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Research Paper

THE EXPERIMENTAL ANALYSIS OF SURFACE CHARACTERISTICS OF INCONEL-718 USING ELECTRICAL DISCHARGE MACHINING

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Electric Discharge Machining (EDM) provides an effective Manufacturing technique that enables the production of parts made of hard materials with complicated geometry that are difficult to produce by conventional machining processes. Its ability to control the process parameters to achieve the required dimensional accuracy and surface finish has placed this machining operation in a prominent position in industrial applications. This project reports on the experimental investigation of machining of Inconel-718 using EDM process. The parameters such as peak current, pulse on time, duty factor were chosen to study the machining characteristics. An electrolytic rectangular copper block of 12 × 8 mm was selected as a tool electrode. The output response was measured were Material remove rate, Avg. Surface Roughness, Hardness. The results are revealed that how material removal rate, surface roughness and hardness are influenced by peek current, duty factor and pulse-on time. The surface crack lengths are also identified.

Keywords: Electric discharge machining, INCONEL-718, MRR, Surface roughness, Hardness

INTRODUCTION

Electric Dischare Machining (EDM)

Electric Discharge Machining (EDM) is one of the most extensively used nonconventional material removal processes. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantages in the manufacture of mould, die, automotive, aerospace and surgical components. In addition, EDM does not make direct contact between electrode and the work piece eliminating the mechanical stresses, chatters and vibration problems during machining.

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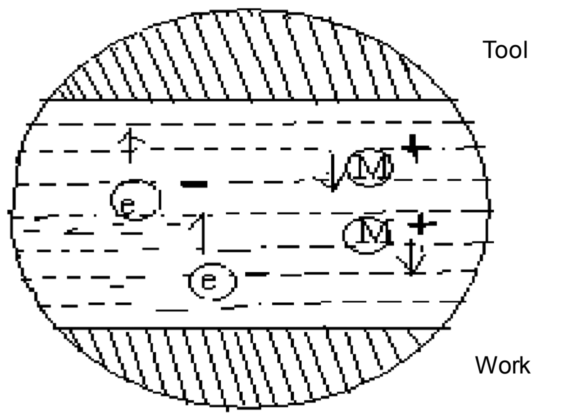
Today, an electrode as small as 0.1 mm can be used to drill holes into curved surfaces at the steep angles without drill wander (Kalpajian and Schmid, 2003).

The basis of EDM can be traced as for back as 1770, when English Chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks (Webzell, 2001). However, it was only in 1943 at the Moscow University where LazarenKo and Lazarenko (Anonymous, 1965) exploited on the destructive properties of electrical discharges for constructive use. They developed a controlled process of machining difficult to machine metals by vaporizing material from the surface of the metal. The Lazarenko EDM system used resistance capacitance type of power supply, which was widely used at the EDM machine in the 1950's and later served as model for the successive development in EDM (Livshits, 1960).

There have been similar claims made at about the same time when three American employees came up with the notion of using electrical charges to remove broken taps and drills from hydraulic valves. Their work become the basis for the vacuum tube EDM machine and an electronic circuit servo system that automatically provided the proper electrode to work piece spacing (spark gap) for sparking, without the electrode contacting the work piece (Jameson, 2001). It was only in 1980's with the advent of Computer Numerical Control (CNC) in EDM that brought about tremendous advances in improving the efficiency of the machining operation. CNC has facilitated total EDM, which implied an automatic and unattended machining from inserting the electrodes in the tool changer to a finished polished cavity or cavities (Houman, 1983). These growing merits of EDM have since then been intensively sought by the manufacturing industries yielding enormous economic benefits and generating keen research interests.

The widely accepted principle of the process based on thermal conduction is presented as a process over-view together with the applications (Figure 1). The core of the paper identifies the major EDM academic research area with the headings of EDM performance measures, EDM operating parameters along with electrode design and manufacture. The final part of the paper discusses these topics and suggests future direction for the EDM research.

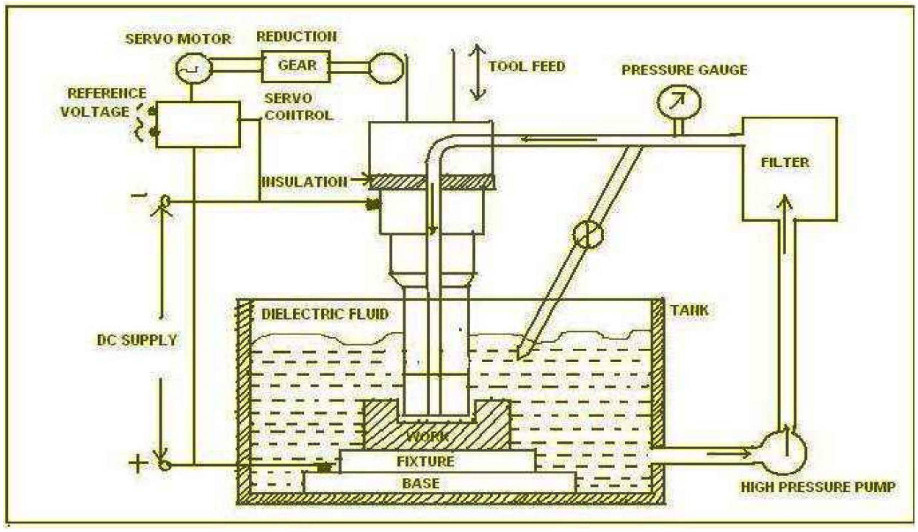
Figure 1: EDM Principle



EDM Process

The material erosion mechanism primarily makes use of electrical energy and turns it into thermal energy through series discrete electrical discharges occurring between the electrode and work piece immersed in a dielectric fluid (Figure 2) (Tsai *et al.*, 2003). The thermal energy generates a channel of plasma between the cathode and anode

Figure 2: Working Diagram of EDM and its Components



(Shobert, 1983) at a room temperature in the range of 8000° to 12000° centigrade (Boothroyd, 1989) or as high as 20000° centigrade (McGeough, 1988) initialing a substantial amount of heating and melting of material at the surface of each pole. When the pulsating the direct current supply occurring at the rate of approximately 20,000-30,000 Hz (Krar and Check, 1997) is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten material from the pole surfaces in the form of microscopic derbies.

