The Effect of Different Electrode Materials on Machining of Inconel 718 by EDM: A Review

Kulwinder Singh Dhindsa
Research Scholar
Mechanical Engineering, Bhai Gurdas Institute of Engineering and Technology, Punjab, India

Sandeep Singh
Research Scholar
Mechanical Engineering, Bhai Gurdas Institute of Engineering and Technology, Punjab, India

Rajbir Singh
Assistant Professor
Mechanical Engineering, Bhai Gurdas Institute of Engineering and Technology, Punjab, India

ABSTRACT
Electric Discharge Machining is a non-conventional machining process, used to machining difficult to machine materials. The major problem faced while doing EDM is high Electrode wear rate, surface roughness and low material removal rate. In this research work experimental investigations have been made to find the machining characteristics of different electrode like copper, graphite, copper tungsten and brass on Inconel 718 super alloy. The present paper presents the effects of peak current and pulse on-time(T_{on}) on the output parameters like Material Removal Rate(MMR), Electrode Wear Rate(EWR) and Surface Roughness(SR).

Keywords
Electrical Discharge Machining (EDM), Material Removal Rate (MRR), Electrode Wear Rate (EWR) Surface Roughness (SR)

1. INTRODUCTION
Inconel 718 belongs to a family of austenitic Nickel-Chromium based high performance alloy having face centred cubic austenitic crystal structure. It is oxidation resistant, corrosion resistant and high strength material well suited for application in extreme environmental conditions from -423° to 1300° F. It also have good creep, fatigue, rapture and tensile strength **[1].** Nickel based super alloy, Inconel 718 is one of the most difficult-to-machine material which attributed to its ability to maintain hardness at elevated temperature and consequently it’s very useful for hot working environment**[2]**. It has the ability to retain its strength and toughness up to temperatures around 500^0C and due to its improved mechanical properties**[3]**. It is used for manufacture of liquid fuelled rockets, rings, casing, Nuclear reactors, pumps and tooling, high temperature fasteners, chemical processing and pressure vessels, heat exchanger tubing, cryogenic storage vessels, missiles, marine industries aerospace applications, such as gas turbines, rocket motors, and jet engines. Inconel are widely used for the hottest parts in anaircraft gas turbine engine and about 50% of aero-engine alloys are nickel base alloys **[4]** Hole making has long been recognized as one of the most important machining processes. Approximately 50 to 70% of production time is spent in making holes **[5]** The term 'deep hole' refers to a depth to diameter equal to five or greater. As the depth-to-diameter ratio increases, it becomes extremely difficult to produce such holes, especially, in super alloys like Inconel 718. The earlier studies on machinability of Inconel 718 were mainly on turning and milling operations. Only very little published information is available on drilling studies of Inconel 718 **[6], [7],[8]**. Drilling macro or micro holes with a high aspect ratio in super alloys is beyond the capabilities of the conventional twist drilling process **[9]** because of its poor thermal properties, high toughness, high hardness, high work hardening rate, presence of highly abrasive carbide particles and strong tendency to weld to the tool to form build up edge **[10].** Low thermal conductivity of nickel based super alloy results in heat concentrated in the cutting zone, making it ineffective to be processed through conventional machining **[11]**To cut this material with high speed and reasonable surface quality is quite impossible in conventional machining. **[12].** So Advanced machining processes (AMPs) are the finest choice for machining Inconel 718 in order to rise above such limits. AMPs are capable of drilling macro or micro holes with high aspect ratios in difficult to cut materials **[13]**. From the different AMPs, electrical discharge machining (EDM) is quite widespread for producing small holes. EDM has successfully used to machine hard materials. By applying latest EDM technology, these materials may be able to be effectively EDM and eventually increase the application of EDM in the aerospace industry **[14]** EDM, sometimes referred to as spark machining, is a nontraditional method of removing metal by a series of rapidly recurring discrete electrical discharges between an electrode (the cutting tool) and the workpiece in the presence of a dielectric fluid. In EDM drilling process, the dielectric is flushed through the rotating tube electrode. EDM drilling of small holes is a well-established technique**[15]** drilled small holes ranging from 0.19–0.71mm diameter**[16]**. Regardless of the application, the workpiece may be of any material, no matter how hard, as long as it is electrically conductive **[17]** However, the main influence in EDM machining will be determined by electrical parameters such a peak current, pulse duration and voltage, material properties of the workpiece and electrode such as the material’s melting temperature, and its electrical and thermal. **[18]**

2. BRIEF OVERVIEW OF THE EDM
2.1 Principle of EDM
Electrical Discharge Machining is process of machining electrically conductive materials by using precisely controlled sparks that occur between an electrode and a workpiece in the presence of dielectric fluid.**[19]** EDM is based on the erosion of electrically conductive materials through the series of spatially discrete high-frequency electrical discharges(sparks) between the tool and the workpiece **[20]**. Each spark occurs between the closest points of the electrode and the workpiece **[19]**. The spark removes material from both the electrode and workpiece, which increase the sparking gap (distance between the electrode and the workpiece) at the point. This causes the next spark to occur at next-closest points between the electrode and workpiece. As EDM is a thermal process, material is removed by heat. Every discharge (or spark) melts a small amount by the dielectric fluid and the remaining solidifies on the surface of the electrodes. The net result is that each discharge leaves a small crater on both workpiece and tool electrode**. [21]**

