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Material removal rate and machining accuracy of electrical discharge machining (EDM) of Inconel 718 using copper electrode

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Abstract. Electrical Discharge Machining (EDM) is a non-contact thermal machining process capable of machining conductive and semi-conductive materials. These capabilities bring to admission of machining materials that characteristically difficult to machine such as Inconel 718 due to its ability to maintain hardness at elevated temperature. Nickel based super alloy, Inconel 718 is one of the difficult to machine material that widely used in such high temperature application. The purpose of the study is to examine the Inconel 718 machinability by applied variable parameters such as peak current, pulse duration and repetitive used of electrode. To obtain the high performance measure in EDM, the selected peak currents were high where it is from 20 to 40A while for pulse duration is from 200 to 400 μ s. The performance measure that being evaluated are material removal rate (MRR), surface topography and machining accuracy. This research used Copper as electrode due to its high electrical conductivity and achieved highly in MRR. With the series of repetition used of electrode, the carbon layer known as black layer will formed at the surface contact of electrode. The relationship between the parameters and performance measure were more profound through the combination of machining parameters and black layer on the electrode. At high material removal rate, the surface topography of Inconel 718 look rougher with bigger sizes of nodules and craters produced. In the case of machining accuracy, it was found that, overall diameter overcut are less than 3.47%. The result shows that, even applying high peak current and pulse duration, the results of the machining accuracy is still acceptable.

1. Introduction

Nickel based super alloy, Inconel 718 is one of the material that machining by nonconventional machining such as Electrical Discharge Machining (EDM). Inconel 718 is a nickel-based high strength and high thermal resistance super alloy. Due to it has good resistance to fatigue, creep, corrosion at high temperature, Inconel 718 is widely used in gas turbine engines, steam turbines, nuclear power plants, rocket engines and spacecraft structural components [1]. This alloy is characteristically difficult to machine due to its ability to maintain hardness at elevated temperature which otherwise is very useful for hot working environment. 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 [2].

EDM is a non-contact thermal machining process capable of machining conductive and semi-conductive materials regardless of their hardness. With the used of EDM, highly accurate geometrically



complex and extremely difficult-to-machine materials can be machine compare with other conventional machining [3]. EDM is an extensively used to produce die and mould-making industry to generate complex cavities, aerospace, automotive industry and surgical components [4].

EDM is a thermoelectric process in which material is remove from work piece by erosion effect of series of electric discharges (spark) between tool and work piece immersed in dielectric liquid. The discrete electrical discharge will occurrence of sparks at the spark gap and as the results, the workpiece will be involved in material removal process. The eroded particles (debris) flushed away by dielectric liquid. Physical and metallurgical properties do not create any limitation for the materials to be machine on EDM, as there is no physical contact between tool and work piece [2].

One of the important decision in EDM when to cut the difficult-to-machine is the type of electrode. The electrode has to be high melting temperature, low wear rate and the cost is reasonable. Since the shaped electrode defines the area in which the spark erosion will occur, the accuracy of the part produced after EDM is high. After all, EDM is a reproductive shaping process in which the form of the electrode is mirror in the workpiece [4].

The machining accuracy becomes important when close tolerance components are required to be produce for space application and also in tools, dies and moulds for presswork, plastic moulding and die-casting. In the other hand, MRR for EDM operation is somehow is slower than with traditional machining methods, where the chips are produced mechanically [5]. Thus, this study has been perform in order to look for the effect of repetitive use of copper electrode by applying high peak current and pulse duration to the MRR and machining accuracy when EDM machining of Inconel 718.

2. Methodology

Before run the experiment, the top surface of workpiece, Nickel based super alloys, Inconel 718, flattened by grinding machine. The Copper electrode with diameter of 8mm flattened by lathe machine. The same electrode will be use repeatedly for the whole trials. The conducting of experiments using a standard Die-sinking EDM machine, Sodick AQ55L with custom-made working tank. This research aimed to investigate the roughing stage in EDM by applied 80% of duty cycle. The EDM experimental conditions and parameters summarized in table 1.

Table 1. Experimental conditions.

