrode, it performs better in larger diameters due to the electrode being much more firmly attached to the machine when compared to the smaller diameter. This then contributes to less vibration when doing the machining. Besides that, the best combination for circularity based on SN ratios are 0.6 mm electrode, 5 mm/min feed rate, 470 μ F capacitance and water-in-sunflower seed oil dielectric fluids as shown in Figure 8(b). These combinations are using medium-level parameters for the diameter, feed rate and capacitance which will result in steady sparks and

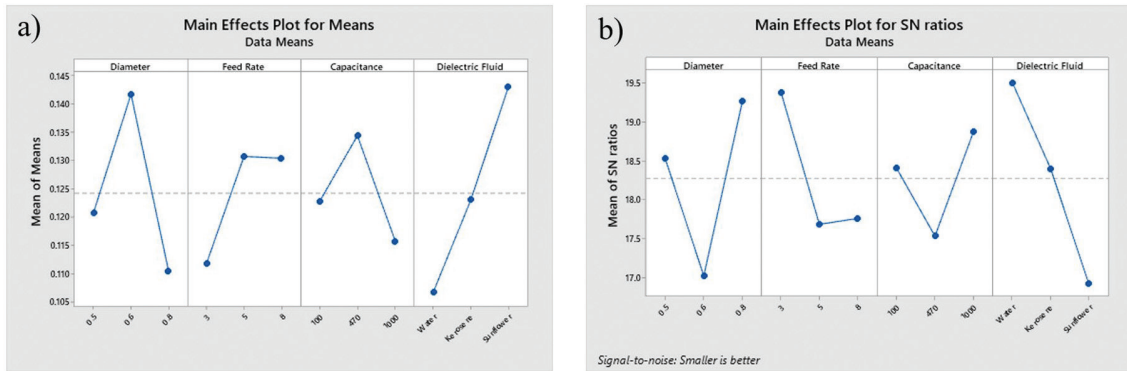


Figure 8: Taguchi analysis of the circularity of the hole for (a) means and (b) SN ratios.

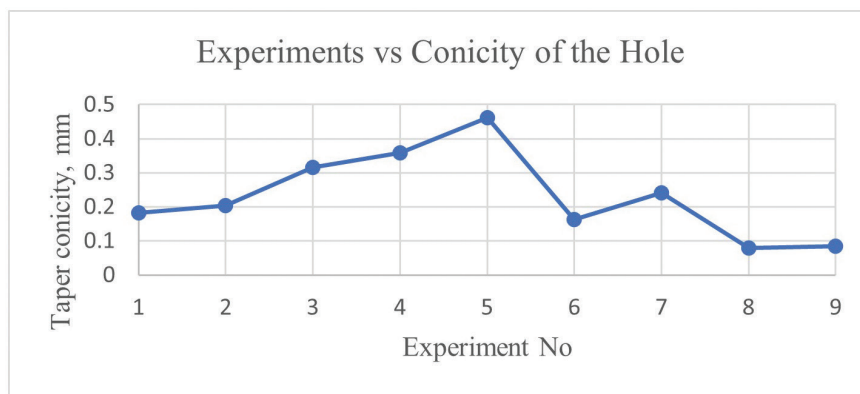


Figure 9: Experiments vs taper concity of the hole.

movement of penetration. This will then provide a better circularity of the hole. This also accords with the earlier observations, which showed that the interrelation of capacitance and electrode material significantly affects the circularity error [38]. When the higher energy plasma channel is disrupted, more material is expelled away from the melted workpiece. As consequence, more debris accumulate in the working gap. It then cause the increase in circularity deviation, due to the occurrence of more sparks where the debris concentration are higher, which explain the dielectric breakdown easily occurs [45]. These results corroborate the findings of the previous work which found at higher peak currents, circularity increases, due to higher discharge energy which leads to bigger craters sizes [46]. Not only that, previous studies also found the effect of different dielectrics on the circularity at micro-EDM. At low discharge current, high degree of circularity of the micro-holes is found using kerosene than de-ionised water. But as the peak current increases, the circularity factor of micro-hole is poorer using kerosene compared to de-ionised water [47]. In addition, circularity error decreased with increase in bore diameter with radial orbital strategy. In the case of the die-sinking machining strategy, initially circularity error is found at minimum and starts increasing with increase in bore diameter up to 11 mm [48].