2.2 Sparking and gap phenomena in EDM

The sparking phenomena during micro-EDM can be sepaated into three important phases named as preparation phase for ignition, discharge phase and interval phase between discharge. **[22]** When the gap voltage is applied, an electric fluid and energy column is decrease of the distance between electrode and workpiece. The point of least resistance between the tool electrode and workpiece determine the discharge location. As the electrode approaches the workpiece, the electrical field eventually break down the insulating properties of the dielectric fluid.**[23]** The resistance of dielectric fluid decreases because of heating due to electric flied and later due to the of removed as a result of sparking. The electric field results in the large amount of current flow through the gap helping in material removal. The material removal mainly occurs by melting and evaporation of both the workpiece and electrode material in addition to dielectric. This sparking phenomenon produces metal debris particles as well as sheath of gases composed of hydrogen, carbon and various oxides. In order for the EDM process to be stable, the proper selection of pulse duration and pulse interval is necessary. During the pulse interval, the current is switched off and the heat source is thereby eliminated and the sheath creates a void or vacuum and draws in fresh to flush away debris and cool the area. In addition, during the pulse interval, the re-ionization occurs which provides favorable condition for the next spark. The phase of the electrical discharges, sparking and gap phenomena during the EDM process.**[23]**

3. MATERIAL REMOVAL RATE USING DIFFERENT ELECTRODE MATERIALS

3.1 MRR using copper electrode

3.1.1 Experimental details

In this study, Nickel base super alloys, Inconel 718 were selected as the material for the work piece (specimens 40mm x 30mm x 10mm) and Copper as a tool electrode with diameter of 10mm. The experiments were carried out on a standard CNC EDM machine, Sodick AQ55L with positive electrode polarity **[2]**

The EDM experimental conditions and parameters are summarized in table 3.1**[2]**

Table 3.1 EDM experimental conditions and parameters

Parameters	**levels**
Workpiece materials	Inconel 718
Electrode	Copper
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 factor
Voltage, V	120
Electrode polarity	Positive
Dielectric fluid	Kerosene
Depth of cut	3mm

The initial weight of the work piece and electrode was weighed using a 0.1mg accuracy digital weight

balance. All the gathered information from machining time, mass loss after machining process for both tool electrode and work piece were used to determine the values of MRR. **[2]**

3.1.2 Peak current and pulse duration against MRR using copper electrode

Results for EDM of Inconel 718 by using copper electrode. The effect of peak current and pulse durations on the MRR is shown in figure 3.1. It is shown that the peak current affects the MRR significantly. An increased in peak current MRR increase for all setting of pulse duration. MRR increases with the increase in peak current due to the increases of the energy per pulse causes temperature raises sharply that leads to rapid melting of work piece material at sparking area. However, higher pulse duration decreased MRR for all peak current used. With a pulse duration longer than 200µs, the MRR start decreases because of the exceeding value of pulse interval. High ignition delay due to high pulse interval in each cycle reduces the machining rate at a constant machining efficiency **[2]**. The highest MRR is achieved at 40A of peak current and 200µs of pulse on with value approximately 34.94mm^3/min.

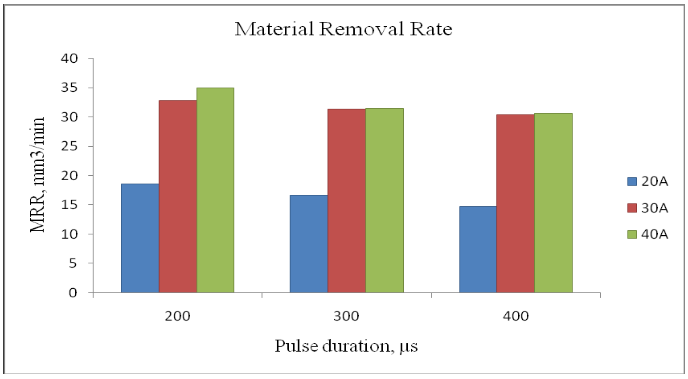

Figure 3.1: Effect of peak current and pulse duration on MRR[2]

3.1.3Remarks

When EDM of Inconel using Copper electrode its is clear that the peak current is the most influence parameter to achieve high MRR while for pulse duration it shows not important for improving. To achieve high MRR 34.94 mm^3/min the higher peak current and pulse duration up to 40Aand 400µs respectively are used.

3.2 MRR using graphite electrode

3.2.1Experimental setup

In this study, Nickel base super alloys, Inconel 718 were selected as the material for the work piece and Graphite as a tool electrode. The experiments have been conducted on a numerically controlled (NC) die-sinking EDM Machine of Electronica India make. The experimental conditions and parameters are given in the following table.

