Experimental investigation and thermal modeling on electro discharge drilling of PCD

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Experimental investigation and thermal modeling on electro discharge drilling of PCD

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University of Nebraska, 2015

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This study presents an experimental investigation and finite element simulation of Electro Discharge Drilling (ED-Drilling) of Polycrystalline Diamond (PCD). PCD has many outstanding properties including uniformly high hardness, high wear resistance and strong corrosion which are the main causes of widely using PCD. While PCD has many advantages and an important role in industrial applications, its high level of hardness and wear resistance cause this material to be difficult to form and machine by using traditional machining methods. EDM as a non-traditional machining process is an effective method among other non-traditional methods for PCDs due to its low cost and flexibility. The objective of this study is to investigate the effect of five process parameters including voltage, spindle speed, pulse on-time, pulse current and gap size on cutting speed on Material Removal Rate. A Taguchi L18 design of experiment (DOE) has been applied to optimize the number of trials in order to save time and raw material. All experimental trials have been conducted using ED-Drilling Hole Popper machine. EDM process is a complicated process and it is very difficult to understand the mechanism which involves electrodynamics, thermodynamic and hydrodynamic. Hence to understand the process and to
identify the effects of various process parameters, it is essential to model the process using a numerical method for analyzing and solving the ED-Drilling of PCD process. ANSYS (Computer simulation tool) finite element simulation has been applied to calculate the temperature distribution on the workpiece. The effect of current and pulse on-time in ED-Drilling process on heat distribution along the radius and depth of the workpiece has been obtained. In experimental study, it is found that voltage, pulse current and spindle speed have the significant impact on MRR. By increasing these parameters, MRR was improved. Also in numerical simulation, by investigating the effects of pulse current and on-time, the results showed that current is the major influencing parameter in thermal analysis which is in an agreement with experimental result.
Acknowledgment

It is with a feeling of great pleasure that I would like to express my most sincere heartfelt gratitude to Prof. Kamlakar P. Rajurkar, Department of Mechanical and Materials Engineering, for his insightful directions and instructions throughout my thesis and in the whole period of my master study.

It is my honor to have Dr. Carl Nelson and Dr. Jeffrey Woldstad as my committee members. I want to extend my gratitude to them for providing valuable suggestions and comments to the original manuscript.

In particular, I appreciate Mr. Jim McManis’s help in conducting experiment at Machine Shop, and helping me find the answer to my questions.

Finally, I express my gratitude towards my parents for their love and constant encouragement. Special thanks to my husband for his support and patience which enabled me to pursue my studies. I love you all and every one of you is the very source of my motivation to pursue my dream.
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Chapter 1

Introduction

1.1. History of Machining

Since non-traditional machining processes were established in modern industries they are called advanced manufacturing processes. These new methods of machining, called non-traditional machining processes, and differ from each other in their characteristic features, operations and applications. In addition, these techniques can be classified into various groups Fig.1.1 according to the energies utilization such as mechanical, thermal, electrical or chemical or combinations of these energies to remove extra material [1].

![Classification of Non-Traditional Machining Processes](image)

**Figure 1.1 Advanced Manufacturing Processes**
Certain parts of the workpieces and removed by different types of machining to change them to final parts. Traditional machining processes, also termed conventional, such as turning, drilling, shaping and milling requires the presence of a tool that is harder than the workpiece and a direct mechanical contact between the tool and the workpiece for machining. These characteristics of traditional machining processes make some difficulties in machining hard and brittle materials. The absence of any of these elements in any machining process such as the absence of tool-workpiece contact or relative motion makes the process a nontraditional one [2].

1.2. Electrical Discharge Machining (EDM)

EDM is a thermo electric process which has been widely used to produce dies, molds and metalworking industries. In the late 1940s the EDM technique was developed and during 1980s and 1990s it was one of the fast methods in developed area. This machining method is an effective process for machining very hard materials and cutting complicated contours or delicate cavities that would be impossible or tough to machine with conventional machining. However, EDM can only manufacture electrically conductive materials [3, 4].

In EDM, the removal of materials is based on series of discrete sparks that occurring between tool and workpiece in the presence of a dielectric fluid. There is a small distance (gap) between the electrodes (tool and workpiece) and there is no mechanical contact between them. The machining process successively removes small volumes of workpiece material and it is carried away from the gap by the dielectric flow in the form of debris. Over the past few decades, in the different modern industries, EDM has been widely applied to produce intricate and complicated shapes.
Figure 1.2 shows the classification of EDM processes. There are three main categories for EDM that is introduced by Pandey and Shan [5].

1.3. Electrical Discharge Drilling (ED-Drilling)

Small hole EDM (electric discharge machining) drilling, also known as fast hole EDM drilling, hole popper, and start hole EDM drilling, was a method of drilling holes. Holes can be drilled in any electrical conductive material, whether hard or soft, including carbide [6].

A schematic illustration of ED-Drilling is shown in Fig. 1.3, where both electrode and workpiece are immersed in dielectric fluid and separated by a certain distance.
ED-Drilling uses the same principles as EDM. The applied voltage creates a channel of plasma in the working gap between work piece and electrode. The discharge takes place with a heavy flow of current in the gap. During the discharging process, electrical energy from a pulse generator is turned into thermal energy which generates a channel of plasma in the working gap. The area where the discharge takes place is heated to an extremely high temperature that leads to melting and removing of surface material. The melted material is removed in the form of debris by the flowing dielectric fluid. Also, here the electrode is given rotation and through the electrode pressurized dielectric is passed.

### 1.3.1. Application of ED-Drilling Process

ED-Drilling process can be applied in order to drill holes in turbine blades, fuel injectors, and hardened punch ejector. Also, it is one of the best choices for removing broken tools in small holes, making plastic mold vent holes, wire EDM starter holes and air vent holes for forging
dies. In addition, this technique can be used for dovetail finger pin removal, cross key pin removal, balance hole drilling and removal of steam strainer rivets etc [7].

1.3.2. **Advantages of ED-Drilling Process**

- ED-Drilling is the practical method for producing deep small holes.
- This process is able to create straight holes which are very difficult to do with conventional methods.
- The torque condition is eliminated during machining since there is not any contact between electrode and workpiece and it prevents breaking electrode (drill).
- It has the ability to drill extremely hard materials to tight tolerances.
- There are no burrs during drilling and this is especially important when difficult holes require deburring.
- ED-Drilling is an efficient method to produce holes on curved and angled surface.

1.3.3. **Disadvantages of ED-Drilling Process**

- ED-Drilling process has a high electrode wear ratio.
- There is a problem regarding the reduction of speed for drilling large holes.
- The depth of the blind holes is difficult to control due to the high electrode wear.

1.4. **Objectives of the Research**

It can be seen that Polycrystalline diamond (PCD) has had a lot of applications as dies and cutting tools in wide variety of industries such as automotive, aerospace and woodworking. PCD has many outstanding properties including uniformly high hardness, high wear resistance and strong corrosion which are the main causes of widely using PCD. While PCD has many
advantages and important role in industrial applications, its high level of hardness and wear resistance cause this material to be difficult to formed and machined by using traditional machining methods. EDM as a non-traditional machining process is an effective method among other non-traditional methods for PCDs due to its low cost and flexibility. Although, there has been a substantial efforts on using EDM for PCD materials in the literature, it can be seen rarely the use of ED-Drilling in the case of PCD as a workpiece. Thus, it is needed to make more attempts on using ED-Drilling for PCD and the first objective of present work is to analyze the ED-drilling material removal rate (MRR) of PCD in relation to process parameters and different electrodes.