3.4. Taper concity of the hole

Figure 9 shows the results of taper concity of the hole, experiment 8 and 9 shows the best taper concity value with the value of 0.079 and 0.0856 respectively. The main contribution can be seen from the capacitance where both sets use 100 μ F and 470 μ F, respectively. A low capacitance will require lower times needed to be recharged for the sparks generation. Therefore, the spark generated will be consistent for every penetration which will contribute to a constant diameter hole. Besides that, the larger diameter used also means it's easier for the machine to grip the electrode. Thus, it reduces the vibration of the electrode and provides more stability during each penetration from the entry of the hole up until the bottom. The highest value for the taper concity is observed in experiment 5. This is due to the small diameter combined with high capacitance and feed rate will create a great impact on the electrode when a spark is generated.

The best machining parameters and most influential parameters for the taper concity of the hole are shown in Figure 10. From Figure 10(a), the means value shows that for better taper concity of the holes, the

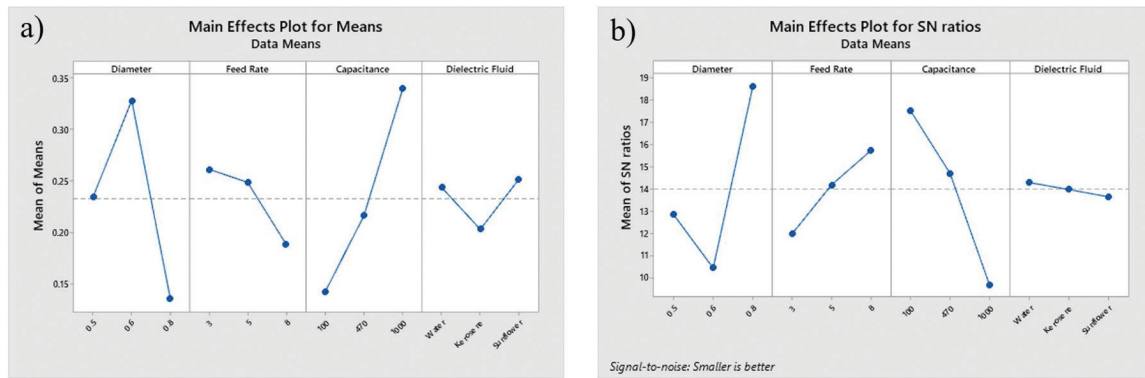


Figure 10: Taguchi analysis on taper conicity of the hole for (a) means and (b) SN ratios.

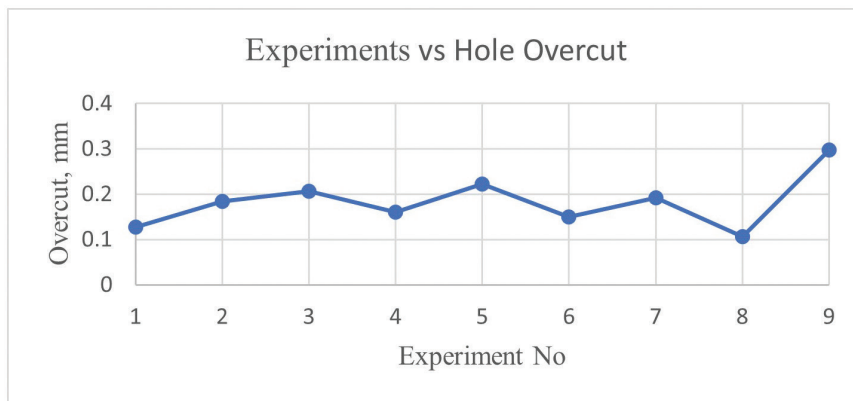


Figure 11: Experiments vs overcut of the hole.

lower the values the better it is. Therefore, the best parameters based on the means value are 0.8 mm electrode, 8 mm/min feed rate, 100 μ F capacitance and kerosene as dielectric fluid. From Figure 10(b), the most influential parameters are the diameter of the electrode and followed by capacitance, feed rate and lastly dielectric fluid. The best combination also can be determined based on the SN ratio values which are closer to zero. Thus, the best combination for better taper conicity based on the SN ratio is 0.6 mm electrode, 3 mm/min feed rate, 1000 μ F capacitance and water-in-sunflower seed oil dielectric fluids. Even though the combination is using a high value of capacitance, it is combined with a low feed rate which allows more time to recharge the capacitor. Therefore, a more stable, and consistent spark can be generated for every penetration.