This process of melting and evaporating material from the work piece surface is in complete contrast to the conventional machining processes, as chips are not measured mechanically produced. The volume of material removed per discharge is typically in the range of 10^{-6} to 10^{-4} mm^3 and the Material Removal Rate (MRR) is usually shaped electrode defines the area in which the spark erosion will occur, the accuracy of the part produced after EDM is fairly high. After all, EDM is a reproductive shaping process in which the form of the electrode is mirrored in the work piece (Konig *et al.*, 1988).

Most of the EDM operations conducted with electrodes (work and tool) immersed in a liquid dielectric, for example paraffin, and the mechanism of sparking is similar to that described above except that the dielectric is contaminated with conductive particles. Furthermore, the particles, removed from the electrodes due to the discharge fall in the liquid, cool down and contaminate the area around the electrodes by forming colloidal suspension of metal. These suspensions, along with the product of decomposition of the liquid dielectric are drawn into the space between the electrodes during the initial part of the discharge process and are distributed along the electric lines of force, thus forming current 'bridges', Discharge then occurs only one of these bridges as a result of ionization, described earlier.

LITERATURE SURVEY

It is essential to understand the past and present status of the EDM process to suggest future areas of work. Extensive literature survey has been carried out to find the state of art at EDM process. Electric Discharge Machining (EDM) provides an effective manufacturing technique that enables the production of parts made of hard materials with complicated geometry that are difficult to produce by conventional machining processes. Its ability to control the process parameters to achieve the required dimensional accuracy and surface finish has placed this machining operation in an prominent position in industrial applications.

EDM can be described as a process for eroding and removing material by transient action of electric sparks on electrically conductive materials one being the work pieces the other being the electrode immersed in a dielectric liquid and separated by a small gap. The main mode of erosion is caused by the local thermal effect of an electric discharge. The charge induced between electrodes by a power supply creates a strong local electric field. This field is strongest where the electrodes are closest to each other. Molecules and ions of dielectric fluid are polarized and orientation between these two peaks. When the dielectric strength of the liquid in the gap exceeds a natural limit, a low resistance discharge channel is formed due to electron avalanche striking to anode and cathode. This collision process transforms and releases the kinetic energy of electrons and ions in the form of heat and pressure in the solid body. The amount of generated heat within the discharge channel is predicted to be as high as 10^{17} W/m^2 and thus, could rise electrode temperatures locally up to 20000° K even for short pulse durations (Kalpajian and Schmid, 2003). No machining process is known to exist for which similar high temperatures can be obtained even in such small dimensions. The pressure increases in the plasma channel forces the discharge channel boundaries to expand and decrease the current density across the inter-electrode gap. Most of the time, the pressure increase is so high that it prevents evaporation of super heated material on the electrode surfaces. Appling consecutive spark discharges and driving one electrode towards the other erodes the work piece gradually in a form complementary to that of the tool electrode. The violent nature of the process leads a unique structure on the surfaces of the machined parts. The microscopic observations have shown that unusual phase changes occur since high temperatures are attained during the machining process. The top most layers are a recast layer formed by resolidification of the molten metal at the base of the craters after the discharge.

This layer is found to be heavily alloyed with the paralysis products of the cracked dielectric when pure iron and ferrous alloys are used as work piece materials; the recast surface layer is often saturated with carbon from the cracked dielectric, as well as other alloying elements introduced via the tool electrode. The material surface is found to be fairly resistant to etching by conventional metallographic reagents. For this reason, the recast layer on the ferrous alloys is often referred as unetchable white layer. Micro hardness have shown that for ferrous alloys, the recast layer generally has a hardness value much higher than that of the underlying matrix and may exceed that attainable by normal quenching techniques (Livshits, 1960; Anonymous, 1965; Houman, 1983; Shobert, 1983; Boothroyd, 1989; Jameson, 2001; Webzell, 2001; and Tsai *et al.*, 2003). Weng and Her (2002) carried out several successful experiments involving an electrode of 50 microns diameter and a multi electrode for the batch production micro parts. The proposed method is reduces the production time and costs of fabricating both the electrodes and parts. The recent trend in reducing the size of products has given micro-shafts as 5 microns in diameter but also complex 3D micro cavities (Rajukar and Yu, 2000).

Konig *et al.* (1988), McGeough (1988) and Krar and Check (1997) also made several attempts to producing micro parts such as micro pins, nozzles, cavities using micro-EDM. In addition a study of applying micro EDM as an alternative method for producing photo-masks used in IC industry has been conducted. The application of CNC to EDM has helped to explore the possibility of using alternative types of tooling to improve the MRR. The EDM commonly employs 3D profile electrodes, which are costly and time consuming to manufacture for the sparking process. However, experimental work has been performed with a frame electrode generating linear and circular swept surfaces by means of controlling the electrode axial motion (Lee and Lau, 1991). These techniques eliminate the need to utilize the 3D electrode to perform the roughing operation by replacing the simple electrode to remove unwanted material in an complete block improving the machining efficiency and MRR.

Lok and Lee (1997) are worked on the two advanced Ceramics with EDM, the two types of ceramics are sialon and Al_2O_3-TiC. They find out the machining performance in terms of material removal rate and surface finish under different cutting conditions. The removal rates of these ceramics were very low and ranging from 4.20 to 6.00 mm^3/min for that sailon 501 and 2.49 to 7.53 mm^3/min for that of SG-4. When similar currents setting were used to machine an alloy steel grade SKD-11, a removal of 28 to 120 mm^3/min was achieved. As far as the sailon 501 ceramics is concerned, the current setting have little effect on the metal removal rate, as the difference from maximum rate and minimum rate is only 1.8 mm^3/min, which is negligible amount (Lok and Lee, 1997). Rozenk and Kozak (2001) are worked on the metal metal composites and investigate the effect of machining parameters current, pulse-on-time, pulse off time on the machine feed rate and surface finish with wire EDM. They conclude that the cutting feed rate and surface roughness for $AlSi_7Mg/20\%\ Al_2O_3$ composite are increased with increase discharge current. With increase in pulse on time the feed rate and surface rough ness is also increases (Rozenk and Kozak, 2001). Hocheng *et al.* (1997) are worked on the Metal Matrix Composite (MMC) SiC/Al with EDM. These materials have increasingly widened their use due to the merits of processing of high specific strength and modulus of elasticity while carrying good deformability and conductivity comparison to other metals. The fundamental analysis starts from the metal removal of MMC by single spark current. They correlates between the major machining parameters current, on-time, crater size produced by the single spark. The metal removal rate is proportional to the applied current, and on-time. For effective EDM of SiC/Al large current and short on-time are required (Hocheng *et al.*, 1997).