EDM is a complicated and stochastic process in which so many mechanisms such as electrodynamics, electromagnetic, thermodynamic, and hydrodynamic are involved and make the process difficult to perceive. Consequently, numerical method such as Finite Element Method (FEM) has been broadly applied to contribute better understanding of the EDM and EDM-Drilling process [8]. Also, the thermal modeling plays an important role in analyzing and solving the ED-Drilling of PCD process in terms of heat distribution. In this study, a development of thermal model by FEM simulation software, ANSYS, is performed in order to characterize the impact of current and pulse on-time in ED-Drilling process on heat distribution along the radius and depth of the workpiece.

1.5. Thesis Organization

Chapter 1 covers brief introduction to non-traditional machining, Electrical Discharge Machining (EDM), Electrical Discharge Drilling (ED-Drilling), EDM-Drilling principal, advantages, disadvantages and applications. The objectives of the investigation are also described.
Chapter 2 presents the literature review of EDM and ED-Drilling process. This literature review is categorized in two classifications, literature based on non-traditional machining (include ED-Drilling) of polycrystalline diamond (PCD) and non-traditional process thermal modeling and analysis.

Chapter 3 presents the development of theoretical model and analysis for single discharge in ED-Drilling.

Chapter 4 includes the experimental methodology, experimental situation and measurement techniques used for single spark crater.

Chapter 5 presents experimental results of single spark. ANSYS finite element simulation has been applied to calculate the temperature distribution on the workpiece. The effect of process parameters on heat distribution is discussed.

Chapter 6 presents the conclusion and recommendation for future work.
Chapter 2

Literature Review

This chapter presents a detailed literature review of non-traditional machining processes especially EDM classifications, as techniques for manufacturing PCD and theory of EDM-Drilling process and review the research have been done on EDM-Drilling. Also, this chapter covers a literature review on the EDM process thermal modeling and analysis.

2.1. Non-Traditional Machining Processes of PCD

Polycrystalline diamond (PCD) is a composite material with high hardness, high toughness, high wear-resistance, good thermal conductivity, and strong corrosion resistance which is produced by sintering selected diamond particles with a metal matrix together at a high pressure and a high temperature. Due to its excellent advantages, PCD has been widely used as dies and cutting tools in the automotive, aviation, aerospace and woodworking industries [9, 10]. PCD application can be limited because of some of its specifications such as high hardness and high wear-resistance. These properties make PCD forming and machining by conventional techniques such as grinding and lapping difficult, long and costly. On the other hand, there are some nontraditional machining processes such as ultrasonic machining, laser machining and water jet machining which can be applied to machine PCD, but they are ineffective to increase productivity. Other electro discharge machining processes like EDM, electric discharge milling, and electrical discharge grinding are more effective process to machine PCD with lower cost and higher accuracy [10]. PCD can be machined by the EDM technique easily since it is sufficiently electrically conductive. Today, the main and effective machining technique for PCD is electrical
discharge machining (EDM) that has offered a solution for difficult-to-machine materials irrespective of their hardness and strength. The mechanical stresses, chatter and vibration problems during machining have been eliminated in the EDM process because there is not a direct contact between the electrode and the workpiece. In addition, the EDM process is flexible and has low cost for machining PCD. As a result, the EDM process can provide a successful machining technique for manufacturing PCD by controlling the EDM conditions [11-13].

The machining performance of micro-hole machining on PCDs by micro-EDM has been studied to investigate the impact of machining polarity, electrode rotation speed and nominal capacitance on the material removal rate (MRR) and the relative tool wear ratio (TWR). In that study, the appropriate machining performance of micro-EDM on PCDs was achieved in negative polarity machining as compared to positive polarity machining. Also, it was found that the appropriate volume of adhesion on the tool electrode has an important effect on MRR enhancing and TWR reduction [9]. A new pulse generator using DSP-based control circuit for micro wire electrical discharge machining was developed to suppress damages on the machined surface of PCD while achieving stable machining. Experimental results of that study showed that width and thickness of the damaged layer increased in the higher open voltage and peak current; therefore, the surface quality became worse [10]. An experimental investigation on the machining characteristics of Polycrystalline Diamond (PCD) in micro wire electrical discharge machining was performed to obtain the optimum conditions of parameter settings for cutting width and material removal rate (MRR). In order to achieve the optimum conditions of parameter settings for cutting width and material removal rate (MRR) a Taguchi method was applied. Also for predicting the significant machining parameters the ANOVA analysis has been used. The results indicated that the PCD grain size played an important role in MRR so that maximum MRR was
obtained in lower PCD grain sizes. In addition, The MRR was increased at greater open circuit voltage and peak current [11]. A combined process of polycrystalline diamond by EDM and ultrasonic machining and combined processing was achieved by using bronze bond diamond grinding wheel. An experimental study was performed in order to determine the effect of different processing parameters on machining performance of polycrystalline diamond. The experiment results indicated that the most significant parameters in machining of PCD are pulse width, pulse interval, peak current, ultrasonic amplitude and open-circuit voltage. In addition, it was found that Ultrasonic vibration had chip removal function and impact of ultrasonic vibration on the material removal rate was negligible [12].

A copper electrode giving ultrasonic vibrations was used to improve the machining efficiency in the die sinking EDM of the PCD. In that investigation three types of ultrasonic vibration modes were selected (axial vibration, flexural vibration and complex vibration). The obtained results showed that giving ultrasonic vibrations to the copper electrode has a positive effect on machining of PCD by die sinking EDM. The cavitation effect of the working fluid and the acceleration of the discharge machining are two important factors on EDM characteristics improvement by giving ultrasonic vibrations. Also, giving ultrasonic vibrations to the electrode improved the surface roughness of the workpiece [14]. A developed model was established to predict the crater size for individual spark in electrical discharge grinding (EDG) of PCD. A useful method to justify the material removal mechanism is single crater modeling. In that investigation, the author applied the modeling of the crater geometry refers solely to thermal stress analysis of the PCD system which referred to the theory was reported by Kozak et al. The experimental results were used to determine the crater size of individual spark. Then, the
obtained model compared with simulation predicated values and the single discharge experiments confirmed the size of the simulated crater [15].

