Powder Mixed Dielectric in Electrical Discharge Machining of Inconel 718

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ABSTRACT

Inconel 718 is one of the most difficult to cut material due to its, high hardness, high toughness, and poor thermal conductivity results in heat concentrated in the cutting zone, making it ineffective to be processed through conventional machining. So usually, an electrical discharge machining (EDM) is chosen in order to overcome such limitations. However, EDM is known as a slow machining process. Thus, by employing powder mixed in the dielectric fluid it is believe to enhance the machining efficiency. To achieve high performance in EDM for this research, higher peak current, I_p *up to 40A, pulse duration,* t_{on} *up to 400µs and powder concentration,* C_p *up to 4g/l were selected as the main parameters. Copper tungsten (CuW) was used as an electrode. The circulating dielectric system called High Performance EDM (HPEDM) was applied to conduct the experiment involving powder mixed dielectric. Their influence on the machinabilities of the material removal rate (MRR), and electrode wear rate (EWR), were experimentally investigated. The surface topography of the machined work piece and surface morphology of the electrode also have been observed. The results have shown that, at a highest* I_p*=40A and the lowest* t_{on}*=200µs with* C_p*=4g/l yields the highest MRR. The improvement is almost 50% when comparing without powder concentration at the same parameter settings. In the case of EWR, lowest value of EWR was obtained at* I_p*=20A,* t_{on}*=400µs and* C_p*=0g/l.*

Keywords: *Powder mixed dielectric, electrical discharge Machining, Surface topography, Surface morphology, Inconel 718.*

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Introduction

Inconel 718 are considered to be difficult to cut material and mostly used in the aerospace industry. Almost half of the manufacturing of the engine alloy are made from Inconel material. The formation of complex shapes by this material along with reasonable speed and surface finish is not possible in traditional machining. Therefore, EDM is one of the most suitable processes to shape this alloy in order to satisfy production and quality requirement [1]. As a non-conventional machining method, EDM is important to facilitate complex machining problems in difficult-to-machine materials especially, for complicated geometric cutting and shape clearance [2, 3]. However, it is such a time-consuming process that its time related cost was almost the top issue to manufacture engineers. As the tool eroded into work piece, accumulation of debris in the cutting zone usually caused poor EDM results. That resulted not only in poor machining stability, but also severe damage to the machined surface [4]. Therefore, it is highly potential to improve the machining speed which leads to higher productivity and to improve surface finish due to safety concern especially in the aerospace industry.

Tool electrode for EDM must have basic properties such as electrical and thermal conductivity, a high melting temperature, low wear rate, and resistance to deformation during machining [5]. From this point of view, to cut special materials such Inconel is the present great importance especially when make a decision what types of electrode materials used and basically material having good electrical and thermal conductivity with a high melting point are preferred to choose. The introduction of new material is continuous and the demand for engineers to produce complicated shapes within tighter tolerances in many industrial applications are gradually increasing [6]. Furthermore, the widespread use of jet engine has increased demand for materials that have excellent high temperature mechanical and chemical properties. Demand for hotter, more powerful and more efficient engines led to the development of ‘super-stainless’ alloys, or super alloys [7]. Therefore, wrong selection of tool electrode to cut this material will cause higher time consume for machining and thus productivity become slower. It is becoming worst when variable setting parameters often chosen such peak current, (I_p) and pulse on-time, (t_{on}) is low in order to control the tool wear and surface quality.

Although in EDM, the material removal mechanism are resulted from the electrical discharge energy, the gap conditions between the two electrodes have strong impact on the machining accuracy and efficiency. This is because the EDM process in the common dielectric oils is very unstable owing to arcing or short-circuiting. To improve this phenomena, many efforts have been directed to enhance the EDM process stability. One of the method is to introduce an additive into the dielectric fluid that was often reported to be effective in improving EDM performance [8]-[10]. It was found that by the use of powder mixed in dielectric oil in EDM could improve the surface quality and material removal rate as well [11, 12]. Powder mixed dielectric in EDM (PMEDM) process is still not widely used in industry. Many fundamental issues of these new processes, including machining mechanism with various additives, are still not well understood [13]. In terms of high speed EDM, maximum MRR is really desired to improved productivity rate and reducing production cost for contribution to industry. Therefore, the complexity of this process, especially from the effects of the physical properties of the suspended additive particles in relation with EDM process parameters, requires further investigations.

Experimental Details

Nickel-base super alloys (NBSA) Inconel 718 were selected as the material for the work piece. The work piece is cut into the desired dimension (40mm x 30mm x 10mm) by using EDM wire cut before machining process is conducted. The tool electrode used is Copper Tungsten (CuW) in cylindrical shape with the dimension of Ø10mm x 30mm (h). CuW is expensive electrode material, has relatively high in electrical conductivity and high hardness. The selected size of electrode is considered appropriate since the machining depth of cut is just 3mm.