The development of different modern composite materials in the list dacade has led to an expansion of EDM applications. Yan *et al.* (2000) surveyed the various machining processes performed on the Metal Matrix Composites (MMC) and experimented with machining Al_2O_3/6061Al composite using rotary EDM coupled with a disk like electrode. The feasibility of machining of ceramic-metal composite steel plate coated with WC-CO using plasma spraying was also examined (Mamalis *et al.*, 1992). Muller and Monaghan (2000) compared the m of particle EDM reinforced MMC with their non-conventional machining processes such as laser beam machining and abrasive jet machining. It was found that EDM is suitable for machining particle reinforced metal matrix composites with a relatively small amount of sub-surface damage but MRR was very less. O A Abu Zeid worked on the AISI TI High Speed Steel with Electrical Discharge machine with a transistorized pulse generator to study the effect of voltage pulse off time, at constant values of pulse-on–time. A copper electrode with a positive polarity, kerosene dielectric, side flushing and current setting of 31.2 Amp were used through out experiment. He conclude that the metal removal rate is not very much sensitive to off-time changes at a lower pulse-on times corresponding to surface finish and show a higher sensitivity to these changes at higher on times corresponding to rough machining. It is recommended to use of short off times when finish machining AISI TI High speed steels, as this can result in higher metal removal rate, less electrode wear and good surface finish. On the other hand, long pulseoff-time values are recommended that when rough machining to secure same effect.

Kuppan *et al.* (2008) worked on the Inconel 718 by making deep hole drilling with EDM. The parameters peak current, pulse-on-time, duty factor and electrode speed were chosen to study behavior. The out put responses were metal removal rate, depth of average surface roughness. The experimented were planned using central composite design. The results revealed that metal removal rate is more influenced by peak current, duty factor and electrode rotation, and MRR is increased with increase in current and duty factor and electrode speed, where as depth of average surface roughness is increased with increase in peak current , electrode speed and pulse on time (Kuppan *et al.*, 2008).

Electrode Design and Manufacture

The design and manufacture of an electrode has progressed along with the technological advancement made in the various computer-aided systems. A CAD system is capable of creating the electrode and holder designs from the work piece 3D geometry and identifying any undesirable s harp corners on the designs, which are difficult to produce, by measuring the surface angle along the edges (Soni and Chakravarthi, 1996). The recent development in CAD/CAM systems and communications controls has also provided a through integration towards the design and manufacture electrodes by selecting essential machining parameters prior to the machining operation (Sato *et al.*, 1986). A Computer-

Aided Process Planning (CAPP) system for electrode design has also been built using future based work Piece decryption (Soni, 1994). In view of growing concern for green manufacturing (Soni and Chakravarthi, 1994) developed an environmentally friendly process planning system using a multi-objective analysis of the EDM process. The system takes both the environment impact, such as process energy and waste, and traditional manufacturing measures, such as production rates and quality, into account when performing the process planning.

In this way a lot of research is going on the different materials for machining metals, alloys, composites, super alloys for high MRR, good surface Finish. But in case of Inconel 718 very less research is done. And Inconel-718 is a High Strength, Temperature Resistant (HSTR) Nickel based super alloy. It is extensively used in aerospace applications such as gas turbines, rocket motors, spacecrafts, pumps and tooling. Inconel-718 is difficult to machine, 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. Because of this wide area of applications in various fields, it is better to know the behavioral properties of Inconel-718 with EDM.

Selection of Work Material

Inconel 718 is a High Strength, Temperature Resistant (HSTR) Nickel based super alloy. It is extensively used in aerospace applications such as gas turbines, rocket motors, spacecrafts, pumps and tooling. Inconel-718 is difficult to machine, 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 (Soni and Chakravarthi, 1994). Because of this wide area of applications in various fields, it is better to know the behavioral properties of Inconel-718 with EDM (Table 1).

Table 1: Chemical Composition of Inconel-718

Ni	Mo	Ti	C	Si	Cu	Cr	Nb(+Ta)	Al	Mn	Co	B
50-55	2.8-3.3	0.65-1.15	0.08	0.35	0.3	17-21	4.75-5.5	0.2-0.8	0.35	1	0.006

Preration of Samples

These blocks were cut from the ingots. They were cut in to 27 pieces by tool and turret machine with dimensions of $(20 \times 8 \times 1)$ mm. The experiments were conducted on the material with copper electrode.

Selection of Tool Material

The choice of the electrode depends upon the performance criteria required (MRR, surface roughness machining stability) and also upon the electrode manufacturing constraints. A good electrical conductor will be selected first in order to create the discharges. This material must have high melting point and vaporizing temperature as well as high thermal diffusivity to ensure the geometrical stability of the electrode. There are 3 types materials are available in market with following compositions.

Toll Material

It has been experienced that certain materials are more suitable than others depending upon the materials to be machined and the type of generator used. The characteristic of tool material should be such that the wear ratio, i.e., ratio of wear rate/metal removal rate is as much less as unity and its hardness does not allow any deformation of the toll during the machining process since in that case the machined surface shape will be damaged. It is interesting to note that the wear ratio for brass work is 0.5, for hardened plain carbon steel work 1.0 and for tungsten carbide work is 3.0. Wear ratio has been reduced to 0.1 by using graphite anode with a pulse generator machine.