A study was performed to develop a prototype Micro-EDM system for fabricating microstructures on PCD. In that study, a copper–nickel (Cu–Ni) alloy, cupronickel, was used as an electrode material for generating microstructures on PCD by EDM. The electrodes were shaped into tiny wheels, the rotation of which was driven by circulation of a dielectric fluid. Raman spectroscopy and energy dispersive X-ray spectroscopy analysis were applied to investigate the material removal mechanisms in the EDM process. The findings of this study provide a new approach for high-precision and high-efficiency micromachining of PCD and other carbon-based ultra-hard materials [16]. In order to fabricate three-dimensional micro cavities and PCD tools a Micro-EDM scanning process was utilized. Micro-EDM scanning process was selected to machine the PCD because three-dimensional PCD shapes were not easily achievable by conventional mechanical processes. Also, in that study the machining performances such as electrode wear, machining time, and roughness of Micro-EDM scanning on PCD were investigated. The experimental results indicated that the PCD workpieces were machined by short-pulse discharge from a resistor-capacitor (RC) circuit were more precise than a transistor (Tr) pulse generator. In addition, the surface roughness of machined PCD workpieces could be as small as Ra 0.2 mm, even when the diamond grain size is considerably larger [17]. An integrated neural network (NN) model and a genetic algorithm (GA) were applied to determine the optimal process parameters and obtain the better machining performance while machining large area polycrystalline diamond by electrical discharge grinding process. The machining performance using the optimal parameters was improved significantly, with the
material removal rate increased from 9.11 to 9.75 mm³/min and the depth of diamond WC interface reduced to 0.03 from 0.035 mm [18].

The vibration effect of tool electrode on machining performance such as material removal rate, tool electrode wear, and surface roughness in micro-EDM of PCD was investigated. In that study, the Taguchi approach was used to evaluate the machining parameters like charge voltage, capacitance, and vibration of the tool electrode. The results showed that the vibration on tool electrode is a significant parameter on material removal rate, leading to an increase in MRR. Furthermore, the surface roughness and the tool electrode wear are affected by the amount of capacitance [19]. A new technique of machining PCD using electric discharge (ED) milling was proposed. This process was able to effectively machine a large surface area on PCD, and effectively machine other advanced conducting materials such as cubic born nitride (CBN), and ceramics. Moreover, the influence of pulse on-time, peak current and polarity on the process performance have been investigated [20]. A study and experimental investigation was reported on machining of PCD by die-sinking electrical discharge machining to improve the EDM performance in terms of material removal rate, relative wear and energetic consumptions [21].

An experimental investigation was performed on die-sinking of PCD conducted in order to demonstrate the possibility of machining using this processing technology. The quantity of material removed from workpiece and tool electrode, the number of total useful pulses and the number of short-circuit pulses have been considered as the electro-technological parameters in that study. Those parameters were necessary in order to determine the relative wear, productivity, and energetic consumptions [22].
2.2. Theory of ED-Drilling Process

Almost about 70 years passed since the discovery of EDM technology, the exact physical phenomenon taking place during material removal in EDM is not yet fully understood. The various theories based on theoretical and experimental research have been proposed to address the material removal mechanism of the EDM process [23].

The EDM hole-drilling method was used in order to measure the residual stress in high-performance materials. In that study, the SKD11 tool steel as the material and two EDM conditions, which have the same EDM energy, to process the stress measurement under different stress conditions, was adopted. The results indicated that both EDM conditions induce compressive additional stresses. In order to reduce the hole-drilling stress and appearance of cracks, the smaller pulse-on duration combined with larger pulse current were applied. Moreover, a linear equation described the stress measurement curve of EDM hole-drilling method which was parallel to the ideal measurement curve. Hence the EDM hole-drilling method possessed the measurement stability under different residual stress conditions and could be calibrated [24]. A rotary EDM with a hollow-tube electrode was used to evaluate the feasibility of machining certain Al2O3/6061Al composite. The EDM performance was evaluated in terms of the material removal rate, electrode wear rate and surface roughness. The experimental results showed the amount of material removal rate was higher while using the rotating hollow-tube electrode during machining Al2O3/6061Al composite by EDM-drilling. Furthermore, the peak current and volume fraction significantly affected the MRR, EWR and SR. On the other hand, the effects of rotating speed and flushing pressure of the electrode on the MRR, EWR, and SR were negligible [25]. The feasibility of machining Al2O3/6061Al composite by EDM blind-hole drilling was evaluated. In that investigation, Taguchi methodology and the analysis of variance
(ANOVA) were applied to represent the relationship between machining parameters and process performance. MRR, EWR, and SR have been consider as process performance and some independent parameters such as polarity, peak current, pulse duration, powder supply voltage, rotational speed of the electrode, injection flushing pressure of the dielectric fluid, and the number of eccentric through-holes in the electrode were chosen as variables in evaluating the Taguchi method. The results revealed two important conclusions: (1) the electrical parameters like polarity, peak current, pulse duration and powder supply voltage has a more significant effect than the other parameters on the machining characteristics, (2) A higher amount of MRR could be obtained by a rotational electrode during machining [26]. A technological application of deep small hole drilling with EDM where the ratio between depth and width is about 10 was discussed to study the influence of high pressure of the dielectric in the gap during machining. Process behavior was studied by means of voltage pulse parameters and the technological characteristic of machined hole. It could be concluded from the results that voltage and current had an important role in the optimization of EDM process. Also, the obtained results could be an important key to control of the gap distance and flow of the dielectric automatically [27]. The important type of defect from hole drilling during EDM process is hole taper and hole accuracy. Due to movement the debris by pressure flow of dielectric fluid, the taper makes on the workpiece. Therefore, a study have been done that focused on influence of EDM parameters such as electrical current, on-time, duty factor, water pressure and servo rate on material removal rate (MRR), electrode wear rate (EWR) and tapered hole of martensitic stainless steel AISI 431. In that research, a brass tube electrode with outside diameter of 1 mm, inner hole diameter of 0.3 mm was used as tool. The experimental results revealed that by increasing of servo rate, the MRR amount decreased and the taper of hole increased with increasing of electrical current and
servo rate [28]. In order to make holes in parts such as turbine blades, fuel injectors, cutting tool coolants, hardened punch ejectors and plastic-mould vents the electrical discharge machining (EDM) fast hole-drilling highly has been used. EDM fast hole drilling is a key manufacturing technology for gas turbine components, and Rolls-Royce currently operates over fifty machines using brass electrodes and deionized water dielectric in a range of factories. A study has been carried out with the purpose of optimizing the EDM fast hole drilling process of nickel-based workpieces. That study focused on evaluation of dielectric and electrode materials. Also, two different dielectric fluids (deionized water, and a solution of water, alcohols and salts) and electrode materials (copper and brass) were used in that research. The water-based dielectric with brass electrodes was the best combination of dielectric and electrode material based on the results. That combination increased the drilling rates and decreased the electrode wear. Moreover, that investigation results showed that the type of dielectric fluid had significant impact on the type of electrode wear and the average recast layer of parts drilled with the water-based dielectric was thinner than that of parts drilled with deionized water [29].

The influence of major operating parameters on the performance of micro-EDM drilling of cemented carbide was investigated and the ideal values for improved performance were identified. The electrode polarity, gap voltage, resistance, peak current, pulse duration, pulse interval, duty ratio, electrode rotational speed and EDM speed were considered as operating parameters. The process performance was evaluated by machining time, material removal rate (MRR), relative electrode wear ratio (RWR), spark gap, surface finish and dimensional accuracy of micro-holes [30]. There are some difficulties in machining titanium and its alloys by conventional machining due to low thermal conductivity of titanium and its alloys and their reactivity with cobalt in most tool materials. On the other hand, unconventional machining
processes especially Micro-Electrical Discharge Machining (Micro-EDM) are more appropriate techniques for machining difficult-to-machine materials like titanium and its alloys. An attempt has been made for simultaneous optimization of the process performances like, metal removal rate, tool wear rate and overcut based on Taguchi methodology. Thus, the optimal micro-EDM process parameter settings have been found out for a set of desired performances. Pulse-on time, frequency, voltage and current considered were as process parameters in that study [31]. A study based on the execution of through micro-holes on stainless steel plates was carried out using a micro-EDM machine Sarix SX-200. The impact of several process parameters, namely peak current, voltage and frequency on material removal rate (MRR) and tool wear ratio (TWR) was evaluated. Tubular electrodes made of two different materials (tungsten carbide and brass) were used in that study. Also, the analysis of variance (ANOVA) which is a statistical method used to test differences between two or more means. The influence of both electrode material and process parameters (peak current and voltage) on the process performance was analyzed by this method [32].