For the dielectric additive, nano Alumina (Al_2O_3) powder as shown in Figure 1 with particle size average 45nm to 50nm has been selected. Alumina powder has a high level of thermal conductivity, which is related to its electrical conductivity. Due to the high thermal conductivity of Alumina, more heat is distributed and dissipated to the work piece surfaces to limit the size of the craters produced. Alumina powder also proves to be the best addition in terms of particle concentration, mainly due to their combined effects of low electrical resistivity, high thermal conductivity and low density. Low electrical resistivity creates a high spark gap and high thermal conductivity takes more heat away. Both effects together lead to low electrical discharge power density resulting in lower gas explosion, thus only shallow craters are produced on the machined surface. Furthermore, the low density of the Alumina powder corresponds with low explosive impact upon the melted zone, generating fine grinding effects [14]. The properties of the Alumina powder is shown in the Table 1.

Figure 1: Nano Alumina powder

Table 1: The properties of nano Alumina powder

Properties	Value
Density, g/cm^3	0.97
Specific heat J/Kg.ºK	880
Thermal conductivity, W/m.K	35
Coefficient of thermal expansion, $^oC^{-1}$	8.4×10^{-5}
Particle size	45-50nm

Table 2: Experimental condition

Parameters	Levels
Workpiece material	Inconel 718
Tool electrode	CuW
Peak current, I_p (A)	20, 30, 40
Pulse duration, t_{on} (µs)	200, 300, 400
Powder concentration, C_p (g/l)	0, 2, 4
Pulse interval, t_{off} (µs)	Base on 0.8 duty factor
Voltage, V	120
Electrode polarity	Positive
Powder mixed	Nano Alumina (50nm)
Dielectric fluid	Kerosene
Depth of cut	3mm

For this study, the peak current and pulse duration were selected as the main parameter process and the other parameter is set as constant. The machining was run until the depth of cut reach to 3mm for each test. Table 2 shows the experimental condition and parameters setting for the research. The full factorial design was selected in order to look for the trend of the effect of the variable parameters selected to the responses.

For the main equipment, the CNC Sodick High Speed EDM die sink AQ55L (3 Axis Linear) was used to conduct the experiment without powder mixed (conventional EDM), then for experiments involving powder mixed dielectric, an external tank device called high performance electrical discharge machining device (HPEDM) as shown on Figure 2 are attached on the CNC Sodick High Speed EDM.

Figure 2: HPEDM system

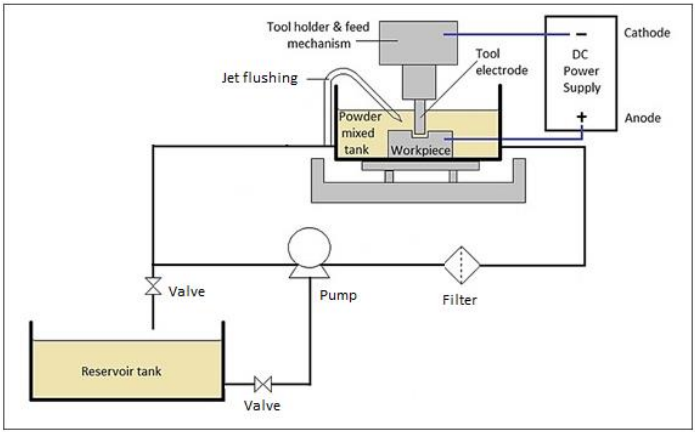


Figure 3: Simple schematic diagram of HPEDM system

The HPEDM device has its own controller and functioning as ‘plug and play’ to the conventional EDM machine. Besides working tank and reservoir tank, HPEDM device has an electric pump to circulate the dielectric and a few valves to control the filling, circulating and cleaning of dielectric during PMEDM operation. It is also supplied with 2 types of filter which is capable to trap the debris from magnetic material and non-magnetic material such as Inconel 718. The schematic diagram of HPEDM system is shown in Figure 3.