The performance of electrode materials can be gauged by its material removal rate, low wear, and ability to be accurately machined or formed. The tool electrode for EDM constitutes the most important part and accounts for major cost. Commercially EDM tool electrodes are made of any of the following three categories of materials, viz., metallic (electrolytic copper, tellurium or chromium copper, copper tungsten brass, tungsten carbide, aluminum, etc.), non-metallic (graphite), and combination of metallic and non-metallic (copper graphite).

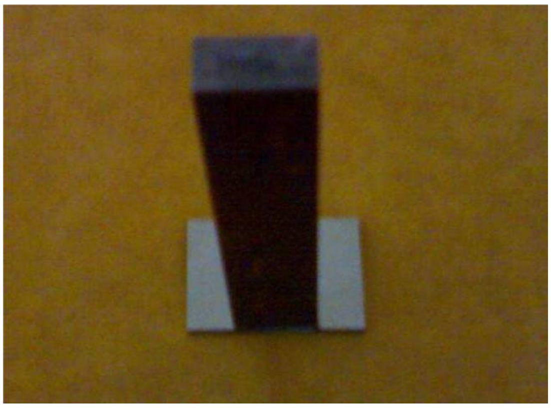
Copper

This is the first choice as EDM tool electrode. It can be produced by casting or machining. Copper electrodes with very complex features are formed by chemical etching or electroforming. Copper was the best tool material used for EDM machine (Figures 3 and 4) because of the following properties:

Good Electrical conductivity, high melting and vaporizing temperatures and Low coefficient of thermal expansion

Figure 3: Copper Electrode (8 × 12) mm

Figure 4: Work Piece and Tool



EXPERMENTAL DETAILS

A number of experiments were conducted to study the effects of the various machining parameters on EDM process. These studies have been under taken to investigate the effects of current, pulse on time and duty factor on the MRR, Surface roughness, hardness and crack propagation. The Inconel-718 metal is machined with the copper tool. Kerosene is the dielectric medium.

Expermental Setup

Machine Specifications

The experiments were conducted on GRACE V6040 Die Sinking Electro Discharge

Machine. The specifications are Single- door, large work tank, Large table traverse, Work tank: 800 × 600 × 400, $X \times Y \times Z$: 600 × 300 × 300, Maximum electrode weight: 100 Kg, Maximum Job weight: 350 Kg and Filter: Paper Filter.

Maximum Current: 50 amps the purpose of dielectric section is to store dielectric, to feed it to the machine in adequate quantity and to remove dirt from the dielectric. MAHATHOL TRANSOL EDM Oil is formulated from high paraffin base stocks having high Viscosity Index. This Oil undergoes repeated treatment and filtrations and as a result, the EDM Oil is having high degree of clarity and is totally odorless. Because of the low viscosity of this EDM Oil, settlement of dust, metal particles and carbon becomes easy.

Di-Electric Selection

Mahathol Transol EDM Oil has high fluidity which enables speedy settlement and is user friendly because of its odorless nature, as compared to other petroleum mineral Oils. Usage of this Oil enhances the filter life and also improves the finish and efficiency of the electrodes.

The following Equipments are used for the measurement of Surface Roughness, Image analysis and hardness (Figure 5).

Figure 5: Electro Discharge Machine

RESULTS AND DISCUSSION

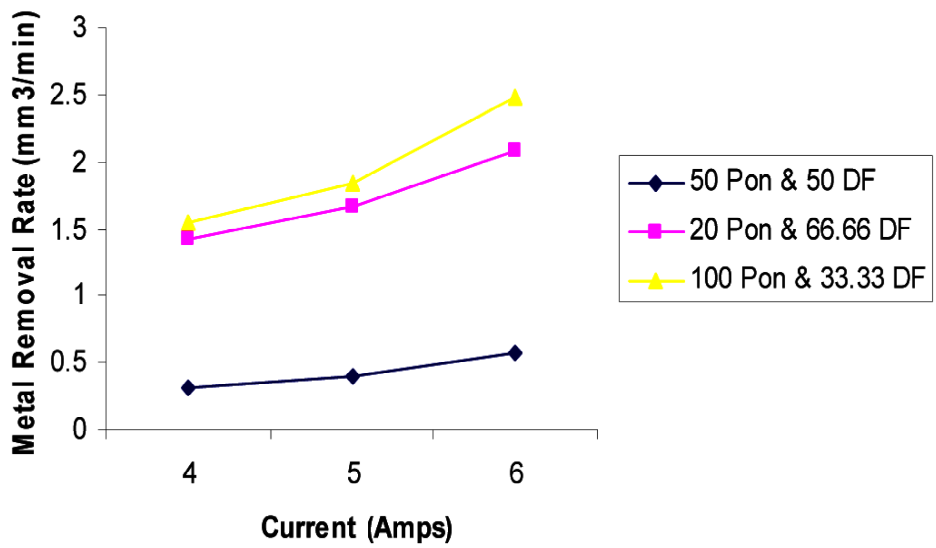
In the present work the influence of current, pulse on-time, duty factor on the performance indices of EDM such as MRR, Surface Roughness, and Hardness is evaluated at different experimental conditions. In this chapter we discuss and analyze the experimental data obtained (Table 2). Relation between input variables and performances measures are depicted in various figures.

Table 2: Variation of MRR at Constant Pulse-On Time and Duty Factor

Exp. No	Current (Amps)	Ton (μs)	Duty Factor (%)	MRR mm^3/min	SR (μm)
1.	4	50	50.00	0.3707	4.2620
2.	5	20	66.66	0.4061	4.2730
3.	6	100	33.33	0.5698	4.3845
4.	4	50	50.00	1.4245	5.4250
5.	5	20	66.66	1.6687	5.7056
6.	6	100	33.33	2.0757	5.9250
7.	4	50	50.00	0.3256	3.9725
8.	5	20	66.66	0.7326	4.1765
9.	6	100	33.33	1.1803	4.2565

Figure 6 shows the relationship between metal removal rate (mm^3/min) and current. From the figure, we can observe that, when the current is increase at constant pulse on time and Duty factor, the metal removal rate is increases. When the current is increased from 4A to 6A the metal removal rate is increased with current. This means that, when current are higher, melting starts earlier, i.e., low machining initiation time. Higher It can be attributed that metal removal rate is proportional to the product of energy and pulse frequency. Increasing the pulse current at a constant frequency increases the energy of the pulse

Figure 6: Variation of MRR with Current



and ultimately higher metal removal rate (Soni and Chakravarthi, 1994).