Table 3.2 Experimental Condition

Experimental Conditions	**Descriptions**
Workpiece	Inconel 718
Electrode	Copper infiltrated Graphite ELLOR +50
Polarity	Negative
Current(A)	2.5, 5.5, 8
T_{on}	2, 12, 51
Duty Factor %	33, 50, 67
Dielectric fluid	Kerosene oil

3.2.2Discharge current and T_{on} against MRR using graphite electrode

The result of figure 3.2 shows the relationship between current and MRR, with increase in discharge current the material removal rate increases. For experimental value of 2.5 Amp and on-time of 2 µs , we get minimum MRR of 1.95 mm3/min and for value of 8 Amp and on-time of 51 µs, we get maximum of 32.58 mm^3/min. The MRR increase sharply with increase in discharge current from 2.5 Amp to 8 Amp and it increase sharply when on-time increase from 2 to 12 µs and there is slight change their after.**[1]**

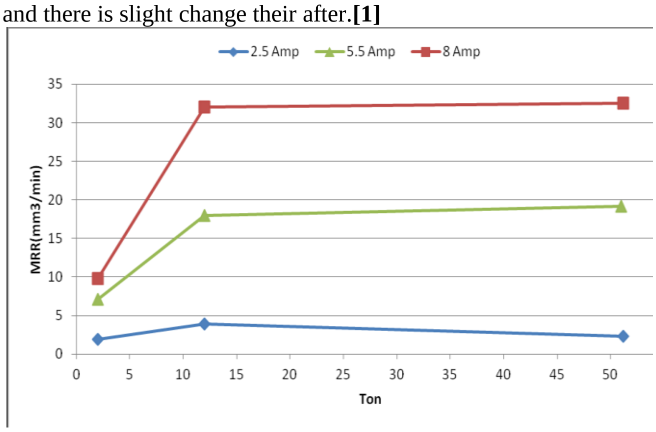

Figure 3.2: MRR at various values of discharge current and T_{on}. [1]

3.2.3Remarks

It is clear that discharge current and T_{on} values had direct influence on the MRR higher the discharge current more is the MRR and vice-versa. Highest MRR is achieved when discharge current is highest along with when T_{on} is highest. MRR increases when value of discharge current increase from 2.5 A to 8 A and the value of pulse on-time increase from 2 to 12 µs. The value of MRR maximum when parameters is set up discharge current 8 A and pulse on-time 51 µs, we get maximum MRR 32.58 mm^3/min.

3.3 MRR using copper tungsten electrode

3.3.1Experimental setup

In this study, Nickel base super alloys, Inconel 718 were selected as the material for the work piece and copper tungsten as a tool electrode. The EDM experiments were conducted on the CNC Sodick High Speed EDM die sink AQ55L (3 Axis Linear) in kerosene as a dielectric medium The experimental conditions and parameters are given in the following table.

Table 3.3 Experimental parameters and levels

Parameters	**Levels**
Workpiece material	Inconel 718
Electrode	Copper Tungsten
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 factor
Voltage, V	120
Electrode polarity	Positive
Dielectric fluid	Kerosene
Depth of cut	3mm

3.3.2Peak current and Pulse duration against MRR using copper tungsten electrode

As shown in Fig. 3.3, MRR increased for all the conditions of pulse duration (t_{on}) as peak current (I_p) increases. This is because, when higher I_p generates high energy intensity, the temperature rises and melt more material and erodes from a workpiece. In overall, MRR increased at higher ton for all I_p except for I_p=20A and t_{on}=400µs, MRR was slightly decreased. The reason behind is that 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 pulse duration of the spark that resulting a larger, deeper and broader crater. **[24]** The low frequency and high power combination results in high material removal. As ton increases the frequency reduces and consequently longer ton increases material removal. **[25]** The results revealed that the combination of high peak current and pulse duration generated more MRR when EDM of Inconel 718 by using CuW electrode. The highest MRR is obtained with the value 28.37mm^3/min at the combination of 40A and 400µs of Ip and t_{on}, respectively.

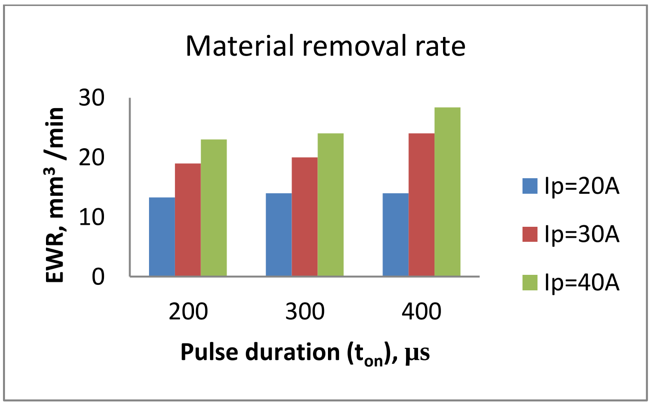

Fig. 3.3. Effect of Peak current (Ip) and Pulse duration (ton) on MRR

3.3.3Remarks

Peak current and pulse duration are significant parameters in MRR for EDM of Inconel 718 by using copper tungsten electrode because MRR increases with the increase in current and pulse duration. Maximum MRR 28.37 mm^3/min can we achieved by using parameters value of peak current 40A and pulse duration 400µs.