The responses for this study is to determine the material removal rate (MRR), and electrode wear rate (EWR). The weight of the workpiece and electrodes before and after machining were measured in order to obtain MRR and EWR. Although other ways of measuring MRR do exist, in this work the material removal rate values were calculated by the volume of workpiece loss per machining time and the unit is mm^3/min. After completion of each machining process, the workpiece was dried before the weight measurement to ensure there is no debris and dielectric was present on the work piece. The following equation was used to determine the MRR value:

$$MRR = {}^{m_W}/_{\rho_W t} \quad (1)$$

where ;
MRR = material removal rate (mm^3/min)
m_w = mass loss of work piece (g)
ρ_w = density of work piece (Inconel 718 = 0.00819 g/mm^3)
t = machining time (min)

Then, the EWR was measured according to the volume of electrode wear per machining time and the unit is mm^3/min. The following equation was derived to determine the EWR value:

$$EWR = {}^{m_e}/_{\rho_e t} \quad (2)$$

where;
EWR = Electrode wear rate (mm^3/min)
m_e = mass loss of electrode (g)
ρ_e = density of electrode (CuW = 0.0133g/mm^3)
t = machining time (min)

For the case of surface topography, the Scanning Electron Machine (SEM) JSM-6380 was used to observe the machined surface of the work piece. The image captured from the SEM can be used to justify the effect of selected parameters to the MRR of Inconel 718. Then, using Optical Microscope (OM) Nikon Eclipse LV150NL, the surface morphology of the electrode after machining was examined. The observation of the electrode surface morphology is used to explain the result gathered from the EWR perspective.

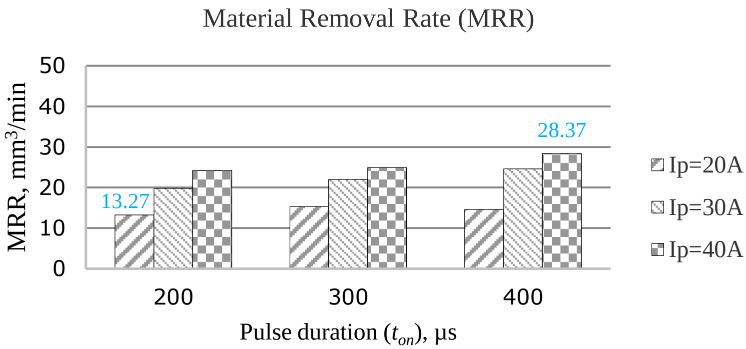
Result and Discussion

The focus of the experiments is to study the effect of higher Peak current (I_p), pulse duration (t_{on}) and powder concentration (C_p) to the selected responses. This various parameters have significant influence on the quality of machining of Inconel 718. It affects the Material removal rate (MRR), surface topography and Electrode wear rate (EWR). These results were extracted from a series of full factorial experiment which overall trials of 27. Then the comparison of performance is made between the conventional EDM and the EDM with powder suspension dielectric.

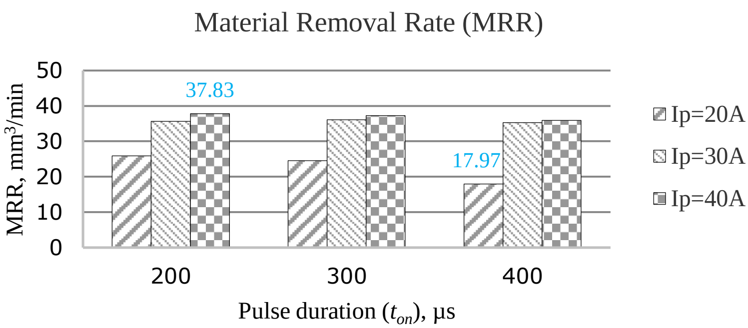
Material removal rate

The effect of Peak current (I_p), Pulse durations (t_{on}) and Powder concentration (C_p) on the MRR is shown in Figure 4. In conventional EDM (C_p=0g/l), an increased in I_p, MRR increased for all levels of t_{on} [15, 16]. The increase of I_p generates high energy intensity that leads to rapid melting of workpiece materials. Overall, MRR increased at higher t_{on}. In general, the power of the spark and frequency defined by the number of pulses per second determines the process performance. Low frequency usually uses in the roughing operation because it consists of long t_{on} of the spark that resulting a larger, deeper and broader crater. The low frequency and high power combination results in high metal removal. As t_{on} increases, the frequency reduces and consequently longer t_{on} increases material removal. Based on Figure 4(a) it is revealed from the results that the combination of highest I_p=40A and longest t_{on}=400μs generated more MRR with value 28.37mm^3/min when EDM without powder mixed in a dielectric fluid.