The Figure 7 shows the relationship between Surface Roughness and current. From the figure we can observe that, the surface roughness is increased with increase in current. When the current is increased, the metal removal rate is also increased. As normal when the metal removal rate increases automatically the surface roughness is increased. When the discharge current is high, the spark intensity and discharge power is more, subsequently causing a large crater depth on the surface of the work piece, which resulted in high surface roughness value (Soni and Chakravarthi, 1994).

Figure 7: Variation of Surface Roughness with Current

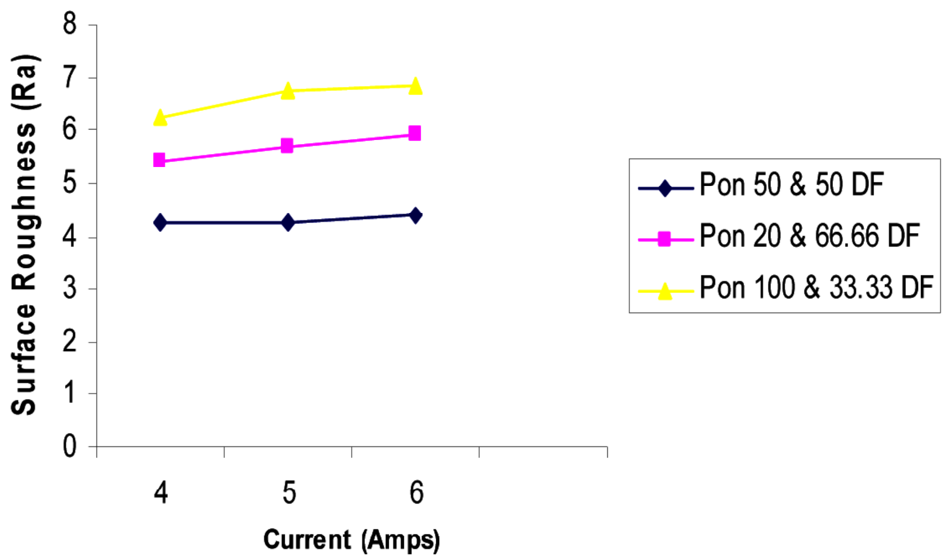


Table 3: Variation of Hardness with Current

Exp. No.	Current (Amps)	Pulse on Time (Ton) (Micro sec)	Duty Factor (%)	Hardness (Hv)
1.	4	20	66.66	425.6
2.	5	20	66.66	989.8
3.	6	20	66.66	765.4

Figure 8 shows the relationship between Hardness and current at constant pulse on time and duty factor. From that figure we can observe that the Vickers hardness value increases from 4A to 5Aand then decreased to words the 6A. Due to the fact that, when current increased from 4A to 5A the carbon particles are deposited on machined surface due to the carbon deposition, the hardness of the machined surface is increased, whereas in case of 6A current, due to the high current, the carbon deposited on the machined surface is flushed out. So that, no carbon deposition takes place and the Vickers hardness value decreased at 6A (Table 3)

Figure 8: Variation of Hardness with Current

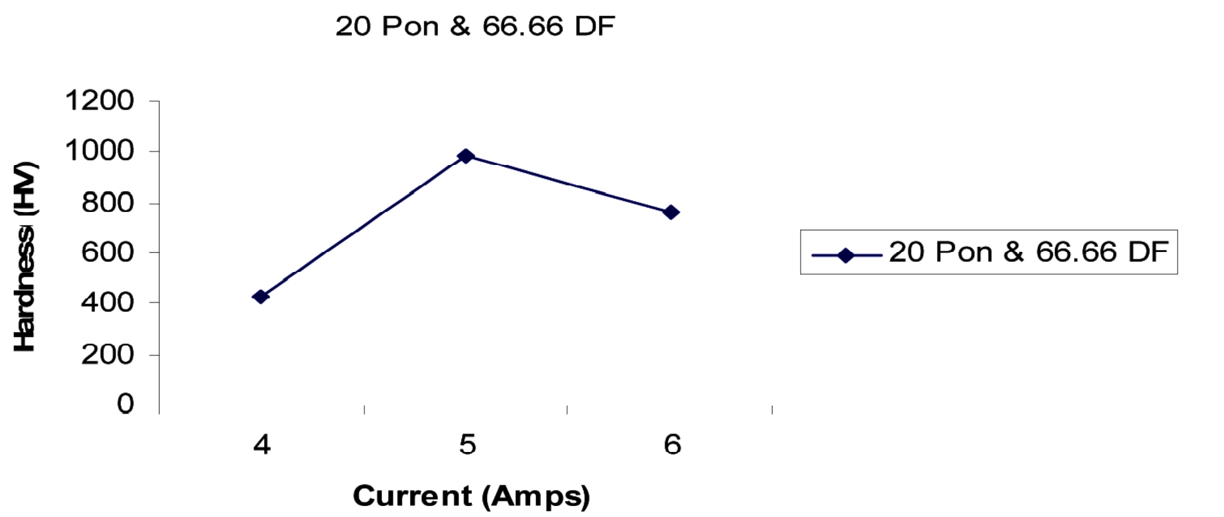
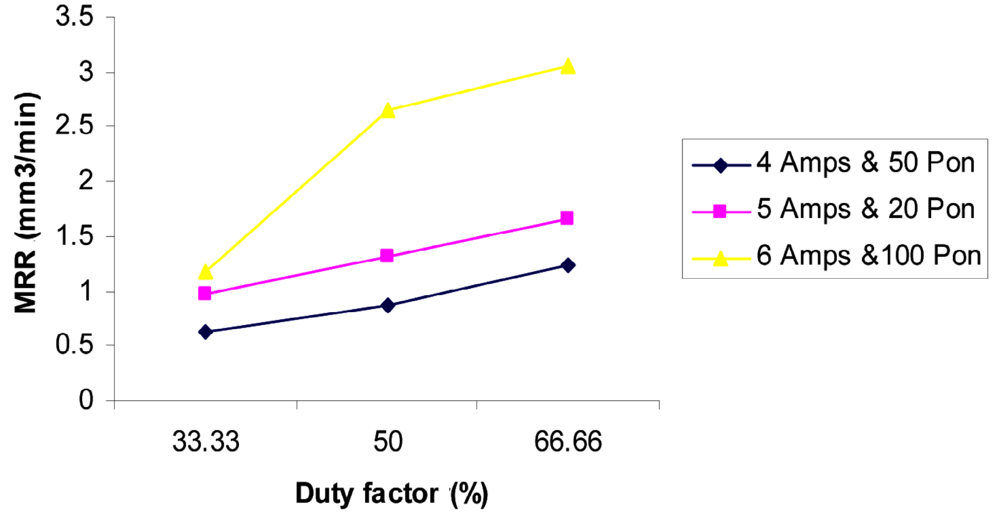