3.4 MRR using brass electrode

3.4.1 Experimental setup

In this study, Nickel base super alloys, Inconel 718 were selected as the material for the work piece and brass as a tool electrode. The equipment used to perform the experiments is a die sinking EDM (Electronica-M100 MODEL) machine. The experimental conditions and parameters are given in the following table.

Table 3.4 Experimental parameters and levels

Experimental Conditions	Descriptions
Workpiece	Inconel 718
Electrode	Brass
Polarity	negative
Current(A)	5, 10, 15
T_{on}(µs)	200, 500, 1000
Dielectric fluid	Titanium carbide nano particle suspended in kerosene.

3.4.2 Current and T_{on} against MRR using brass electrode

Fig. 3.4(a) and Fig. 3.4 (b)describes the influence of the input process parameters like current, pulse on time and pulse off time on the process responses. When using brass electrode, MRR gets improved at 15A as shown in Fig. 3.4(a).At a pulse on time of 200µs, MMR gets increased and then slightly decreases with the increasing pulse on time as shown in Fig. 3.4(b).The increase in pulse off time from 100µs to 500µs, the MRR gets decreased for brass electrodes. At short pulse off time, MRR is a smaller amount. This is due to the fact that during tiny pulse off time, the possibility of arcing is very high, since the dielectric gap between the work piece and electrode cannot be flushed away correctly. The debris particle at rest gets waited in discharge gap and results in arcing. Due to this, MRR decreases as discussed.**[26]**

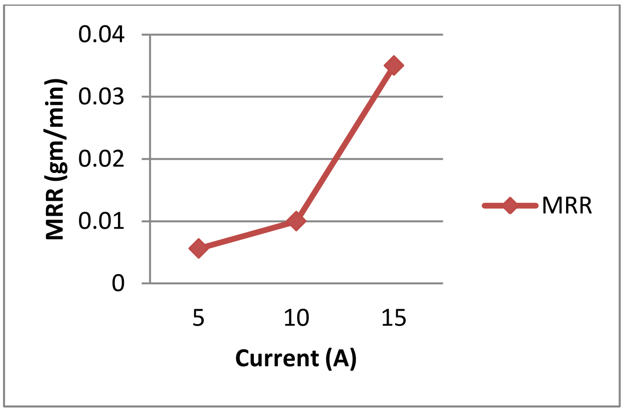

Fig. 3.4 (a) MRR against current

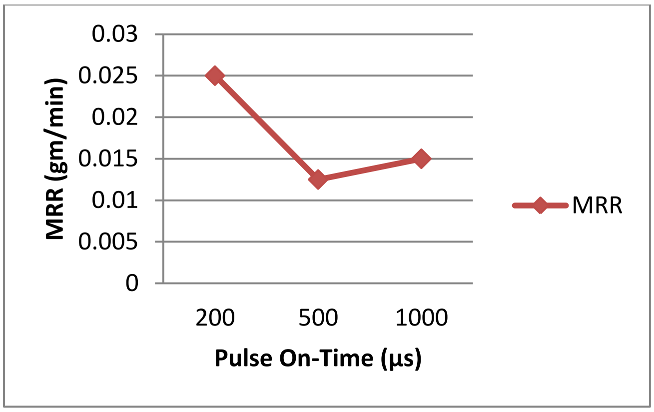

Fig. 3.4(b) MRR against Pulse On-Time

3.4.3 Remarks

Material removal rate gets increased with the increasing Current but with increase in pulse on time, material removal rate gets slightly decreased. Maximum material removal rate was obtain when current at 15A and maximum material removal rate obtain when pulse on-time 200 µs.

4. ELECTRODE WEAR RATE USING DIFFERENT ELECTRODE MATERIAL

4.1 EWR using copper electrode

4.1.1 Peak current and pulse duration against EWR

The effect of peak current and pulse durations on the EWR is shown in figure 4.1. The higher peak current resulting an increasing in EWR for constant pulse duration. High discharge current leads to high spark energy causes more material removal from work piece and tool electrode which in effect increases the EWR. EWR decrease when increasing of pulse duration for each of peak current used respectively. **[2].** This is because of deposition of carbon on tool electrode at a high temperature for a longer pulse on time. The negative value for the lowest EWR is indicating that the electrode is deposited by the carbon is more compare to the wear of electrode Longer pulse duration tends to increase the possibility of carbon deposition on the electrode surface, which function as wear resistant layer for copper electrode and helps to decrease the electrode tool wear. The lowest EWR is approximately -0.01mm^3/min at 20A of peak current and 400µs of pulse duration. **[2]**