Parameters	Levels
Peak current, I_p (A)	20, 30, 40
Pulse duration, t_{on} (μs)	200, 300, 400
Pulse interval, t_{off} (μs)	Based on 80% duty cycle
Voltage, V	120
Electrode polarity	Positive
Dielectric fluid	Kerosene
Depth of cut	3mm

The weight of the workpiece and electrode for initial and after machining was measure using a digital weighing scale with four decimal point accuracy for MRR collected data. The microstructure of the surface workpiece after machining was taken using Scanning Electron Microscope (SEM), while for diameter measured of the machined hole and electrode was taken using flexible measuring machine with four decimal point accuracy. Figure 1 shows the experimental setup before running the EDM operation. The following equation was use in this research:

$$\text{Duty cycle} = \frac{\text{Pulse On time}}{\text{Pulse On time} + \text{Pulse Off time}} \quad (1)$$

$$\text{MRR(g/min)} = \frac{\text{weight}_{\text{before}} - \text{weight}_{\text{after}}}{\text{machining time}} \quad (2)$$

$$\text{Diameter overcut (\%)} = \frac{\text{diameter machining} - \text{diameter electrode}}{\text{diameter electrode}} \times 100\% \quad (3)$$

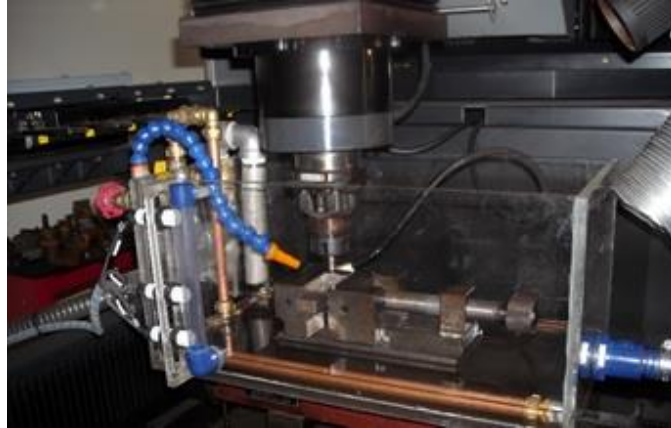


Figure 1. Experimental setup.

3. Results and discussion

Table 2 shows the experimental results for EDM of Inconel by using Copper electrode.

Table 2. MRR and machining accuracy result.

Peak current, IP (A)	Pulse duration, T_{on} (μs)	MRR (g/min)	Diameter overcut (%)
20	200	0.0591	2.77
20	200	0.0685	3.07
20	200	0.0720	2.62
20	300	0.0321	3.24
20	300	0.0317	2.74
20	300	0.0354	3.35
20	400	0.0216	3.47
20	400	0.0222	3.26
20	400	0.0216	3.31
30	200	0.1325	2.77
30	200	0.1433	2.61
30	200	0.1349	2.90
30	300	0.0973	2.83
30	300	0.1165	2.61
30	300	0.1232	2.78
30	400	0.0709	3.46
30	400	0.0818	2.59
30	400	0.0973	2.80
40	200	0.1685	2.99
40	200	0.1838	2.97
40	200	0.1784	3.03
40	300	0.1324	2.89
40	300	0.1590	2.97
40	300	0.1607	2.68
40	400	0.1213	2.92
40	400	0.1277	2.98

40	400	0.1241	2.92
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3.1. MRR Analysis

The highest MRR value is 0.1838g/min on the second hole (40A, 200 μ s), while the lowest is 0.0216g/min on the first hole (20A, 400 μ s) and third hole (20A, 400 μ s) shown in Figure 2. This shows that the highest MRR own by the highest peak current in this experiment. Figure 2 shows MRR value increase proportionally with increasing the peak current with all pulse duration conditions. These phenomena happen to attribute the high peak current in large impulsive force towards workpiece during high frequency series of discrete electrical discharges. Further facilitates the melting and vaporization process, resulting faster machining time [2].