Figure 9 shows the relationship between metal removal rate and duty factor at constant current and pulse on time. As the duty factor is increased, increase in percentage of machining time (or pulse on time) and increase in total current occurs. Due to the increase in machining time, the metal removal rate on work piece is also increases. when the duty factor is increased from 33.33 to 66.66 at 6 Amps and 100 μsec pulse on time the metal removal rate is increased drastically where as at the

Table 4: Variation of MRR with Constant Current and Pulse-On Time

Exp. No	Current (Amps)	Pulse on Time (Ton) (Micro sec)	Duty Factor (%)	MRR (mm^3/ min)	SR (μm)
1.	4	50	33.33	0.6250	4.225
2.	4	50	50.00	0.8750	4.260
3.	4	50	66.66	1.2405	5.700
4.	5	20	33.33	0.9703	5.225
5.	5	20	50.00	1.3227	5.450
6.	5	20	66.66	1.6687	5.700
7.	6	100	33.33	1.1803	5.742
8.	6	100	50.00	2.6548	5.860
9.	6	100	66.66	3.0606	6.730

Figure 9: Variation of MRR with Duty Factor



current 4 and 5 Amps and pulse on time 20, 50 µsec MRR is increased gradually. For higher MRR the duty should be high.

The Figure 10 shows the relationship between surface roughness and Duty factor at constant current and pulse on time .It can noted from figure that, the surface roughness is increased with increase in duty factor from 33.33.to 66.66. This is due to the fact that at higher duty factor (Table 4), Increase in percent of machining time and increase in total current then automatically metal removal rate is increased rapidly. Due to faster metal removal rate, surface roughness is increased. So that at lower duty factor, we can get good surface finish rather than at higher duty factor.

The Figure 11 shows the relationship between Vickers hardness and duty factor at constant current and pulse on time. When the duty factor increases from 33.33% to the 50%

Figure 10: Variation of Surface Roughness with Duty Factor

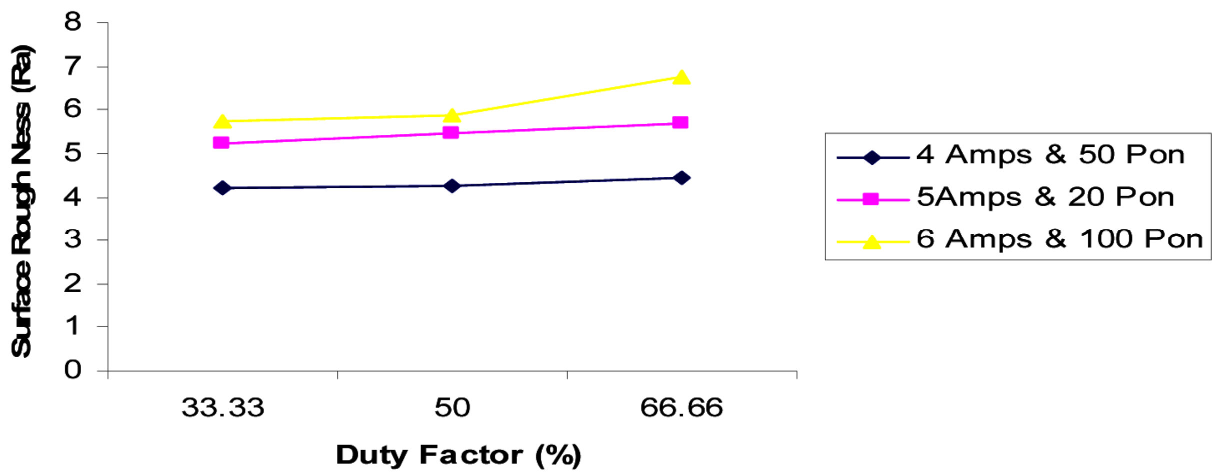


Table 5: Variation of Hardness with Duty Factor

Exp. No.	Current (Amps)	Pulse on Time (Ton) (Micro sec)	Duty Factor (%)	Hardness (Hv)
1.	6	100	33.33	425.80
2.	6	100	66.66	987.50
3.	6	100	50.00	725.66

the hardness value also increases due the deposition of carbon and then, the hardness value decreases at 66.66% due to the high duty factor (Table 5). Because high duty factor the carbon deposition layer is flushed out from the work piece. So when duty factor increases beyond the 50%, the hardness value decreased.