2.3. EDM Process Thermal Modeling and Finite Element Analysis

The exact material removal mechanism in EDM-Drilling is not fully understood due to lack of knowledge. Therefore, the thermal modeling plays an important role in analyzing and better understanding of ED-Drilling of PCD process in terms of heat distribution. In this study, a development of thermal model by finite element method (FEM) simulation software, ANSYS, is performed in order to characterize the impact of current and pulse on-time in ED-Drilling process on heat distribution along the radius and depth of the workpiece.
FEM was used to study the Electro-thermal models of the micro-EDM process. A simplified heat conduction model was applied for modelling, and then replacing the simplified conditions such as uniform heat flux, constant thermal physical properties, and fixed plasma radius. Also, the realistic conditions and experimentally determined model parameters helped to investigate the effect of these modifications on the output of the model. To get better predictions by models, an analytical method with experimental data is used to determine the critical parameters, which are energy distribution ratio and plasma radius. Comparing simulation results with experimental data indicated by adding more realistic conditions the prediction of the models was improved [8]. In order to determine crater geometry at anode at different energy level, a thermal electrical theoretical model has been developed for a single discharge micro-EDM. Moreover, Finite Element Analysis was performed to solve the model using commercial available software COMSOL. A Gaussian distribution of heat source was used in the model to predict crater geometry, temperature distribution on the workpiece at different energy level. In addition, this model assumed that the material was removed when its temperature exceeds the melting temperature during pulse on time [23].

An attempt has been made to develop two-dimensional axi-symmetric model in order to predict the variation of temperature and residual stresses in EDM of Molybdenum with the help of ANSYS software. In that study, the influences of most significant machining parameters such as current, voltage and pulse duration on the workpiece has been analyzed. Based on the FEM study it was concluded that residual stresses built up near the crater boundary in all directions during the EDM process. These residual stresses were both tensile and compressive in nature and it remained in the workpiece in small quantity after a single spark, but may compound over many spark cycles which leads to surface damage in the form of micro-cracks [13]. The numerical
approach was developed with the finite element analysis solver ANSYS to obtain the thermal model of die-sinking EDM process and this model was verified with the published work. Also, the material removal rate and the surface roughness were determined based on the achieved model. The two-dimensional numerical simulation model for electro discharge machining (EDM) was developed in order to achieve different objectives such as:

- To understand the EDM process and its governing process parameters considering numerical approach.
- To study the various existing developed models for EDM process.
- The numerical simulation model for EDM considering multi-disciplinary approach.
- To evaluate the numerical simulation model of EDM with published as well as experimentation.

Since, the reported theoretical models were based on the assumptions like the use of constant spark radius, approximation of heat source to a point or disc shaped (uniform) and constant thermal properties of work/tool materials, the thermal analysis have limited applicability [33]. The die-sinking EDM process was simulated by a theoretical thermal model. That model was proposed to determine the MRR and the surface roughness as a function of the main process parameters such as the arc voltage, the current, the spark duration and the idling time. The single spark discharge crater geometry on the workpiece surface has been determined to develop a model capable of predicting the material removal rate. For that reason some following assumptions have been considered:
- The crater had circular paraboloid geometry and its diameter on the surface was determined from empirical relations.
- The crater’s depth was determined from the temperature distribution within the workpiece.
- The problem was considered as a one-dimension conduction problem.
- The heat was transferred to the workpiece only by conduction

The model predicted that the higher amount of material removal rate and surface roughness was obtained by increasing the discharge current, the arc voltage or the spark duration. On the other hand, the idling time had a significant effect on the material removal rate and surface roughness. By decreasing of idling time, the material removal rate increased and surface roughness of the workpiece was improved. Also, the theoretical predictions were compared with the experimental results to verify the approach [34].

A Thermal model for electrical discharge machining of AISI H13 tool steel was proposed to calculate the theoretical amount of MRR. The presented model was solved numerically by means of ANSYS finite element code. The developed model in that research was more realistic compared to the previous models because of incorporating factors such as plasma flushing efficiency, latent heat of melting, and Gaussian distribution of heat flux, considering material properties as a function of temperature, and calculating an exact value for the portion of energy absorbed by the cathode. In that study, the Fourier heat conduction equation independent of circumferential condition was considered as the differential equation because the model was axisymmetric. One of the most important factors in the simulation process is the type of heat flux applied onto the model as a heat source which has a direct effect on the accuracy of the results.
Thus, the nature of the EDM process and sparks necessitates using Gaussian distribution for heat flux. Also, numerous experiments have been done in order to investigate the accuracy of the predicted MRR. Theoretical MRR was calculated in various pulse powers and compared with experimental results.

![Figure 2.1 Interactive effect of pulse current and pulse on-time on heat distribution: a across the radius of the workpiece, b in depth of the workpiece](image)

Figure 2.1 Interactive effect of pulse current and pulse on-time on heat distribution: a across the radius of the workpiece, b in depth of the workpiece

Figure 2.1a, shows that for a constant value of current, the temperature along the surface of the workpiece decrease while the pulse duration increases and it is because of increasing the duration of heat loss. On the other hand, the gradient of heat loss decreases by increasing the pulse duration because of an increase in the area affected by the heat flux. Figure 2.1b illustrates heat distribution through the depth of the workpiece for different machining conditions. It is obvious from the figure that the variation of heat distribution shows a similar trend to heat distribution across the radius of the workpiece.
Figure 2.2 Effect of pulse on-time on crater size: (a) on crater width, (b) on crater depth

Figure 2.2a, b shows the effect of pulse on-time on crater size for different values of pulse current for a constant pulse voltage. In the low values of pulse on-time, crater radius shows an increasing trend but converges to a constant value as the time increases. Crater depth possesses a similar behavior for low values of time but attains a decreasing trend as the value of time exceeds a certain critical value [35].