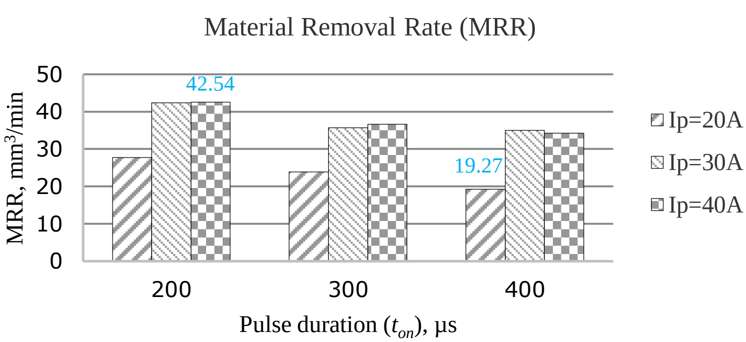
However, the experiment revealed that MRR yielded by conventional EDM is low. Thereafter, with the suspension of 2g/l of nano Alumina powder into the dielectric fluid, MRR is increased up to 37.83mm^3/min at I_p=40A and t_{on}=200μs as shown in Figure 4(b). Then, as indicated in Figure 4(c), the maximum MRR=42.54mm^3/min is produced at C_p=4g/l. This is due to the additive particle suspended in the dielectric has an important influence on the discharge process by increase both the gap distance and the discharging rate. The high electric field energizes the conductive powder particles. These conductive particles form chains at different places under sparking area, which bridges the gap between the tool electrode and workpiece material. Due to this bridging effect, the gap voltage and insulating strength of the dielectric decreases, this causes easy short circuiting and hence the early explosion in the gap between the electrode and the work piece which result in faster machining time and increased the MRR [17, 18].



(a) C_p = 0g/l (without powder mixed)



(b) C_p = 2g/l



(c) C_p = 4g/l

Figure 4: Effect of peak current (I_p) and pulse duration (t_{on}) on MRR at a different powder concentration (C_p) [(a) C_p=0g/l, (b) C_p=2g/l and (c) C_p=4g/l]

It was noticed that, when EDM machining with powder suspension, the MRR was decreased at longer t_{on}. It is noted that a continuation lengthening of the t_{on} does not necessarily improve the MRR. This is particularly evident for I_p from 20A to 40A, where it is observed that the MRR decreased with an increment value of t_{on}. This phenomenon is attributed to the extension of the electric plasma channel associated with excessive t_{on} and C_p. When the plasma channel becomes large, its energy density decreases, and the heat energy absorbed by the workpiece per unit area is reduced [19,20]. The highest MRR when using CuW electrode is 42.54mm^3/min produced at C_p=4g/l with I_p=40A and t_{on}=200µs. The improvement about 50% as shown in Figure 5 in comparison to the highest MRR achieved at parameter setting without powder concentration (C_p=0g/l).

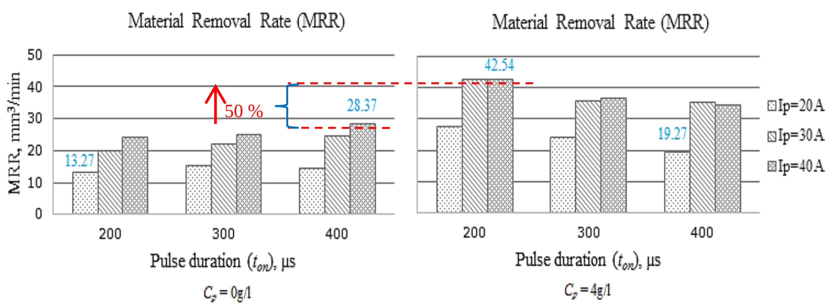
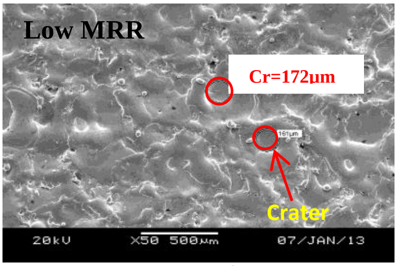


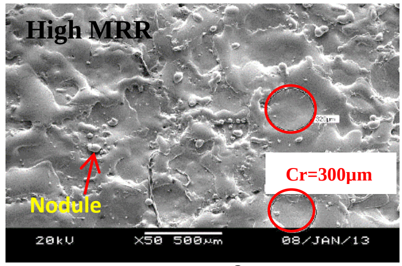
Figure 5: The improvement of MRR when EDM machining of Inconel 718 employing powder mixed dielectric

Figure 6 shows the surface topography of the Inconel 718 machined surfaces after EDM machining. The topography figures are listed based on the lowest and the highest MRR value at different powder concentration. It appears that the conditions of craters are smaller and flatten at lower I_p and without powder suspension in the dielectric fluid as observed in Figure 6(a-1). At high MRR, when higher I_p was supplied, it increased the amount of thermal energy that melts and vaporizes the machine surface in larger area which produced widen craters and globules. This is due to the fact that, when I_p is increased, more intensively the spark had struck to the surfaces. The impact from the spark that leave the deterioration of the machined surface. There are also nodules on the machined surface produced from reattachment of molten metal during an improper flushing condition as shown in Figure 6(a-2). The distribution of the nodules is more prominent on the machined surface with high MRR in comparison of low MRR.