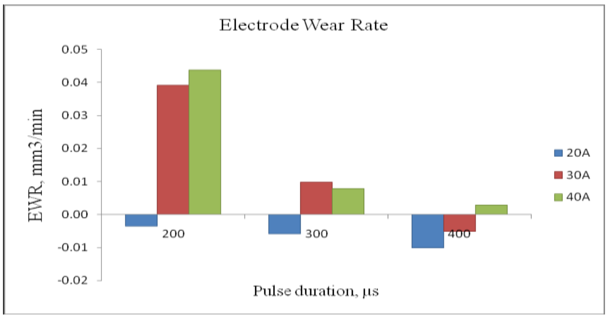

Figure 4.1: Effect of peak current and pulse duration on EWR [2]

4.1.2 Remarks

EWR using Copper Electrode the higher peak current resulting an increasing in EWR. EWR decrease when increasing of pulse duration for each of peak current. The lowest EWR is approximately -0.01mm^3/min at 20A of peak current and 400µs of pulse duration.

4.2 EWR using graphite electrode

4.2.1 Current and T_{on} against EWR

Figure.4.2 shows the relationship between current and end wear %; with increase in discharge current and on-time the end wear % decreases. For discharge current of 2.5Amp and on-time of 2 µs we get end wear of 74.38 % , which reduced sharply for on-time of 12 µs and further increase upto 81.88 % at 51 µs . The end wear % for discharge current of 5.5 Amp and 8 Amp is similar at the beginning (for on-time 2 and 12 µs) and shows insignificantly different values at the end. **[1]**

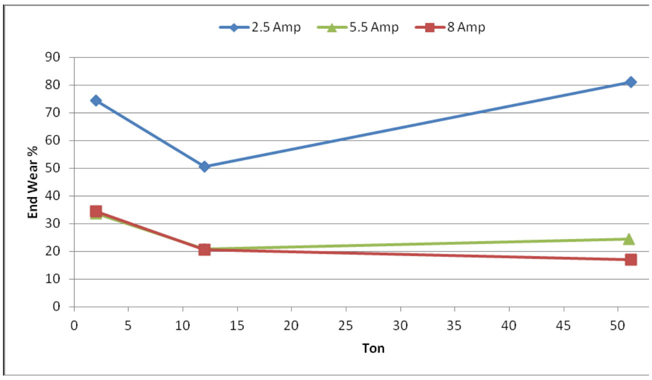

Fig. 4.2: Electrode Wear % at various values of discharge current and T_{on}.(Sandhu, H.S. et al.,2015)

4.2.2 Remarks

The electrode tool with negative polarity performs better in terms of elevated lesser tool wear. EWR increases with an increase in peak current but decreased slowly with the increase in pulse duration.

4.3 EWR using copper tungsten electrode

4.3.1 Peak current and pulse duration against EWR

Fig. 4.3 shows the effect of Peak current (I_p) and Pulse duration (ton) on the electrode wear rate (EWR) of CuW. The high I_p resulted an increasing of EWR for all conditions of ton. Higher I_p generates higher spark energy which facilitates more material removal from the workpiece and the tool electrode which in effect to the increment of MRR and EWR. However, an increasing in ton the EWR was decreased for all value of I_p used. An explanation to this 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 surface during the spark. The effect of deposition on EWR is shown clearly at I_p=20A which the EWR decreased linearly with the increases in the level of ton. The lowest EWR is approximately -0.005mm3/min obtained by a combination of 20 A of I_p and 400 µs of ton. The negative value for the lowest EWR indicates that the electrode weight after machining is higher than before machining due to the deposited by the carbon and material from the workpiece **[27].**

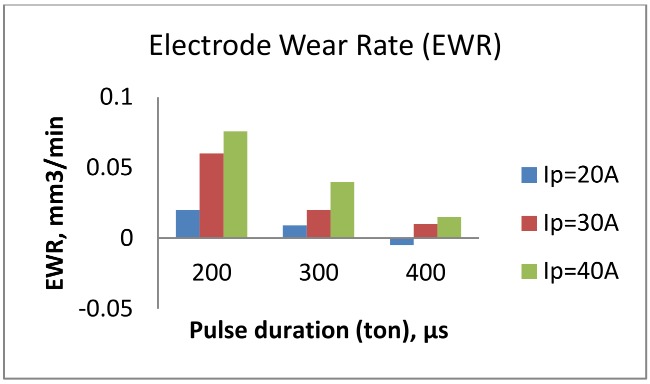

Fig. 4.3: Effect of peak current (Ip) and pulse duration (t_{on}) on EWR

4.3.2 Remarks

EWR increases with an increase in peak current but decreased slowly with the increase in pulse duration. The lowest EWR with value -0.005mm^3/min is achieved at 20A and 400µs of peak current and pulse duration.