A finite element analysis (FEA) model of single spark EDM of Al6063/Sic was provided to calculate the temperature distribution and it was extended to simulate the second discharge. In addition, material removal was calculated by calculating the number of pulses and was compared to the experimental results. In development of the model some important features of the process have been considered such as individual material properties, shape and size of heat source (Gaussian heat distribution), percentage of heat input to the workpiece and pulse on/off time. Finally, the predicted analytical results were compared with the experimental results obtained under the same process parameters to validate the model. In order to obtain residual stress distributions, thermal stress distribution mechanism of reinforcement particle bursting phenomenon, the developed model in that study could be used [36]. Powder Mixed Electrical
Discharge Machine process of H13 Hot Die steel workpiece was simulated using finite element model (FEM) simulation software to generate the temperature variation. In that work, the relevant boundary conditions and reasonable assumptions were used to model the process. The axi-symmetric model two-dimensional model was developed to predict volume removed in a single crater from the temperature profiles along with the cooling rate and stresses induced due to the heating of the work-piece by spark [37]. An axisymmetric two-dimensional thermal model was generated to predict the material removal mechanism in Powder Mixed Micro-Electrical Discharge Machining of Ti-6Al-4V Alloy. The modeled used ANSYS (version 14) software to calculate the temperature distribution in the workpiece material and then material removal rate was estimated from the temperature profiles. The effect of various process parameters such as voltage, polarity, capacitance, tool electrode type and powder type on temperature distributions along the radius and depth of the workpiece has been studied. To validate the model the theoretical MRR was compared with the experimental results obtained from the setup developed in the laboratory. The results showed that the PM Micro-EDM produces smaller and shallower craters than Micro-EDM under the same set of conditions. This is because of the uniform distribution of spark among a large no of powder particles. Hence there is a uniform distribution of discharge energy on the workpiece surface [38]. A MATLAB-based thermo-numerical model was presented to simulate a single spark discharge of micro-EDM process on molybdenum and then the material removal for the process was analyzed using the developed model. Also, in this study the effects of important EDM parameters such as the pulse duration on the crater dimension and the tool wear percentage were studied. The crater dimension compared with the experimental data and the results illustrated that the thermo-numerical model could effectively approximate the size of a crater created by a single spark in molybdenum for the micro-EDM.
The model estimated that the percentage of tool wear decreases with an increase in the pulse duration and was much higher for molybdenum than steel at the same machining conditions. In order to show how the thermal action of the micro-EDM process affected the surface integrity of machined workpiece, a coupled thermal-structural finite element analysis was performed [39]. To predict the temperature distribution, thermal stress and residual stresses, an axisymmetric model for AISI D2 steel was developed using ANSYS software. Finite element simulation and modeling were carried out for a single spark with temperature-dependent material properties. Incorporating some certain parameters such as spark radius equation based on discharge current and discharge duration, the latent heat, the plasma channel radius and Gaussian distribution of heat flux, the percentage of discharge energy transferred to the workpiece have made this study more realistic. It was found that the radial component of the residual stresses acquired from FEM are dominant than other components for all the machining parameter combinations [40]. A finite element-based model for the electric discharge machining (EDM) process was presented. In order to predict the transient temperature distribution, liquid- and solid-state material transformation, and residual stresses, the model applied process parameters such as power input and pulse duration. The finite element method model simulated the effects of a single spark using the well-known commercial software called DEFORM. The results revealed that the model could provide good predictions of the temperature distribution, material transformation, residual stress and the final crater shape. For most of these predicted results (except the thermal results) experimental data have been shown to agree quite well with the model. Therefore, the developed model could be used to investigate the effects of multi-sparks and different process parameters on different kinds of materials that were used in EDM applications [41]. A non-linear, transient, thermo-physical model of die-sinking EDM process has been developed using the FEM. The
two-dimensional axi-symmetric process continuum has been considered to perform the numerical analysis of the single spark operation of EDM process. The analysis was based on more realistic assumptions such as Gaussian distribution of heat flux, spark radius equation based on discharge current and discharge duration, latent heat of melting, etc., to predict the shape of crater cavity and the material removal rate (MRR). Comprehensive thermal analysis of the process was carried out and the results obtained from the numerical model were compared with analytical models, published experimental data and the experimental results. It was found that the MRR values predicted by developed model were closer to the experimental results when compared with all the earlier reported analytical models [42].

2.4. Gaps in the Literature

- Although, a lot of studies on nontraditional machining of PCD material have been reported in recent years, it seems that more attempts need to be done on machining of PCD by EDM-Drilling and the effect of process parameters on machining performance.

- EDM process is a complicated process and it is very difficult to understand the mechanism. Also, there is limited research about thermal modeling on EDM-Drilling of PCD. Hence to understand the process and to identify the effects of various process parameters, it is essential to model the process using a numerical method for analyzing and solving the EDM-Drilling of PCD process.
Chapter 3

Process Modeling & Theoretical Analysis

Electrical Discharge Machining (EDM) is a controlled metal-removal process that is used to remove metal by means of electric spark erosion. In this process an electric spark is used as the cutting tool to cut the workpiece to produce the finished part to the desired shape [43].

Figure 3.1 Schematic of the material removal phenomena in EDM
In EDM, for a particular machining condition there are numerous phenomena involved. The Figure 3.1 illustrates that each spark occurs between the closest points of the electrode and the workpiece. The removal of material in EDM is associated with the erosive effects produced when discrete and spatial discharge occurs between the tool and workpiece. EDM is a thermal process, material is removed by heat. Every discharge (or spark) is responsible for melting a small quantity of material from both the electrodes. Part of this material is removed by the dielectric fluid and the remaining solidifies on the surface of the electrodes [44].

The material removal mechanism in EDM is stochastic in nature and it involves combination of several disciplines. In order to present a simple and applicable model explaining the nature of process in detail, the thermal loading and boundary conditions while developing material should be simplified. This model can be solved either by analytical or numerical methods. Analytical approach has a limitation of applying specific thermal loading, boundary condition and material properties. On the other hand, numerical approach does not have these limitations which help to add wide range aspects of electrical discharge erosion process in order to investigate further insights into material removal process. Finite element method is one of the numerical analysis methodologies implemented for investigating process mechanism in EDM [23].

3.1. Thermal modeling of EDM

The EDM machining is a complicated process which involves mainly heat transfer modes. The major mode throughout the workpiece substrate is heat conduction and the other mode occurred between workpiece and dielectric fluid is convection.

EDM is a stochastic process because of the uncertainty arising due to factors such as plasma radius, shape of plasma channel heat source, energy distribution between workpiece and
tool electrode. There are some important parameters such as amount of heat input, radius of plasma channel and the thermo-physical properties of the material which contribute to the accurate prediction by EDM models.

The following assumptions are considered to simplify the problem and make problem mathematically feasible:

1. **Assumptions**
   - The workpiece domain is assumed to be axisymmetric.
   - The Workpiece material is considered homogeneous and isotropic.
   - The Gaussian distribution of heat flux is applied as a heat source on the surface of the workpiece and thermal analysis is transient.
   - The modeling and analysis are done for single spark.
   - The material flushing efficiency is assumed to be 100%.
   - The material properties of workpiece are considered temperature independent.
   - The workpiece is free from any type of stress before the EDM process.
   - Thermal expansion due to heating is assumed negligible and element shape would remain unchanged.
   - The initial temperature is considered as room temperature.
2. **Governing Equation**

The governing heat conduction equation for axi symmetric, transient and nonlinear model is achieved by the Fourier heat conduction equation and is as follows:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( k r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = \rho c_p \frac{\partial T}{\partial t} \tag{3.1}
\]

Where, \( \rho \) is density \( (kg/m^3) \), \( c_p \) is specific heat \( (J/kg.K) \), \( k \) is thermal conductivity of the workpiece \( (W/m.K) \), \( T \) is temperature \( (K) \), \( t \) is the time and \( r \) & \( z \) are coordinates of the workpiece.