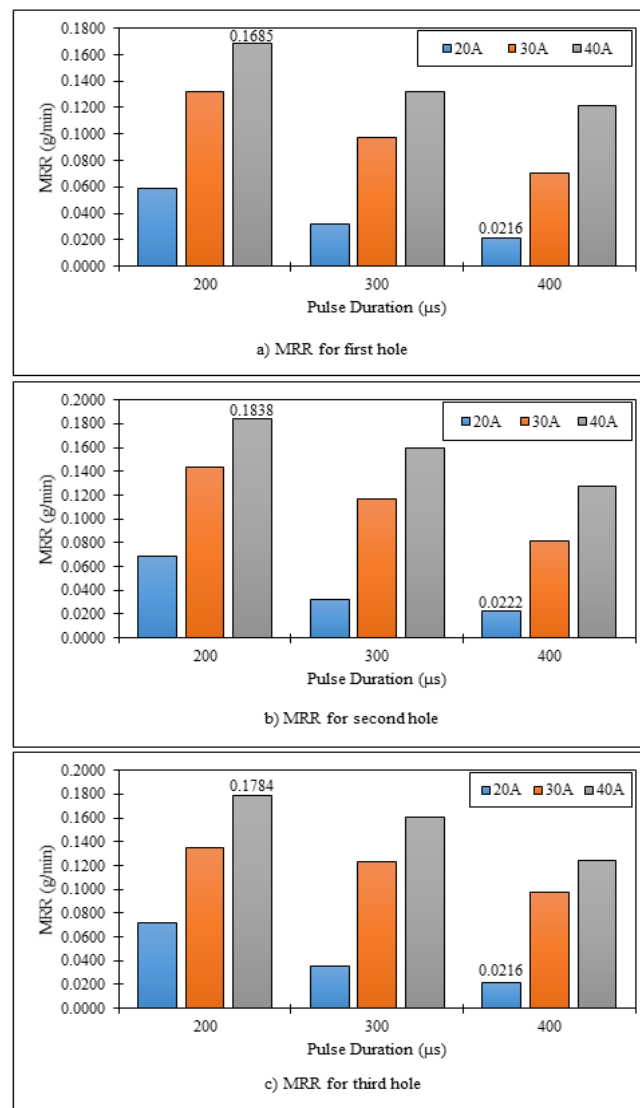


Figure 2. Effect of peak current and pulse duration on MRR by repetition used of electrode [(a) first hole, (b) second hole and (c) third hole].

As shown in figure 2, the highest MRR obtained by 200 μ s pulse duration for each hole as 0.1685, 0.1838 and 0.1784g/min respectively. As demonstrated, the MRR keep decrease as pulse duration increased from 200 to 400 μ s. this results proved that by continuously increasing the pulse duration does not necessarily improve the MRR. To illustrate this result, the higher pulse duration makes the longer

extension of the plasma channel to collapse and resulting the bigger size of plasma channel. Further, its will ensue reduction on its energy density and heat energy per unit plasma [6]. Thus, by increasing pulse duration resulting decrease in MRR. It is notice that, the highest MRR obtained at second hole with 0.1838g/min compare to the first hole with 0.1685g/min with 9.08% of increment. Then, the MRR is slightly decrease at the third hole with 0.1784g/min. This is due to the formation of carbon layer known as black layer on the contact surface of electrode at second hole and third hole. When the thermal energy process through high frequency series of discrete electrical discharges between the electrode and workpiece happens, the molten material been evacuating on the surface of workpiece. Crater is form on the workpiece surface while on electrode surface, the forming of black layer occurred as react with dielectric fluid through pyrolysis occurring during the discharge plasma [7]. The results was corresponding with Rajesha et. al. [8], they found that with the high peak current, MRR could improve with assistant of carbon deposited on the electrode.

This could explain that black layer on the electrode are harder than electrode materials that resulting difficult erosion to the electrode base and improve in increasing MRR. However, the effect of carbon is complex and still not fully discover on the aspect of the plasma breakdown such ionization [9].

3.2. Surface topography analysis

In order to simplify the surface topography result, two different magnifications for each parameter were observe, respectively. Figure 3 shows three-dimensional SEM images for surface topography of Inconel 718 machine by EDM that indicate the highest and lowest MRR for first hole. It was notice that the surface topography characteristic are closely relate to the MRR and directly depends on the applied peak current. Referring to figure 3(a), at low MRR, the micro geometry characteristics of the surface shows the existence of craters, micro-cracks, nodules, voids, pork marks and globules.