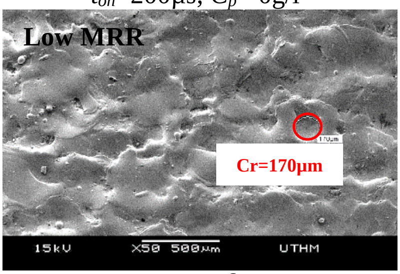
Based on the Figure 6(b-1), when powder concentration, C_p=2g/l was promoted into the dielectric fluid at low I_p=20A and the highest t_{on}=400µs, the surface topography of the workpiece is in bad condition. This is due to the suspended powder particles into the dielectric fluid has increased the MRR and usually in EDM machining, high MRR will cause severe condition on the machined surface. Then, when higher peak current is used, the surface condition is worst as shown in Figure 6(b-2). The same surface condition also can be observed when the highest powder concentration, C_p=4g/l was supplied in the dielectric fluid as shown in Figure 6(c-1) and 6(c-2).



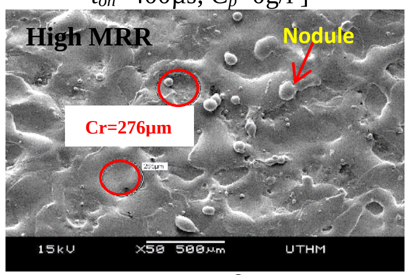
a-1) MRR=13.27mm^3/min; I_p=20A; t_{on}=200µs; C_p= 0g/l



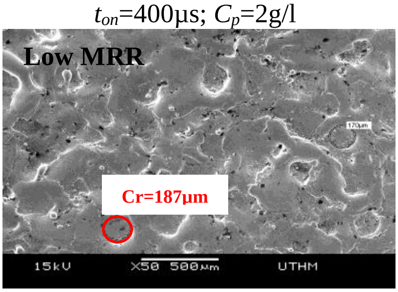
a-2) MRR=28.37mm^3/min; I_p=40A; t_{on}=400µs; C_p=0g/l]



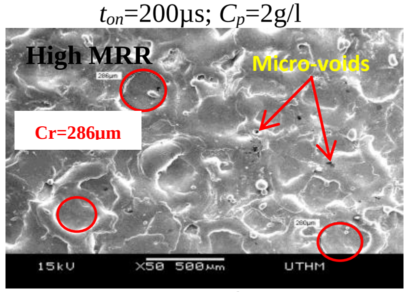
b-1) MRR=17.97mm^3/min; I_p=20A; t_{on}=400µs; C_p=2g/l



b-2) MRR=37.83mm^3/min; I_p=40A; t_{on}=200µs; C_p=2g/l



c-1) MRR=19.27mm^3/min; I_p=20A; t_{on}=400µs; C_p=4g/1



c-2) MRR=42.54mm^3/min; I_p=40A; t_{on}=200µs; C_p=4 g/

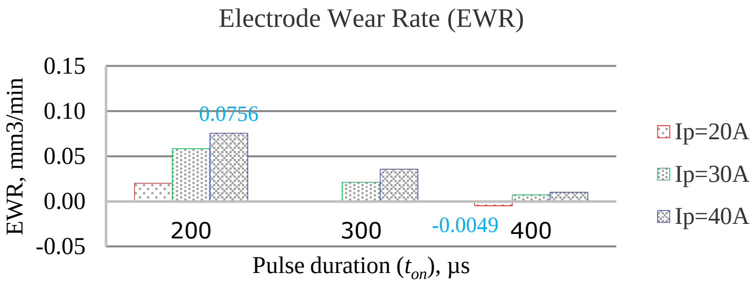
Figure 6: The EDM machined surface topography of Inconel 718 at a different powder concentration (C_p) [a) C_p=0g/l, b) C_p=2g/l, and c) C_p=4g/l]

There is also an existence of nodules and micro-voids on the machined surface. This is due to existence of powder additive in the dielectric fluid caused early explosion in the gap thus produced faster erosion, more molten metal is ejected from the surface and some of the molten metal reattached on the machined surface. At high MRR, the size of the nodule is bigger and this is related to the size of craters produced during high discharge energy reattached to the machined surface. While, for the formation of micro-voids is due to the released of bubble gases from the underneath of machined surface. The presence of large volume of gases in the channel during the discharge, will lead to a high super saturation of gas in the molten metal. The discharge energy in the plasma channel melts the material, but is not all the molten metal will eject away from the machined surface. When the remaining molten material solidified on the surface, the gas bubbles would explode from the molten material, and result in micro voids [21].