Figure 11: Variation of Hardness with Duty Factor

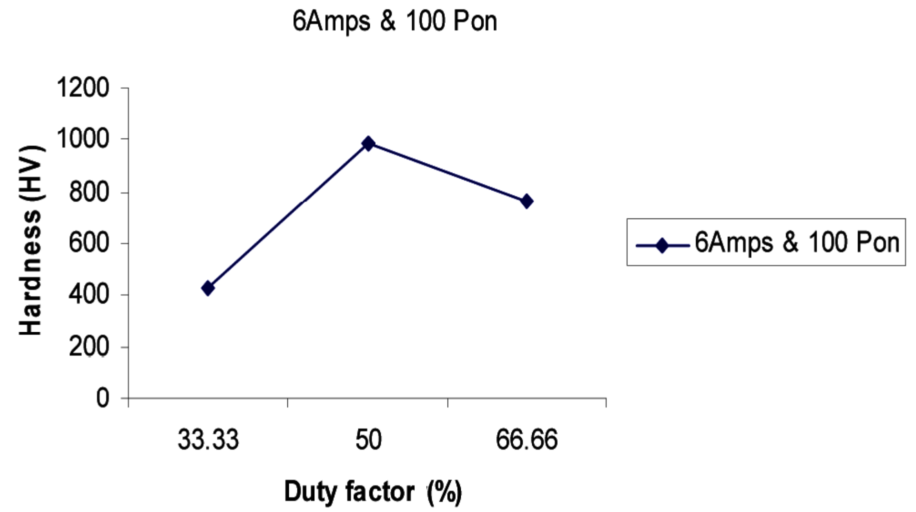


Table 6: Variation of MRR with Constant Current and Duty Factor

Exp. No	Current (Amps)	Pulse on Time (Ton) (Micro sec)	Duty Factor (%)	MRR (mm^3/ min)	SR (μm)
1.	4	20	50.00	0.5087	5.165
2.	4	50	50.00	0.3707	4.829
3.	4	100	50.00	0.3561	4.260
4.	5	20	66.66	1.6687	5.870
5.	5	50	66.66	1.5453	5.675
6.	5	100	66.66	1.3270	5.105
7.	6	20	33.33	1.9332	6.750
8.	6	50	33.33	1.7533	6.425
9.	6	100	33.33	1.0415	5.824

The Figure 12 shows the relationship between metal removal rate and pulse on time at constant current and Duty factor. The metal removal rate is decreased with increase in pulse on time. When the pulse on time is increased from 20 μsec to 100, the metal removal rate is decreased. Because the short pulses cause less vaporization, where as long pulse duration cause the plasma channel to expand. The expansion of plasma channel cause less energy density on the work piece, which is insufficient to melt and/ or vaporize the work piece material (Soni and Chakravarthi, 1994). The metal removal rate is maximum at around 50 pulse on time (in μsec) (Soni and Chakravarthi, 1994).

The Figure 13 shows the relationship between Surface Roughness and Pulse on

Figure 12: Variation of MRR with Pulse on Time

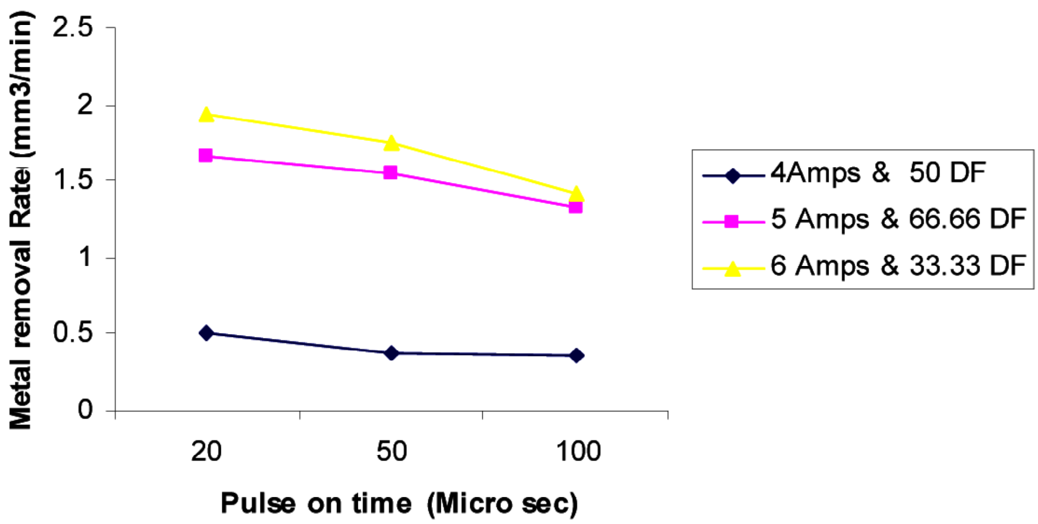
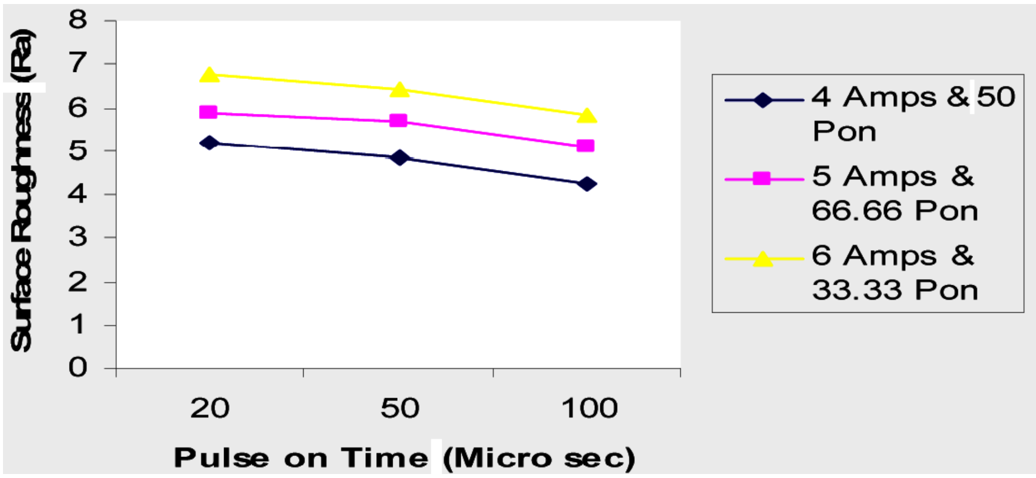