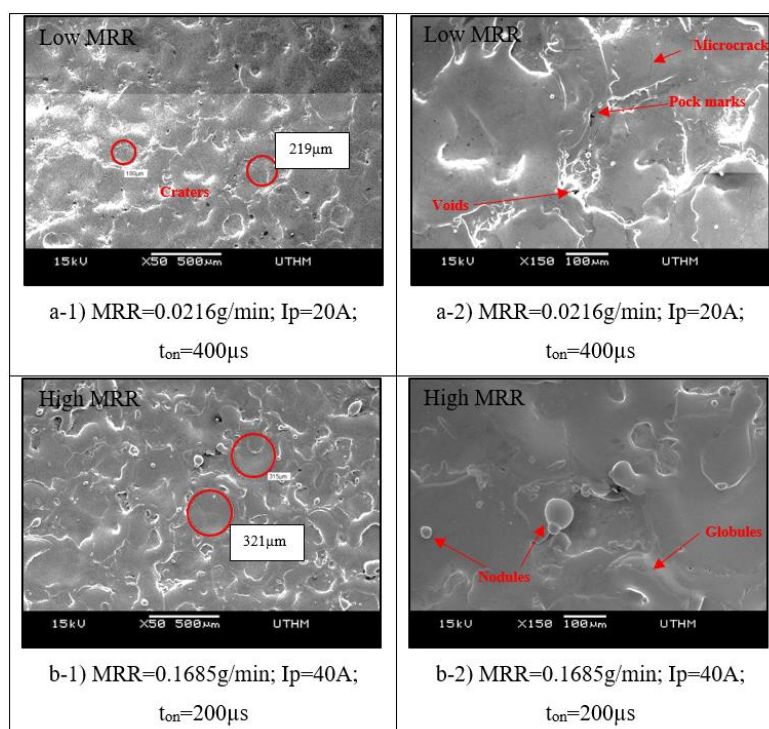


Figure 3. Surface topography of Inconel 718 at first hole with different magnification.

However, in figure 3(b) at high MRR, the craters and nodules size were noticeable bigger than low MRR, which is for low MRR was 219µm, and the high MRR was 321µm. Besides that, the globules become thicker and the craters got deeper. This could be explain by low MRR the pulse duration was in

high setting resulting more material melted at long time and cause the molten material not swept away from the surface workpiece. Hence, the nodules and globules of the debris formed [10]. Besides, with the high peak current, the massive material melting made the nodules and globules become multi-layer. On the other hand, pork mark produced by the re-solidification of the materials that made the structure become sharp-edge-geometry [11].

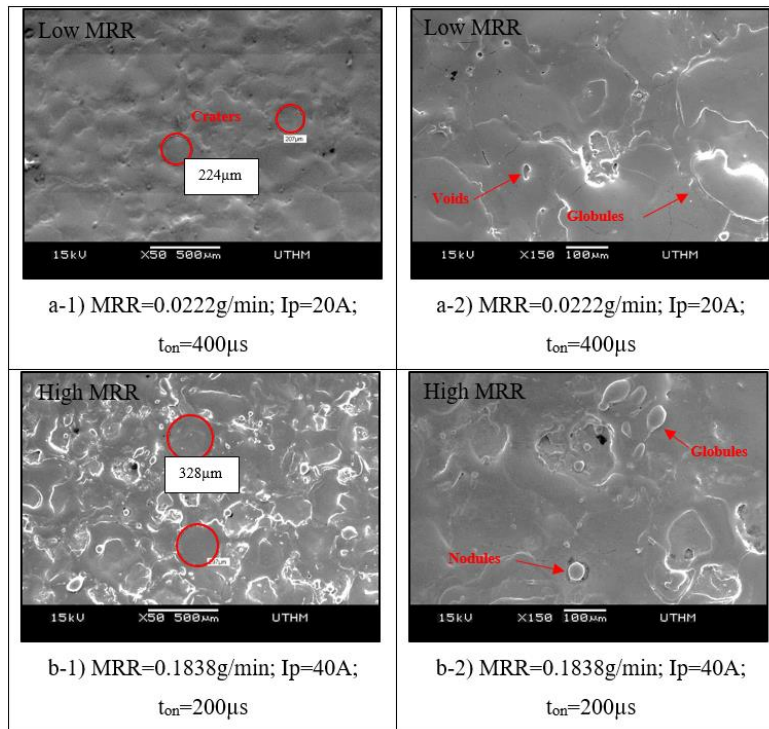


Figure 4. Surface topography of Inconel 718 at second hole with different magnification.

Based on figure 4, when electrode was use for second time with the same peak current and pulse duration, the surface topography at low MRR and high MRR produced slightly rougher surface with the bigger nodules and craters size than shown in Figure 3. The crater size for low MRR is 224µm and for the high MRR is 328µm, respectively. This can be explain that, by having black layer coating the outer surface of electrode produced higher thermal energy. This is due to the hardened shape of the carbon that increased the MRR and further increase the surface roughness. When peak current and pulse duration high, the deterioration of the surface texture on Inconel 718 composed of bigger size of craters and nodules that cause from the overlapping of melting materials during the successive electrical discharge in machining process. Furthermore, the micro-crack is cause from the high apply of temperature. This is due to the intern stress grow during the solidification progresses of the materials [12].