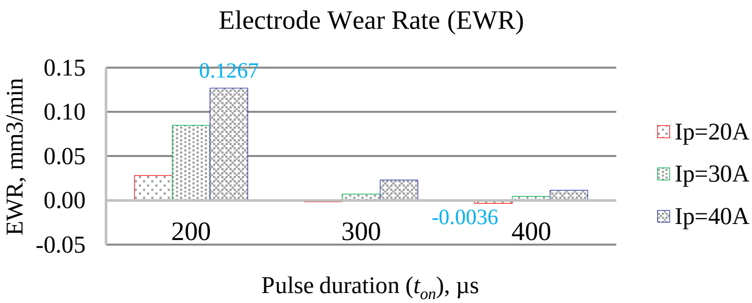
Electrode wear rate

Figure 7 shows the effect of Peak current (I_p), Pulse duration (t_{on}) and Powder concentration (C_p) on EWR of CuW electrode. As indicated in Figure 6(a), at C_p=0g/l, the EWR was increased with the increase of I_p for all conditions of t_{on}. It can be seen that the EWR was increased significantly from 0.0201mm^3/min to 0.0756mm^3/min with increasing of I_p from 20A to 40A. It is obvious that the pulse energy increases as the peak current increased. The increasing of energy intensity will produce more heat, which leads to increase the melting of the electrode which is effected to the increment of EWR. However, an increasing in t_{on} the EWR was decreased for all value of I_p used. An explanation to this may be given by the longer discharge durations that promote more melting of the workpiece and solidification of the molten material on the electrode surface during the spark. Consequently the MRR increases and the EWR decrease.

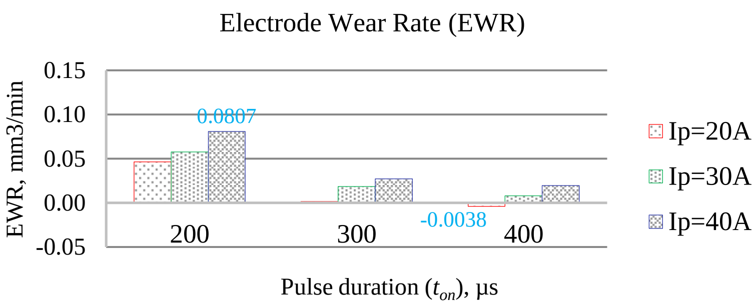
It seems like the effect of powder concentration in EDM machining of Inconel 718 by using CuW is not significant in improving the EWR. At I_p=40A and C_p=2g/l, the EWR reaches its highest value at 0.1267 mm^3/min as shown in Figure 7(b). The reason behind is that, the introduction of powder will increase discharge intensity and produce more spark at a time. Therefore, more erosion of the tool electrode occurred. Then the EWR decreased to 0.0807mm^3/min when C_p=4g/l was used as shown in Figure 7(c) due to high concentration of powder, high spark intensity was generated, hence the temperature of the sparking area was increased. As a consequence, the decomposed carbon from dielectric during the rise of temperature was attached to the electrode surface and become wear resistant layer. Thus, the EWR decreased at a further increment of C_p. The lowest EWR is approximately -0.005mm^3/min at a combination of 20A of peak current and 400μs of pulse duration without powder concentration.



(a) C_p = 0g/l



(b) C_p = 2g/l

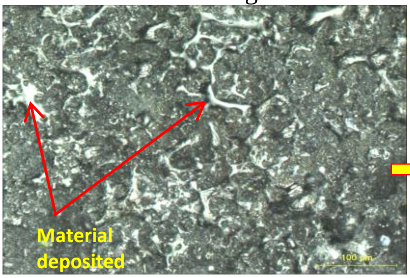


(c) C_p = 4g/l

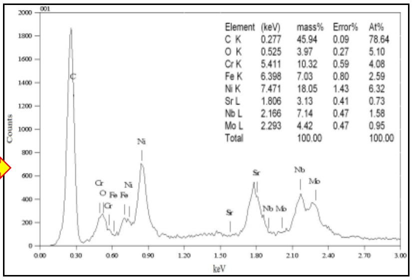
Figure 7: Effect of peak current (I_p) and pulse duration (t_{on}) on EWR of CuW electrode at a different powder concentration (C_p)

The results also showed that the lowest value of EWR is not only very small but also reaches negative values. This is due to the fact that the measurements of the weight of CuW electrodes evidently were heavier after the machining process resulted in a negative weight loss. An explanation for this is due the longer discharge duration promotes more melting of workpiece material and solidification of the molten material and the deposition of the carbon on the electrode during the spark [22]-[24] as shown in Figure 8 until Figure 10, and the EDX analysis has proved that the deposition has occurred on electrode surfaces which were identified as a carbon layer originating from the used oil based dielectric and machined workpiece material [24, 25].