4.4 EWR using brass electrode

4.4.1 Current and pulse-on time against EWR

Fig. 4.4(a) describes the relation between the current density and the electrode wear rate. Heat is more dissipated into the electrode causing less electrode wear. It can be completed that thermal conductivity is an important factor that reduces the electrode wear. The influence of the input process parameters like current, pulse on time and pulse off time on the process responses, EWR were analyzed. Influence of pulse on time in EWR is shown in Fig. 4.4(b) describe the relation between the current density and the electrode wear rate. As shown in figure, higher current produces stronger spark with more thermal energy and results in more electrode wear.**[26]**

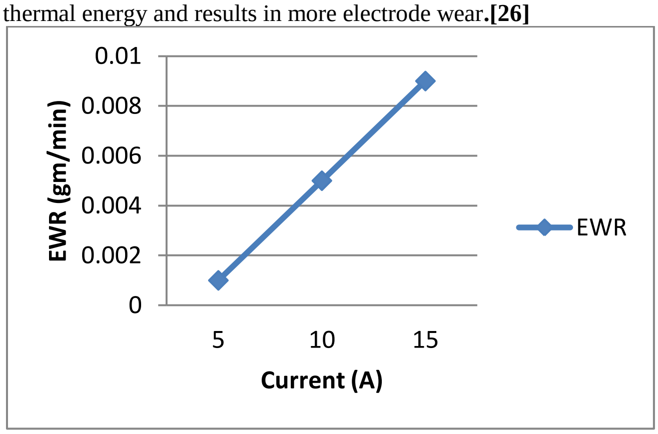

Fig. 4.4 (a) EWR against current

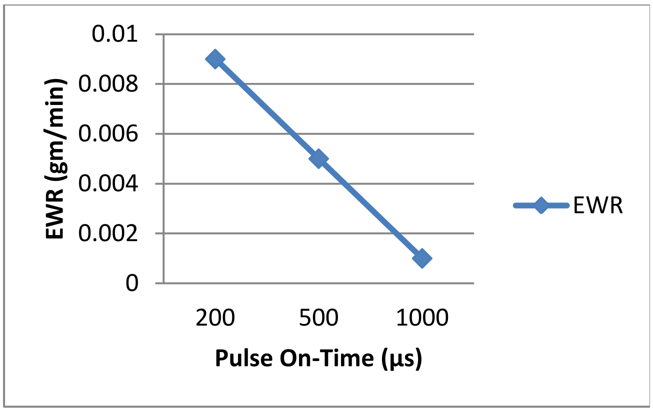

Fig. 4.4(b) EWR against Pulse On-Time

4.4.2 Remarks

Tool wear rate using brass electrode a little gets increased by the increasing current. For electrode wear rate, the longer pulse duration used may improved the EWR but affect badly when higher peak current used.

5. SURFACE ROUGHNESS(RA) USING DIFFERENT ELECTRODE

5.1 Ra using copper electrode

5.1.1 Peak current and pulse duration against Ra

Fig. 5.1 shows the effect of peak current and pulse durations on surface roughness of Inconel 718. Ra Increases with the increase in discharge current and pulse duration. When the discharge current is high, then the spark intensity are more, as a result, a larger crater depth on the surface of the work piece are produced, hence Ra is high. Pulse duration also strongly influences the Ra. An increase in pulse duration results in proportional increase in spark energy and consequently melting boundary becomes deeper and wider, and hence increases the roughness value **[28]**. The lowest Ra with value of 8.53µm is achieved at a peak current of 20A and pulse duration of 200µs.

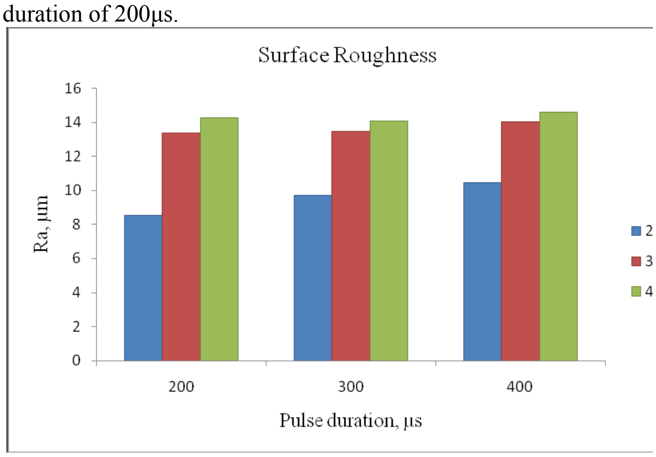

Fig. 5.1: Effect of peak current and pulse duration on Ra(S Ahmad and M A Lajis,2013)

5.1.2 Remarks

For surface roughness, lowest peak current and the lowest pulse duration is suggested in order to achieve good surface finish. When peak current 20A and pulse duration of 200 µs is used lowest value of Ra 8.53 µm is obtained.