3. **Boundary conditions**

One of the most important factors in the simulation process is the type of heat flux applied onto the model as a heat source. Also, the type of heat flux directly affects the accuracy of the results. Figure 3.2 shows the boundary conditions and Gaussian heat distribution for the model. The previous studies proved that Gaussian heat distribution is the main source of heating for EDM spark because it is more realistic and accurate than other proposed models [36]. Since model is axi symmetric about z axis the half of body is applied for thermal simulation.

![Figure 3.2 Thermal model of EDM](image-url)
On the top surface, the heat transferred to the workpiece during a single spark is represented by a Gaussian heat flux distribution. Heat loss to the dielectric is modeled using convective boundary conditions on surface $B_1$. No heat transfer conditions were applied for the boundaries $B_2$ and $B_3$ because these boundaries are very far from the spark radius. Due to $B_4$ is the axis of symmetry and there is no net heat gain or loss from this region, the heat flux has been taken as zero for boundary $B_4$. In mathematical terms, the applied boundary conditions are given as follows:

$$B_1: \quad k \frac{\partial T}{\partial z} = q_r \quad if \ 0 \leq r \leq R$$

$$k \frac{\partial T}{\partial z} = h \left( T - T_0 \right) \quad if \ R < r \quad (3.2)$$

$$B_2, B_3, B_4: \quad \frac{\partial T}{\partial n} = 0$$
Where $q^*$ is heat flux, $R$ is the spark radius, $h$ is convection coefficient and $T_0$ is the dielectric temp.

4. **Heat flux and spark radius**

A Gaussian distribution for heat flux [36] is assumed in present analysis.

$$q^*(r) = 4.45 \frac{PVl}{\pi R^2} e^{-4.5\left(\frac{r}{R}\right)^2}$$  \hspace{1cm} (3.3)

Where $P$ is the percentage heat input to the workpiece and is considered 15% for PCD [15], $V$ is the discharge voltage and $I$ is the current.

For calculation of spark radius, a semi empirical equation is used [38]. In this equation, spark radius can be computed by using pulse current and on-time as follows:

$$R = (2.04E - 3)I^{0.43}T_{on}^{0.44}$$  \hspace{1cm} (3.4)
Chapter 4

Experimental Methodology, Situation & Parameters Selection

4.1. Machine

An ED-Drilling Hole Popper machine was used to perform the experiments for the sake of making holes on Polycrystalline Diamond (PCD).

Figure 4.1 Pictorial View of EDM-Drilling, Hole Popper Machine
Small hole drilling EDM machines with an x–y axis also known as a super drill or hole popper that can machine blind or through holes. Small hole EDM drilling is used for production work. Holes can be drilled in any electrical conductive material, whether hard or soft, including carbide.

The machine consist of dielectric fluid tank, electrode guide, servo motors, work table and electrode holder.
4.1.1. Dielectric and Flushing Pressure

The dielectric fluid flushes the minute spherical chips eroded from the workpiece and the electrode. The dielectric fluid also provides an insulating medium between the electrode and the workpiece so the sufficient energy can be built. In addition, the dielectric fluid cools the section that was heated by the discharging effect. Deionized water is preferred dielectric in EDM process. To accomplish small hole EDM drilling, high-pressure flushing is used. Flushing pressure is one of the most important variables for high speed EDM drilling [6]. De-ionized water was selected as the dielectric for experiments, as that is the standard for EDM-Drilling.

4.1.2. Electrode Guides

The electrode guide keeps the electrode on location and prevents drifting while the rotating electrode is cutting. The electrode guide prevents electrode wobbling and aids in minimizing the EDM overcut, generally. The guides are above the workpiece, this allows the high pressure dielectric to escape from the hole [6].

4.1.3. Servo Motor

The servo motors are controlled by a microprocessor which measures the gap voltage. By monitoring the gap voltage, the servo motor maintains in the proper gap voltage. To the servo-controlled feed, the tool electrode may have an additional rotary or orbiting motion. Electrode rotation helps to solve the flushing difficulty encountered when machining small holes with EDM. In addition to the increase in cutting speed, the quality of the hole produced is superior to that obtained using a stationary electrode [2].
4.2. Workpiece Material

Polycrystalline diamond (PCD) is a synthetic, extremely tough, intergrown mass of randomly orientated diamond particles in a metal matrix. It is produced by sintering together selected diamond particles at high pressure 6000 MPa and temperature 1400 °C. The sintering process is rigidly controlled within the diamond stable region and an extremely hard and abrasion resistant structure is produced. Typical commercial blanks have a PCD layer approximately 0.5 to 0.7 mm thick bonded to a thicker supporting layer of cemented carbide [45, 46]. The physical and thermal properties of workpiece material (PCD) are given in Table 4.1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>4300</td>
</tr>
<tr>
<td>Thermal Conductivity (W/(m·K))</td>
<td>400</td>
</tr>
<tr>
<td>Specific Heat (J/(kg·K))</td>
<td>512</td>
</tr>
</tbody>
</table>

Table 4.1 Physical and Thermal properties of PCD

The physical properties of PCDs, such as hardness, toughness, and thermal conductivity, are close to those of natural diamonds. PCDs are widely used as cutting tools for such non-ferrous metals as nickel, aluminum, and titanium, because of their superior cutting characteristics. Because of their lower resistance force and lower tool wear, PCDs also boast greater durability than other cutting tool materials [17].

4.3. Electrodes

Two types of electrode with the same material (copper) were used, namely solid and single channel. The diameter of solid electrode is 1.4 mm. The internal hole diameter of single
hole electrode (tube electrode) is 0.38 mm and its external hole diameter is 1.4 mm. Also, their length is 300 mm. Figure 3 shows the two electrode types.

![Figure 3](image.png)

Figure 4.3 (a) Single channel (b) Solid

### 4.4. Measurement of Process Performance

Material Removal Rate (cutting speed) was considered as output responses of EDM-Drilling process and is presented in the following subsections. In EDM the metal is removed from both the workpiece and the tool electrode. As can be seen from Fig. 4.4, the material removal rate depends not only on the workpiece material but on the material of the tool electrode and the machining variables such as pulse conditions, electrode polarity, and the machining medium. For EDM-Drilling, large cutting rate is a desirable characteristic and high productivity of EDM-Drilling achieved with maximum amount of cutting speed. The S/N ratio and average value of the cutting speed for each variable at different levels were calculated from experimental data.
4.5. **Parameters of Process**

An Ishikawa cause and effect diagram was constructed and is shown in Figure 4.5 to identify the process parameters that may affect the machining characteristics of EDM machined parts.
4.5.1. Pulse On-Time

All the process is done during pulse duration (on time). During this time the voltage is applied across the electrodes, the current is generated and the work is accomplished. Increasing pulse duration results in higher cutting speed because the single pulse discharge energy increases. Consequently, the broader and deeper craters will be produced that results in smoother surface. Also, higher pulse width leads to wire breakage [47, 48].
4.5.2. Pulse Off-Time

Off-time is the duration between the sparks. This time allows the molten material to solidify and to be wash out of the arc gap. This parameter is to affect the speed and the stability of the cut. Thus if the off-time is too short, it will cause sparks to be unstable [49].