As shown in figure 5, both craters size for low MRR and high MRR at third hole were less compare to the second hole. The low MRR produce the size of craters 210µm and the high MRR produce 322µm. The craters on the surface were shallow than second hole. This is due to the low MRR value that directly affected the outcomes of surface topography. When low eroding process, the surface roughness is low due to the shallow craters that produces from the low impact of the discharge energy [12].

Furthermore, the craters size depends on the explosion of the spark occur during machining time. The craters become bigger and deeper when the peak current is high due to the spark intensity and high energy bombarded on the workpiece surface. However, the micro-cracks are not noticeable within low MRR and high MRR.

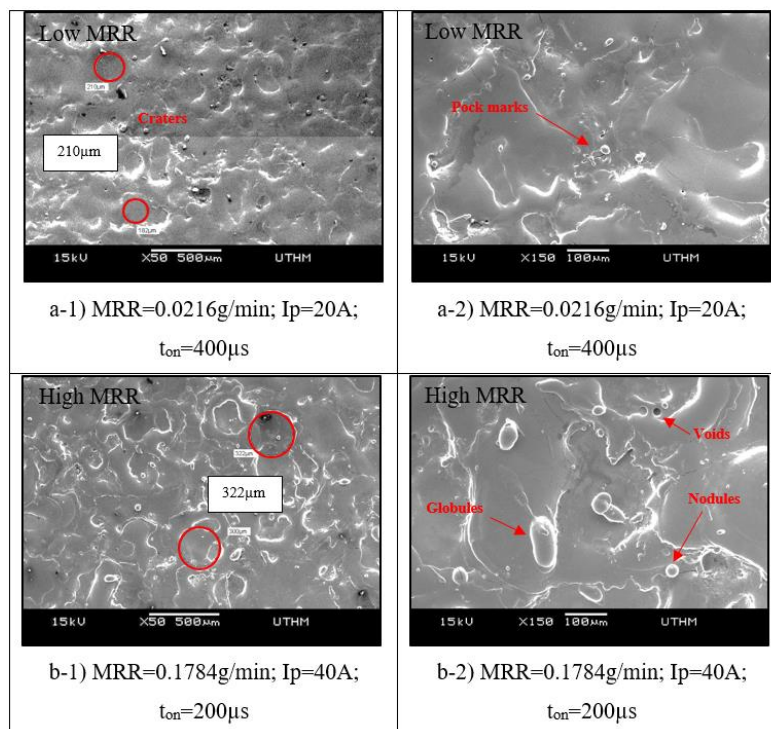


Figure 5. Surface topography of Inconel 718 at third hole with different magnification.

3.3. Machining accuracy analysis

In general, the less diameter overcut indicate the better machining accuracy. As mention earlier, machining may take place on the side space leading to diameter overcut. The highest diameter overcut is 3.47% on the first hole (20A, 400µs), while the lowest is 2.59% on the second hole (30A, 400µs) shown in figure 6. This shows that the highest machining accuracy obtained by lowest peak current and directly to the lowest MRR. Besides, the lowest machining accuracy owns by the average peak current and MRR. However, for overall trends of machining accuracy were fluctuated towards peak current and MRR.

The results shows that the machining accuracy were not attach to any parameters input. However, as seen in the graph, the diameter overcut slightly fluctuated by increasing peak current but still in consistent trend. Owing to the earlier discussion that by increasing peak current obtained high MRR, this can be explain that as MRR is high the high frequently spark produced were at the limit and leads to constant explosion to form crater. The crater produced were constant and leads to constant overcut of machining. The experimental results here may further show that as more heat transferred to the workpiece as the peak current increases, the more constant of diameter overcut. However, this experiment result contrast with Ghewade and Nipanikar [13] finding which the machining accuracy proportionally increase with peak current increase as at low peak current resulting low spark energy which indicate the smaller crater formed on the surface of workpiece, further resulting in good machining accuracy. It can be seen that the parameter used were smaller than this experiment conducted. This could explain that by using the smaller parameters indicate the proportional increase in machining accuracy. However, the result of MRR for this parameter used were not satisfied for roughing stage where objective of this research conducted. Therefore, from the machining accuracy result, it shows that by increasing the peak current indicate the constant machining accuracy.