5.2 Ra using graphite electrode

5.2.1 Current and Pulse on time against Ra

Fig. 5.2 shows the relation between current and surface roughness of the workpiece, with increase in discharge current and on-time the surface roughness increases. The discharge current leading to the least surface roughness (Ra) was 2.5 Amp, and the Ra value was 0.68 µm. The results of the experiment showed that a variation of the discharge current led to insignificant differences in the surface roughness, with the highest values of the current leading to Ra value of 2.93 µm.**[1]**

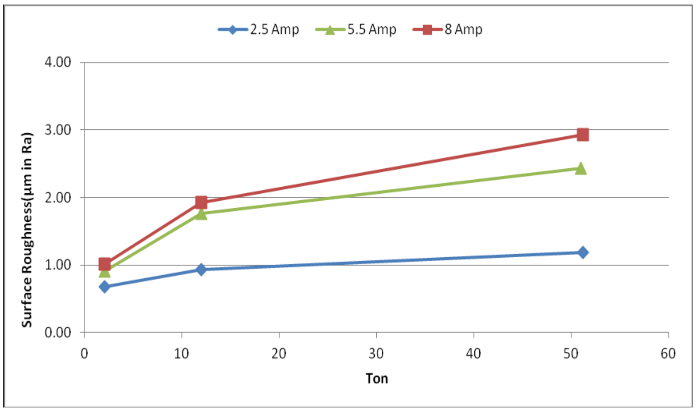

Fig. 5.2: SR at various values of discharge current and T_{on}.(Sandhu, H.S. et al.,2015)

5.2.2 Remarks

When discharge current and T_{on} is highest, the surface roughness is found to be maximum. A minimum surface roughness of 0.68 µm is achieved on 2.5Amp and T_{on} of 2 µs,

5.3 Ra Using Copper Tungsten Electrode

5.3.1 Peak current and pulse duration against Ra

The effect of peak current and pulse duration on the surface roughness (Ra) of Inconel 718 machined surfaces is shown in Fig. 5.3. The Ra is better at lower peak current but increased with the increase in discharge current with all t_{on} conditions. By increasing Ip, the amount of energy in the EDM process will increase. Therefore, the melting and vaporizing of the workpiece will produce the larger and deep crater. The analysis was observed that the t_{on} is the one of the significant factors that can improve Ra. Normally, an increase in t_{on} the Ra value will increase because of melting boundary becomes deeper and wider **[29].** however, due to longer t_{on}, the frequency and intensity of the sparking will reduce. As a consequence, a shallower and flatten crater is produced. Thus, Ra value was decreased with increasing t_{on} throughout the overall trials, and the lowest Ra value is 8.62µm is obtained at a combination of the lowest Ip and the short t_{on} of 20A and 200µs, respectively.**[2]**

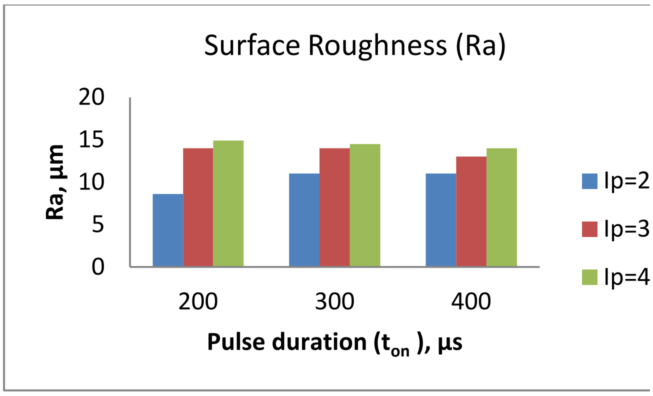

Fig. 5.3. Effect of peak current (Ip) and pulse duration (ton) on Ra. [2]

5.3.2 Remarks

The improved Ra value produced by the arrangement of lower peak current and higher pulse duration was used. Minimum Ra 8.62µm was obtained at the 20A and 400µs of peak current and pulse duration.

6. CONCULSIONS

In this study MRR, EWR and Ra is most important performance measure. In this study we measure the performance of different electrode on Inconel 718. We try to find which electrode material is more suitable to machine Inconel 718. . The conclusion can be made the peak current and pulse duration is the most influence parameter on MRR, EWR and Ra. Higher the discharge current more is the MRR, TWR and SR and vice-versa. Highest MRR is achieved when discharge current is highest along with when T_{on} is highest. The MRR can be achieved using copper electrode as compared to other electrodes. Using copper electrode highest MRR is achieved at 40 A of peak current and 200 µs of pulse on-time with value of approximately 34.94mm^3/min which is higher than other three electrodes. EWR increases with an increase in peak current but decreased gradually with the increase in pulse duration. The lowest EWR is also achieved by using copper electrode which is approximately -0.01mm^3/min at 20A of peak current and 400µs of pulse duration. Discharge current and T_{on} values inversely affects the surface smoothness i.e. when discharge current and T_{on} is highest, the surface roughness is found to be maximum. For surface roughness, lowest peak current and the lowest pulse duration is suggested in order to achieve good surface finish. A minimum surface roughness of 0.68 µm is achieved on 2.5Amp and T_{on} of 2 µs using graphite electrode. While using copper electrode when peak current 20A and pulse duration of 200 µs is used lowest value of Ra 8.53 µm is obtained.

7. REFERENCES

[1] Sandhu H.S., Mehta V, Manchanda Jatin, Phull G.S.(2015) " *Investigation of Electric Discharge Machining of Inconel 718*" IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE): 56-61

[2] Ahmad S., and Lajis M. A. (2013) "*Electrical discharge machining(EDM) of Inconel 718 by using copper electrode at higher peak current and pulse duration*" IOP Conference Series: Materials Science and Engineering 50: 012062

[3] Kuriachen B and Mathew J(2014), "*Modeling and multi-response prediction of micro EDM drilling on inconel 718*" All india manufacturing technology, design and research conference, 2014.