4.5.3. Pulse Current

The discharge current (Id) is known as the quantity of electrical charges flowing between the tool and workpiece electrode through dielectric medium. This parameter is important in EDM machining because it causes primary heating mechanism. The discharge energy increases with increase in current [23].

4.5.4. Servo Voltage

Servo voltage controls the machining voltage between the electrode and work piece and is not to be confused with servo speed. Servo voltage allows an operator to increase cutting speed or allow for better flushing because this parameter controls the spark gap via voltage. Lowering the servo voltage forces the electrode closer to the work piece in order for the spark to jump it. We increase cutting peed because, “the lower the voltage, and the higher amps” [50].

4.5.5. Gap Size

The gap is distance between the electrode and workpiece during the process of EDM. It may be called as spark gap. Spark gap can be maintained by servo system [49].
4.6. Taguchi Experimental Design and Analysis

4.6.1. Taguchi’s Philosophy

Taguchi’s comprehensive system of quality engineering is one of the greatest engineering achievements of the 20th century. His methods focus on the effective application of engineering strategies rather than advanced statistical techniques. It includes both upstream and shop-floor quality engineering. Upstream methods efficiently use small-scale experiments to reduce variability and remain cost-effective, and robust designs for large-scale production and market place. Shop-floor techniques provide cost-based, real time methods for monitoring and maintaining quality in production. The farther upstream a quality method is applied, the greater leverages it produces on the improvement, and the more it reduces the cost and time. Taguchi’s philosophy is founded on the following three very simple and fundamental concepts (Ross, 1988; Roy, 1990):

- Quality should be designed into the product and not inspected into it.
- Quality is best achieved by minimizing the deviations from the target. The product or process should be so designed that it is immune to uncontrollable environmental variables.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi proposes an “off-line” strategy for quality improvement as an alternative to an attempt to inspect quality into a product on the production line. He observes that poor quality cannot be improved by the process of inspection, screening and salvaging. No amount of inspection can put quality back into the product. Taguchi recommends a three-stage process:
4.6.2. **Experimental Design Strategy**

Taguchi recommends orthogonal array (OA) for laying out of experiments. These OA’s are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. The array forces all experimenters to design almost identical experiments (Roy, 1990).

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives (Ross, 1988):

- To establish the best or the optimum condition for a product or process
- To estimate the contribution of individual parameters and interactions
- To estimate the response under the optimum condition

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trends of influence of each parameter. The knowledge of contribution of individual parameters is a key in deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control (Ross, 1988).
Taguchi suggests (Roy, 1990) two different routes to carry out the complete analysis. First, the standard approaches, where the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal-to-noise ratio (S/N) for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function (Barker, 1990). By maximizing the S/N ratio, the loss associated can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. The S/N ratio is treated as a response (transform of raw data) of the experiment. Taguchi recommends (Ross, 1988) the use of outer OA to force the noise variation into the experiment i.e. the noise is intentionally introduced into experiment. However, processes are often times subject to many noise factors that in combination, strongly influence the variation of the response. For extremely “noisy” systems, it is not generally necessary to identify specific noise factors and to deliberately control them during experimentation. It is sufficient to generate repetitions at each experimental condition of the controllable parameters and analyze them using an appropriate S/N ratio (Byrne and Taguchi, 1987).

In the present investigation, the raw data analysis and S/N data analysis have been performed. The effects of the selected EDM-Drilling process parameters on the selected quality characteristics have been investigated through the plots of the main effects based on raw data. The optimum condition for each of the quality characteristics has been established through S/N data analysis aided by the raw data analysis. No outer array has been used and instead, experiments have been repeated three times at each experimental condition.
4.6.3. Loss Function

The heart of Taguchi method is his definition of the nebulous and elusive term “quality” as the characteristic that avoids loss to the society from the time the product is shipped (Braker, 1986). Loss is measured in terms of monetary units and is related to quantifiable product characteristic. Taguchi defines quality loss via his “loss function”. He unites the financial loss with the functional specification through a quadratic relationship that comes from a Taylor series expansion. The quadratic function takes the form of a parabola. Taguchi defines the loss function as a quantity proportional to the deviation from the nominal quality characteristic (Roy, 1990).

He has found the following quadratic form to be a useful workable function (Roy, 1990):

\[ l(y) = k(y - m)^2 \]  \hspace{1cm} (4.1)

Where,

L = Loss in monetary units

m = value at which the characteristic should be set

y = actual value of the characteristic

k = constant depending on the magnitude of the characteristic and the monetary unit involved

The loss function represented in Eq 4.1 is graphically shown in Figures 4.1. The characteristics of the loss function are (Roy, 1990):

- The farther the product’s characteristic varies from the target value, the greater is the loss. The loss must be zero when the quality characteristic of a product meets its target value.

- The loss is a continuous function and not a sudden step as in the case of traditional (goal post) approach (Figure 4.7). This consequence of the continuous loss function illustrates the point that merely making a product within the specification limits does not necessarily mean that product is of good quality.
Figure 4.6 Taguchi Loss Function

Figure 4.7 Traditional Approach
4.6.4. Signal to Noise Ratio

The loss-function discussed above is an effective figure of merit for making engineering design decisions. However, to establish an appropriate loss-function with its k value to use as a figure of merit is not always cost-effective and easy. Recognizing the dilemma, Taguchi created a transform function for the loss-function which is named as signal -to-noise (S/N) ratio (Barker, 1990).

The S/N ratio, as stated earlier, is a concurrent statistic. A concurrent statistic is able to look at two characteristics of a distribution and roll these characteristics into a single number or figure of merit. The S/N ratio combines both the parameters (the mean level of the quality characteristic and variance around this mean) into a single metric (Barker, 1990).

A high value of S/N implies that signal is much higher than the random effects of noise factors. Process operation consistent with highest S/N always yields optimum quality with minimum variation (Barker, 1990).

The S/N ratio consolidates several repetitions (at least two data points are required) into one value. The equation for calculating S/N ratios for “smaller is better” (LB), “larger is better” (HB) and “nominal is best” (NB) types of characteristics are as follows (Ross, 1988):

4. Larger the Better:  \( (S/N)_{HB} = -10 \log(MSD_{HB}) \)  

Where:

\[ MSD_{HB} = \frac{1}{R} \sum_{j=1}^{R} \left( \frac{1}{y_j^2} \right) \]
5. Smaller the Better:  

\[(S/N)_{LB} = -10 \log(MSD_{LB})\]

Where:

\[MSD_{LB} = \frac{1}{R} \sum_{j=1}^{R} (y_j^2)\]

6. Nominal the Better:  

\[(S/N)_{NB} = -10 \log(MSD_{NB})\]

Where:

\[MSD_{NB} = \frac{1}{R} \sum_{j=1}^{R} (y_j - y_0)^2\]

R= Number of Repetitions  

\[y_j = \text{Respective characteristic}\]

The mean squared deviation (MSD) is a statistical quantity that reflects the deviation from the target value. The expressions for MSD are different for different quality characteristics. For the “nominal is best” characteristic, the standard definition of MSD is used. For the other two characteristics the definition is slightly modified. For “smaller is better”, the unstated target value is zero. For “larger is better”, the inverse of each large value becomes a small value and again, the unstated target value is zero. Thus for all three expressions, the smallest magnitude of MSD is being sought.