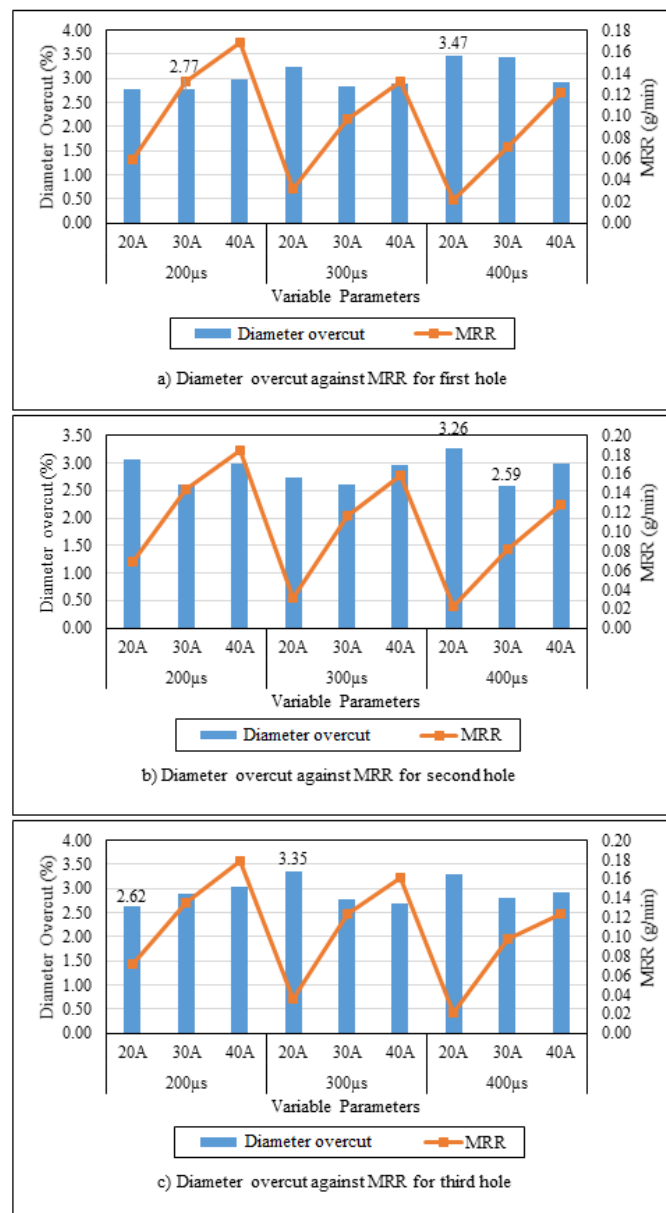


Figure 6. Effect of peak current and pulse duration on diameter overcut against MRR by repetition used of electrode.

The effect of repetition used electrode on the machining accuracy of Inconel 718 also more profound. Based on Figure 6, at low peak current 20A shows that vary on machining accuracy by repetition used of electrode (first, second and third). However, by increasing the peak current the machining accuracy indicate to consistent on repetition used of electrode. This is due to the suspension of black layer on the surface of electrode that cause the erosion of material goes fast on the surface of Inconel 718. Therefore, the crater produced were at maximum and leads to constant erosion of materials. This result may assistance towards accurate of machining.

4. Conclusion

This experiment investigates the material removal rate (MRR), surface topography and machining accuracy applying high peak current and pulse duration when EDM machining of Inconel 718. Within selected parameters and experimental condition, the following conclusion could be draw; Peak current

appeared to be the main effect to improve the MRR. As the peak current increased, the MRR increased. Then, the effect of pulse duration is inversely proportional with MRR. As increasing the pulse duration increased, the MRR was decrease. The result indicate that the using of the same electrode repeatedly still capable to enhance MRR.

For the case of surface topography, at low MRR resulting the appearance of micro-geometry characteristics where machining damages take placed. This include void, micro-crack, nodules, pork mark and globules. However, the sizes of the nodules and globules increase at high MRR. This resulted increase in surface roughness. It is also believe that, the surface topography conditions also affected by the carbon and material deposited on the electrode surface due to the repetition used of one electrode for the whole experiments.

On the machining accuracy perspective, the diameter overcut shows slightly fluctuated condition but still consistent by increasing peak current. With deposited of black layer on the surface electrode, high MRR is still obtainable and more consistent of machining accuracy. The result shows quite high of machining accuracy even at higher peak current and pulse duration applied.

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