3.5. Overcut of the hole

In the electrical discharge machining (EDM) process, the overcut give significant effects on precision and accuracy of the workpiece dimensions. Nonetheless, the overcut and the final dimensions of workpiece are difficult to predict due to the non-linear, complex relationship among the electrode wear, the machine positioning accuracy, electrical discharging parameters, and electrode diameter. The debris present in the machining zone generally decrease the insulating property (breakdown voltage) of the dielectric medium and thus increases electrical conductivity. Due to this, the debris present in the machining zone triggered secondary discharges, and increase the size of the feature produced [49]. The overcut average of the hole for each experiment is shown in Figure 11. The lowest overcut value can be obtained from experiment 8 which uses machining parameters of 0.8 mm electrode, 5 mm/min feed rate, 100 μ F capacitance and water-in-sunflower seed oil dielectric fluids. The major contribution to overcut is due to the capacitance value. The capacitance value will determine how big is the sparks generated. Therefore, due to the lower value of capacitance from experiments 1, 6 and 8, they recorded good performance on the overcut of the hole. The highest value of overcut can be observed in experiment 9. This is due to the influence of water as dielectric fluid will generate a bigger spark compared to oil-based dielectric fluid. This finding broadly supports the work of other studies that also found at higher peak current overcut is higher when using deionized water compared to pure kerosene dielectric. At high discharge energies, more decomposition of deionized water occurs and release more oxygen. This oxygen effect the machining efficiency and triggered the second discharge spark. This secondary discharge sparking cause the rise in overcut compared to machining with pure kerosene [50].

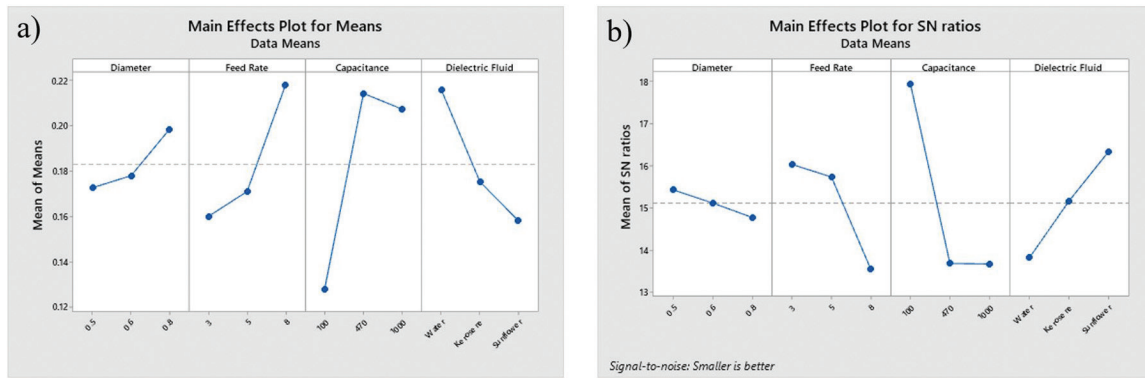


Figure 12: Taguchi analysis on overcut of the hole for (a) means and (b) SN ratios.

The high feed rate also will impact the overcut since it will create more vibration in the electrode which will affect the stability of the electrode on each penetration.

Taguchi analysis was done on the overcut of the hole to find the major effects parameters and also the best combination for the optimum performance was shown in Figure 12. From Figure 12(a), the best overcut performance for each parameter was observed at 0.5 mm electrode, 3 mm/min feed rate, 100µF capacitance and water-in-sunflower seed oil dielectric fluids. Low feed rate and capacitance will produce the generation of a more stable spark which is important in preventing overcut. Besides that, water-in-sunflower seed oil dielectric fluids also provide better surface finishing compared to water-based. Based on Figure 12(b), the most influential parameters is the capacitance and followed by dielectric fluid, feed rate and lastly diameter of the electrode. Besides that, the best combination which having closer SN values to zero is 0.8 mm electrode, 8 mm/min feed rate, 1000µF capacitance and water as dielectric fluid. The combination seems not really accurate since the results show that higher capacitance and feed rate combined together with water as dielectric fluids will result in a larger spark generated. This will cause more overcutting to happen. However, from a different view, the fast feed rate will create not enough time for the capacitor to recharge the high value of capacitance, hence sparks generated will be less powerful than the actual value.