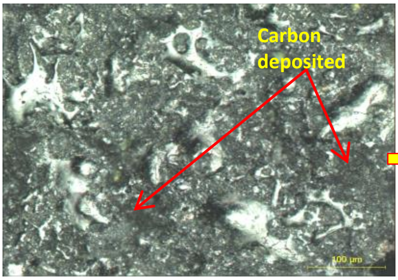
Figure 8 - 10 shows the surface morphology of electrode according to low and high EWR at a different powder concentration, C_p. Referring Figure 8(a-1) at low EWR with pure dielectric condition (C_p=0g/l), the formation of the deposited material on the electrode surface looks thinner in shape. Then, at high EWR as shown in Figure 8(b-1), the deposited material looks widen due to higher peak current was melted the deposited material more than at low peak current, thus the deposited material on electrode surface is flattened. However, according to EDX testing as shown in Figure 8(a-2), at low EWR, the mass percentage of Carbon, C=45.94% from decomposed dielectric and Nickel, Ni=18.05%, which is the main elements in Inconel 718 were slightly higher in comparison to at high EWR as indicated in Figure 8(b-2) with C=17.15% and Ni=17.09%. Thus, we could say that, this deposited phenomena was contributed in decreasing the EWR.



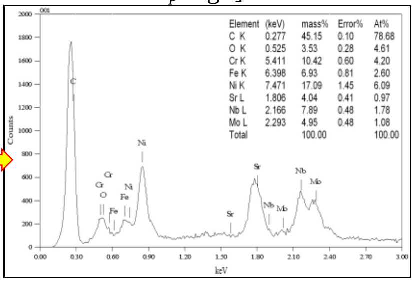
a-1) Low EWR [I_p=20A; t_{on}=400µs; C_p=0g/l]



a-2) EDS test [I_p=20A; t_{on}=400µs; C_p=0g/l]



b-1) High EWR [I_p=40A; t_{on}=200µs; C_p=0g/l]

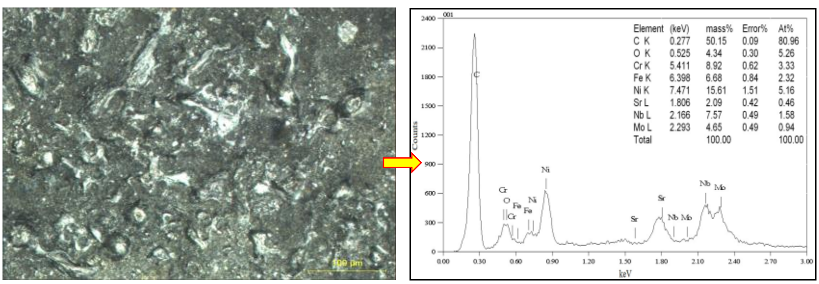


b-2) EDX test [I_p=40A; t_{on}=200µs; C_p=0g/l]

Figure 8: Surface morphology and EDS testing of the CuW electrode at a powder concentration, C_p=0g/l [a) Low EWR and b) High EWR]

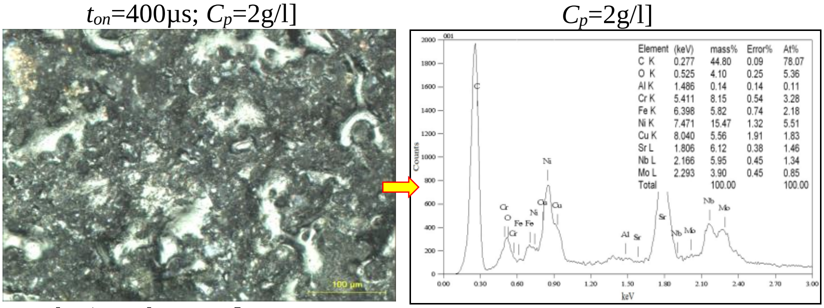
It is observed that the same phenomena also occurred after 2g/l and 4g/l of powder concentration has been suspended in the dielectric fluid as stated in Figure 8 and Figure 9, respectively. The morphological of electrode surface was distributed with small and thin deposited of Carbon and alloy element of material at the low EWR condition. Conversely, the distribution of the deposited material at High EWR was wide and thick due to high heat generated at high I_p.