[4] Ezugwu E O(2005), "*Key improvements in the machining of difficult-to-cut aerospace superalloys*." International Journal of Machine Tools & Manufacture 45:1353-67

[5] Benes J(2000), "*Hole making trends run deep, fast and dry*." Am Mach 144(5):97–104

[6] Chen JC, Liao YS (2003), "*Study on wear mechanisms in drilling of Inconel 718 super alloy*." J Mater Process Technol 140:269–273

[7] Wei YX (2002), "*Experimental study on the machining of a shaped hole in Ni-based super-heat-resistant alloy*." J Mater Process Technol 129:143–147

[8] Tam SC, Yeo CY, Jana S, Lau MWS, Lim LEN, Yang LJ, Noor YM (1993), "*Optimization of laser deep-hole drilling of Inconel 718 using the Taguchi method.*" J Mater Process Technol 37:741–757

[9] Bellows G, Khols JB (1982) "*Drilling without drills"* Special Report, Am Mach 743:173–188

[10] Sharman ARC, Hughes JI, Ridgway K (2004) "*Workpiece surface integrity and tool life issues when turning Inconel 718 nickel based superalloy*" Mach Sci Technol 8(3):399–414

[11] Ahmad S and Lajis M A (2015), "*An Electrical Discharge Machining (EDM) of Inconel 718 ing Copper Tungsten Electrode with Higher Peak Current and Pulse Duration*" International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS 15(05)

[12] Rajesha S., Sharma A., and Kumar P. (2011): "*On Electro Discharge Machining of Inconel 718 with Hollow Tool*." Journal of Materials Engineering and Performance. 1-10.

[13] Bellows G, Khols JB (1982), "*Drilling without drills*". Am Mach 743:173–188, Special Report.

[14] Benedict G. F. (1987) "*Nontraditional Machining processes*." Marcel Dekker, INC, New York.

[15] Jeswani ML (1979) "*Small hole drilling in EDM*" Int J Mach Tool Des Res 19:165–169

[16] Jain VK (1989) "*Analysis of electrical discharge drilling of a precision blind hole in HSS using bit type of tool*" Microtecnic 2:34–40

[17] Fonda P., Wang Z., Yamazaki K., and Akutsu Y. (2008) "*A fundamental study on Ti-6Al-4V's thermal and electrical properties and their relation to EDM productivity"* Journal of Materials Processing Technology. 202(1-3): 583-589.

[18] Lee S. H., and Li X. P. (2001) "*Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide*" Journal of Materials Processing Technology. 115(3): 344-358.

[19] E.C. Jameson, (2001), "*Description and development of electrical discharge machining (EDM)*," in: Electrical Discharge Machining, Society of Manufacturing Engineers, Dearbern, Michigan, 12.

[20] L. Llanes, E. Idanez, E. Martinez, B. Casas, J. Esteve(2001), "*Influence of electrical discharge machining on the sliding contact response of cemented carbides.*" International Journal of Refractory Metals and Hard Materials 19:35–40.

[21] D.M. Allen, A. Lecheheb (1996), " *Microelectro discharge machining of ink jet nozzles: optimum selection of material and machining parameters*." Journal of Materials Processing Technology 58: 53–66.

[22] B.M. Schumacher (2004), "*After 60 years of EDM the discharge process remains still disputed"* Journal of Materials Processing Technology 149: 376–381.

[23] M. Kunieda, B. Lauwers, K.P. Rajurkar, B.M. Schumacher (2005), "*Advancing EDM through fundamental insight into the process*." Annals of the CIRP 54:599–622.

[24] Guitrau E. B. (1997) "*The EDM Handbook*". Hanser Gardner Publications, Cincinnati.

[25] Rahman, M. M., Khan, M. A. R., Kadirgama, K., Noor, M. M. and Bakar, R. A. (2010) "*Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity"* World Academy of Science, Engineering and Technology. 71.

[26] P Shankar , R Boopathi and M Prabu(2015) "*Investigating the Effect of Brass Electrode on Inconel 718 on Electrical Discharge Machine"* International Journal of Innovative Science, Engineering & Technology, 2(4).

[27] Kang S., and Kim D. (2003) "*Investigation of EDM characteristics of nickel-based heat resistant alloy*" Journal of Mechanical Science and Technology. 17(10):1475-1484.

[28] Patel K M, Pandey P M and Venkateswara R P (2009) "*Surface integrity and material removal mechanisms associated with the EDM of Al2O3 ceramic composite"* International Journal of Refractory Metals and Hard Materials 27(5):892-899

[29] Kuppan P., Rajadurai A., and Narayanan S. (2008): "*Influence of EDM process parameters in deep hole drilling of Inconel 718*" International Journal Advance Manufacturing Technology. 38:74-84.