3.6. Simulation of finite element analysis

FEA simulation was done to simulate the mechanism of heat transfer during the EDM process. The simulation is done which duplicates the heat produced by the sparks as the heat source and transfers it into the workpiece. Then using FEA, a mesh was created to calculate the heat distribution on the workpiece. Based on the results, the area which exceeds the melting temperature of the workpiece which in this case is nickel (melting temperature = 1465°C) will be removed and then the next heat source will be put in again, and the process continues until it reaches the end of the hole. There are some assumptions made in order to complete the simulation such as the temperature of the sparks generated is assumed to be equal to the melting temperature of nickel. The ambient temperature and convection coefficient is assumed to be in the air at room temperature ($T_{\text{ambient}} = 300\text{K}$, Convection coefficient = 75 W/m².K). This assumption was made and fixed for every diameter used because this will simplify the result obtained from the simulation. The simulations were done on SOLIDWORKS using three different diameters of the electrode (0.5 mm, 0.6 mm and 0.8 mm). The simulation is started by creating a cuboid shape (1.5 mm × 1.5 mm × 1.0 mm) which represents the workpiece. This is to provide a surface to place the heat source equal to the size of the diameter of the electrode. Then, the cuboid shape will be used for heat transfer simulation. The heat source will be placed on the top surface which follows the diameter used, while the other surface is set as a convection area. After finishing setting the thermal source, the mesh will be created, and run the FEA simulation. Examples of simulation using tool electrode diameter 0.5 mm for heat transfer after 1st, 14th and 23rd penetration are shown in Figure 13. The red zone indicates the material was melted and removed away.

Next, the depth of the cut will be measured and the results of the depth of cut for every penetration for each diameter are shown in Figure 14. The number of penetration needed to complete the hole are 23, 20 and 17 for the diameter of 0.5 mm, 0.6 mm and 0.8 mm respectively. The larger the diameter, the lower the penetration required to drill fully through. This is due to the area of the heat source at the starting being bigger compare to the lower diameter. Therefore, a bigger area of the workpiece will receive the heat from the source for every penetration and be considered to melt away.

Besides that, from Figure 15, based on the line pattern, the depth of cut for every penetration was consistent in the early phase up until almost the end of the hole before it increases gradually. This was due to thermal

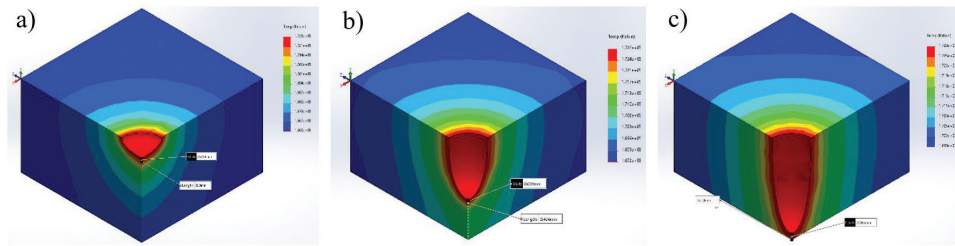


Figure 13: Result of simulation of heat transfer after (a) 1st, (b) 14th and (c) 23rd penetration with 0.5 mm diameter tool electrode.

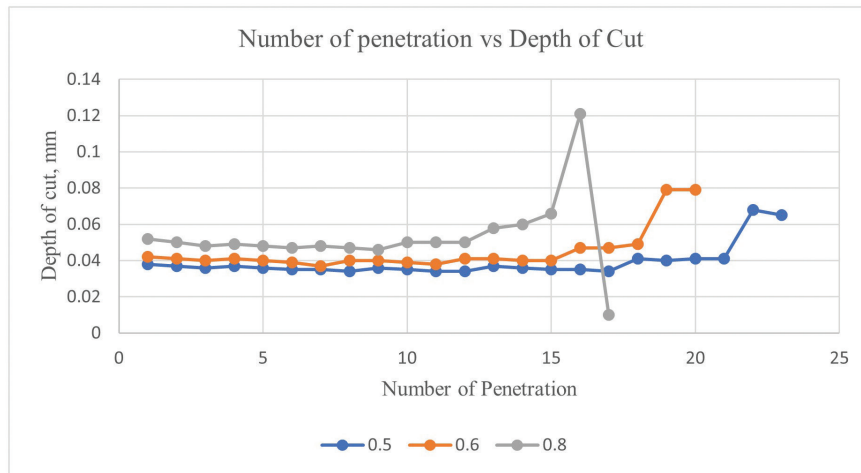


Figure 14: Number of penetration vs depth of cut for all diameters.