However, again after EDX testing for both conditions at low and high EWR at C_p=2g/l and C_p=4g/l, the mass percentage of deposit Carbon and material is higher at low EWR in comparison to at high EWR. Hence, this is a proof that, the deposition effect helped to decrease the EWR. It is a fact that, even at low I_p, the wear of electrode still occurs, but due to the deposition effect, the weight of electrode may increase after the machining process and contributed in the negative value of EWR as shows in previous Figure 7.



a-1) Low EWR [I_p=20A; t_{on}=400µs; C_p=2g/l]

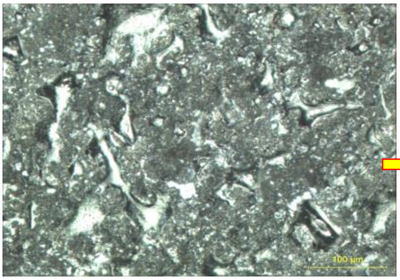
a-2) EDX test [I_p=20A; t_{on}=400µs; C_p=2g/l]



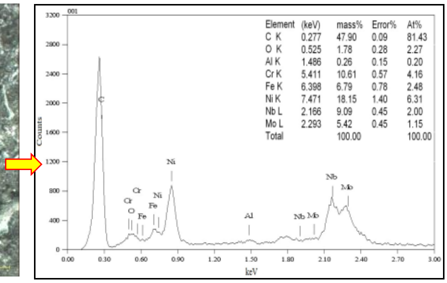
b-1) High EWR [I_p=40A; t_{on}=200µs; C_p=2g/l

b-2) EDS test [I_p=40A; t_{on}=200µs; C_p=2g/l]-

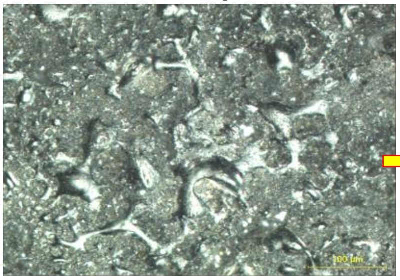
Figure 9: Surface morphology and EDS testing of the CuW electrode at a powder concentration, C_p=2g/l [a) Low EWR and b) High EWR]



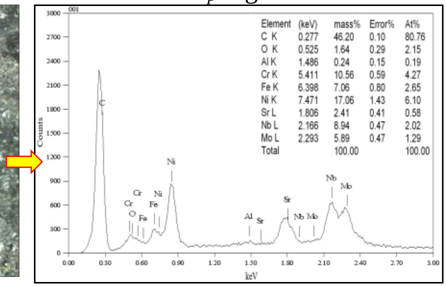
a-1) Low EWR [I_p=20A; t_{on}=400μs; C_p=4g/l]



a-2) EDS test [I_p=20A; t_{on}=400μs; C_p=4g/l



b-1) High EWR [I_p=40A; t_{on}=200μs; C_p=4g/l]



b-2) EDS test [I_p=40A; t_{on}=200μs; C_p=4g/l]

Figure 10: Surface morphology and EDS testing on the CuW electrode at a powder concentration, C_p=4g/l [a) Low EWR and b) High EWR]

Conclusion

The primary goal of this research is to enhance the machinability of the difficult to cut material of Inconel 718 in EDM by introducing of powder mixed in a dielectric fluid. In order to accomplish the objectives, the circulating system for a powder mixed dielectric system called High Performance Electrical Discharge Machining (HPEDM) has been fabricated. The experimental work was conducted in two phases; first, the conventional EDM was used and second, the HPEDM system was applied to the conventional EDM and run the experiment with the same parameters setting. High peak current and high pulse duration with different powder concentration was selected to improve the machining speed. The experiment also conducted at full factorial design by using Copper tungsten (CuW) electrode. From the analysis, the following conclusions could be drawn.

i. The Peak current (I_p) and Powder concentration (C_p) is the most contributing factor that improves the material removal rate (MRR).

The MRR is increased as the peak current and the powder concentration increased. The result shows the highest of MRR obtained at 40A and 4g/l of peak current and powder concentration respectively. The improvement is about 50% compared to without powder concentration (C_p=0g/l).

ii. The result shows that the introduction of powder in dielectric fluid will helps to enhance the machining efficiency. It is also found that within selected parameters, 4g/l is the best powder concentration to achieve high MRR.

iii. The electrode wear rate (EWR) is increased when peak current is increased, but inversely proportional with pulse duration. The EWR is decreased with the longer pulse duration at the same peak current value.

iv. The EWR did not show any significant improvement when concentrations of powder mixed are introduced in dielectric fluid. The lowest EWR is -0.0049mm^3/min at I_p =20A, t_{on} =400µs with C_p=0g/l.

v. Through the EDX analysis, it was found that the carbon from dielectric and the work piece material has been deposited on the electrode surface. The negative value for the EWR is due to this deposited effect on the electrode after machining process.

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