Figure 13: Variation of Surface Roughness with Pulse on Time



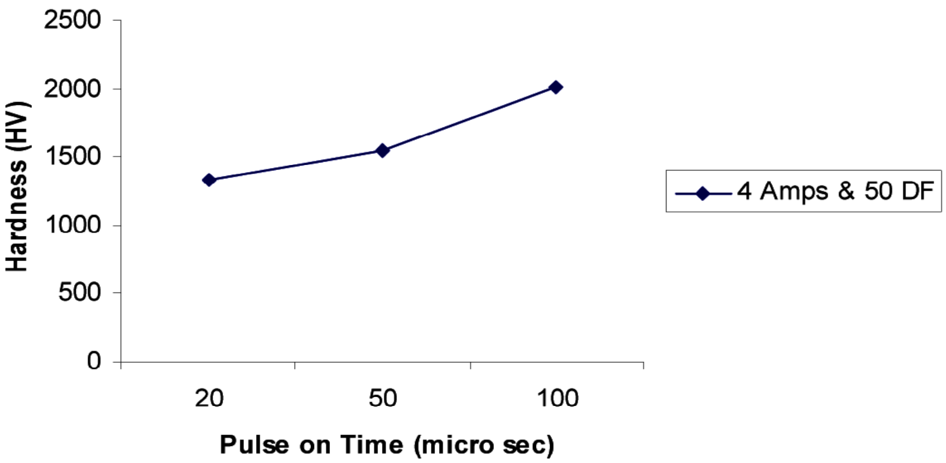
time at constant current and duty factor. From the figure we can observe that, the surface roughness is increased with increase in pulse on time from 20 micro sec to 100 micro seconds (Table 7). At low pulse on time we will get good surface finish when compared with high pulse on time. At constant current and duty factor setting ,increase in pulse on time results in proportional increase in spark energy and consequently melting boundary becomes deeper and wider, and increases the surface roughness value (Soni and Chakravarthi, 1994).

Table 7: Variation of Hardness with the Pulse-On Time

Exp. No.	Current (Amps)	Pulse on Time (Ton) (Micro sec)	Duty Factor (%)	Hardness (Hv)
1.	4	20	4	1326
2.	4	50	4	1550
3.	4	100	4	2013

The Figure 14 shows the relationship between the Vickers Hardness Value (HV) and Pulse on time at constant current and duty factor. From the figure we are observing that, the Vickers hardness value increase with increase in pulse on time from 20 μsec to 100 μsec.This is due to the fact that, along pulse duration causes the plasma channel to expand. The expansion of plasma channel causes less energy density on the work piece, which is insufficient to melt the work piece material and at same time it won't deplete the deposition of carbon layer on work piece. So that Vickers hardness value increased with increased pulse on time.

Figure 14: Variation of Hardness with Pulse on Time



Crack Propagation

When Inconel metal undergone EDM operation, high temperature will be generated at the machining surface. When the current increases, the spark intensity also increases. Due to the increase in intensity of spark the temperature of the machining surface will also increases, so that when the current increases the crack length and crack width also increases. When the duty factor increases, the machining time and spark intensity also increases due to which crack length and width are also increases. When pulse-on time increases, the crack length and width decreases because of low intensity of plasma channel. So that low temperature will be generated at the machining surface. Finally, we will get low crack length and width with higher pulse-on time (Figure 15).

Figure 15: Variation of Cracks Length and Crack Width

(a) I_p = 4A, DF = 33.33%, Ton = 50 μsec

(b) I_p = 6A, DF = 66.66%, Ton = 20 μsec

Recast Layer

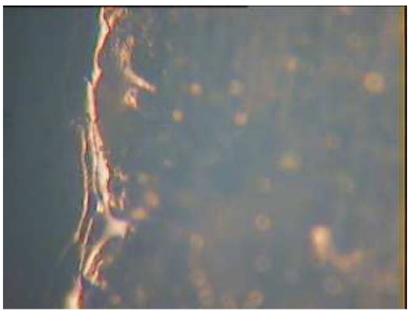
When Inconel metal undergone EDM operation, high temperature will be generated at the machining surface. When the current increases, the spark intensity also increases. Due to the increase in intensity of spark the temperature of the machining surface will also increases, so that when the current increases the recast layer also increases.

When the duty factor increases, the machining time and spark intensity also increases due to which recast layer is also increases. When pulse-on time increases, the recast layer decreases because of low intensity of plasma channel. So that low temperature will be generated at the machining surface. Finally, we will get less recast layer on surface of work piece with higher pulse-on time (Figure 16).

Figure 16: Variation of Recast Layers of Inconel-718

(a) I_p = 4A, DF = 33.33%, Ton = 50 µsec

(b) I_p = 6A, DF = 66.66%, Ton = 20 µsec



CONCLUSION

- When current increases, the MRR also increases. The higher the current, intensity of spark is increased and results in high metal removal will takes place.
- When the current is increased, surface roughness is also increased. Because due to increase in current, the spark intensity is also increases. So the MRR per minute increases. Finally the surface roughness is increases.
- When current is increases, hardness will decreased. Because due to increase current, the intensity of spark increases. Due high spark intensity the carbon layer will depleted. So that the hardness is decreased.
- When current is increased, the crack length, crack widths are also increased due to the high temperature generation at high currents.
- When duty factor is increases, the MRR is also increases. The higher the duty factor, intensity of spark and machining time is increased and results in high metal removal will takes place.
- When the Duty factor is increased, surface roughness is also increased, because due to increase in duty factor, the spark intensity, machining time is also increases. So the MRR per minute increases. Finally the surface roughness is increases.
- When Duty factor is increases, hardness will decreased. Because due to increase Duty factor, the intensity of spark increases. Due high spark intensity, the carbon layer will depleted. So that the hardness is decreased.

- When duty factor is increased, the crack length, crack widths are also increased due to the high temperature generation at high duty factors.
- When pulse on time is increases, the MRR is decreased. The higher the pulse on time, intensity of spark is decrease due expansion of plasma channel and results in less metal removal will takes place.
- When the Pulse on time is increased, surface roughness is decreased, because due to increase in pulse on time, the spark intensity is also decreases due to the expansion of plasma channel. So the MRR per minute decreases. Finally the surface roughness is decrease.
- When the Pulse on time is increases, hardness will increased. Because increase in pulse on time, the intensity of spark decreases due to the expansion of plasma channel. Due low spark intensity, the carbon layer will deposited, so that the hardness is increased.
- When pulse on time is increased, the crack length, crack widths are increased due to the low temperature generation at high pulse on time due the expansion of plasma channel.

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