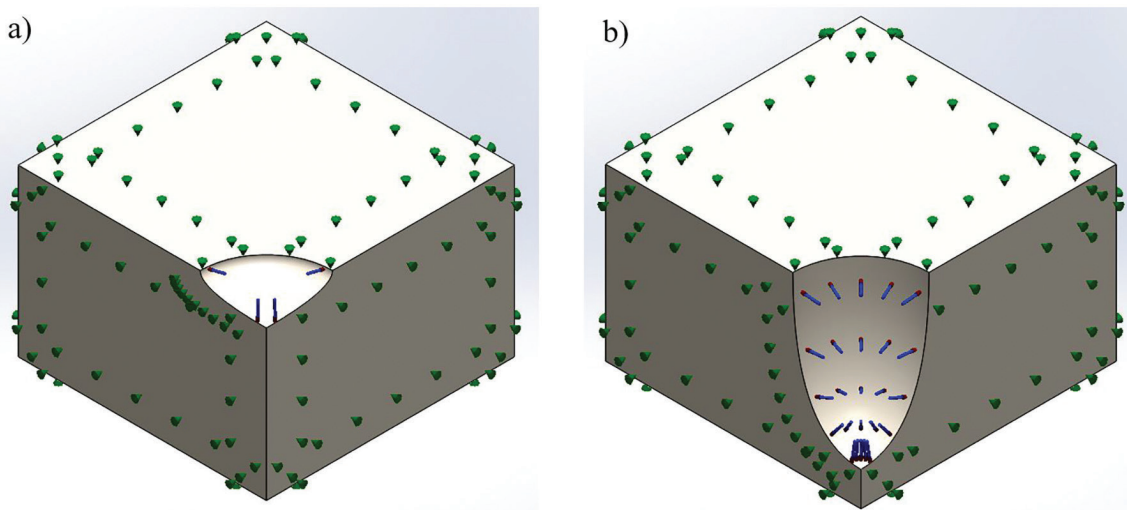


Figure 15: Area of conduction (blue) and convection (green) at (a) early phase and (b) ending phase.

loads used are only conduction for the heat source and convection for heat loss to the surrounding, where only the depth is changing for each penetration and not the diameter of the heat source which is kept fixed until the end. Thus the area of the melted workpiece is almost consistent for every penetration in the early phase.

When the depth is getting towards the end of the hole, the cut increases due to the convection area getting smaller towards the end of the shape as shown in Figure 15(b). This is because most of the hole is already removed, hence it left a smaller area of convection to occur, thus resulting in more heat trap inside the cuboid rather than loss to the atmosphere due to convection. Furthermore, the area for heat source also becomes more concentrated at

the bottom part since the shape is getting narrower compared to in the early phase. This will result in greater heat energy concentrated at the bottom part of the hole which increases the depth of the melted workpiece.

4. CONCLUSIONS

This study uses various machining parameters combinations and dielectric fluid to determine the optimal machining parameters for improving the performance of micro hole fabrication using EDM on nickel using brass electrode based on the MRR, TWR, circularity, taper conicity and overcut of the hole. Results shows that improved of 324.45% of MRR when 1000 μ F of capacitance is used compared to 100 μ F. However, in return the TWR also can increased up to 487.45% and overcut of the hole also boost up to 67.82% due to the very high capacitance. Besides that, dielectrics fluids influence the circularity of the hole the most where up to 34.02% improvement is recorded for water compared to sunflower oil. Next, diameter of the electrode and capacitance influence the conicity of the hole, where up to 142.96% and 139.73% of improved performance is observed, respectively. Lastly, finite element analysis on heat transfer of EDM using three different diameters (0.5 mm, 0.6 mm and 0.8 mm) also has been successfully simulated using SOLIDWORKS simulations.

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