4.6.5. Steps in Experimental Design and Analysis

The Taguchi experimental design and analysis flow diagram is shown in Figure 4.8.
Noise?
- Consider noise factors and use appropriate outer array
- Decide the number of repetitions (at least two repetitions)

- Run the experiment in the random order
- Record the response
- Determine the S/N ratio

Conduct ANOVA on raw data
Identify control parameters which affect mean of the quality characteristics

Conduct ANOVA on S/N data
Identify control parameters which affect mean and variation of the quality characteristics

Classify the factors
- Class I: affect both average and variation
- Class II: affect variation only
- Class III: affect average only
- Class IV: affect nothing

Select proper levels of Class I and Class II factors to reduce variation and Class III factors to adjust the mean to the target and Class IV to the most economic levels

Predict the mean at the selected level
- Determine confidence interval
- Determine optimal range
- Conduct confirmation experiment
- Draw conclusion

Figure 4.8 Taguchi Experimental Design and Analysis Flow Diagram
4.6.6. Experimentation and Data Collection

The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried to reduce bias in the experiment. The data (raw data) are recorded against each trial condition and S/N ratios of the repeated data points are calculated and recorded against each trial condition.

4.6.7. Data Analysis

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average response curves, interaction graphs etc. (Ross, 1988). However, in the present investigation the following methods have been used:

- Plot of average response curves
- ANOVA for raw data
- ANOVA for S/N data
- S/N response graphs
- Interaction graphs
- Residual graphs

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of parameter on the response. The change in the response characteristic with the change in levels of a parameter can easily be visualized from these curves. Typically, ANOVA for OA”s are conducted in the same manner as other structured experiments (Ross, 1988).
The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. A standard ANOVA can be conducted on S/N ratio which will identify the significant parameters (mean and variation). Interaction graphs are used to select the best combination of interactive parameters (Peace, 1993). Residual plots are used to check the accuracy.

4.6.8. Confirmation Experiment

The confirmation experiment is a final step in verifying the conclusions from the previous round of experimentation. The optimum conditions are set for the significant parameters (the insignificant parameters are set at economic levels) and a selected number of tests are run under specified conditions. The average of the confirmation experiment results is compared with the anticipated average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended to verify the experimental conclusion (Ross, 1988).
Chapter 5

Results & Discussion

The present chapter deals with ANSYS finite element simulation to calculate the temperature distribution on the workpiece and designed experiments based on Taguchi experimental design method to show the application of Taguchi method. ANSYS was applied to simulate a two dimensional thermal, finite element model based on heat transfer physics for of single spark EDM-Drilling. ANSYS software allows the user to define material properties and equation within program to yield accurate representation of the problem. The objective of the experiments was to investigate the effect of five process parameters including voltage, spindle speed, pulse on-time, pulse current and gap size on cutting speed. The numerical and experimental results are discussed subsequently in the following sections.

5.1. Numerical Results

The effects of current and pulse on time are studied using FEA thermal simulation tool (ANSYS- Mechanical APDL 15.0) to obtain the temperature distribution along the radius and depth of the workpiece. The results of thermal analysis for PCD material applying pulse current of 8 A, voltage 40 V, pulse on time 20 μs and pulse off time 30 μs with stationary electrode for a single spark are given in Figure 5.1.
Figure 5.1 Numerical results for PCD with I=8A, V=40V, (a) Temperature contour for a single spark just at the end of pulse on time (20 \mu s), (b) Temperature contour for a single spark just at the end of pulse off time (30 \mu s), (c) Temperature distribution along workpiece radius, (d) Temperature distribution along workpiece depth.
Figure 5.1a demonstrates the temperature contour just at the end of pulse on time and Figure 5.1b shows the temperature contour just at the end of pulse off time. It is apparently evident from Fig. 5.1 that the maximum temperature occurs at the top surface on the centerline of the workpiece, where the intensity of heat flux is maximum according to Gaussian distribution of heat flux. Also, figure 5.1a shows that during the spark on-time the temperature rises in the workpiece and temperature rise is sufficient enough to melt the material, because the maximum temperature is higher than the melting point of PCD (since PCD is a complex material it is really hard to specify the melting point, however we can assume the melting point of PCD around 1500 K).

During the pulse-off time (Fig 5.1b) plasma channel does not exist between the electrode and workpiece, therefore the workpiece does not experience heat flux. Convection is the only mechanism for heat transfer which is occurred between workpiece and dielectric fluid. It can be seen from Fig 5.1b due to sharp rise in temperature in on-time step, even at the end of cooling time (pulse off-time step), the area around spark is kept in temperatures quite higher than room temperature. Most of the heat is taken away by the dielectric fluid through convection and some part of heat is taken away by molten metal.

Figures 5.1c, d are the graphs indicating the temperature distribution along radius and depth of the workpiece respectively. By comparing Figure 5.1a and b, it reveals that the maximum temperature would decrease dramatically during pulse off time. Also it can be seen from Figures 5.1c, d that the decrease in temperature at the vicinity of the workpiece center in the radius direction is slighter than depth direction. Therefore, the material removal rate is more along the radial direction than along the depth resulting in shallow craters. In other words, it can be clearly realized from the graph that at the melting point there exists the higher value of radius
(32 \mu m) and it means that a hole (crater) created by a single spark has the greater dimension in radius rather than its depth (22 \mu m).

The effect of pulse current on heat distribution is investigated and Figure 5.2 displays that by increasing the pulse current there would be a significant rise in distributed temperature. Increasing in current value leads to have high level of energy densities. We can also conclude from this figure that area influenced by heat flux would be increased by increasing the current, which can be explained by the growth of the plasma channel's radius. It is clear that the top surface temperature goes on increasing with increase in current. This is because, the current is a function of the heat energy transferred to the workpiece. The larger the current, the greater the heat energy generated and transferred to the workpiece. In addition, the discharge energy increases by increasing the current. Also, from figure 5.2, it can be seen that the distribution of temperature follows the shape of Gaussian curve. As expected, farther the distance from the workpiece center, lower the temperature.

![Figure 5.2. The effect of current on heat distribution](image_url)
According to the empirical equation (3.4), we can see that by increasing the current, spark radius rises. Also, we know based on previous literature [36], crater volume (volume removed per spark) is a function of spark radius, thus the area and volume influenced by heat flux would be increased.

Also in order to compare and understand the effect of current on heat distribution easily, the temperature profile and contours are obtained from ANSYS. Fig. 5.3 depicts that current has the direct impact on maximum temperature occurred at the top surface on centerline of the workpiece. For the current 8 A at the first case, temperature reaches a peak of almost 2820 k, while for the last case with 18 A the maximum temperature would be around 3750 k. Also, by taking an accurate look into these three cases, it could be realized that the heat affected zone becomes slightly larger by rising current.

Figure 5.3 Effect of current on pulse on-time, (a) 8A, (b) 13A, (c) 18A
For the case of pulse off-time, Fig. 5.4 says that unlike the significant impact of current on maximum on-time temperature and heat affected zone, it does not play any role in the cooling period of EDM process.

Figure 5.4 effect of current on pulse on-time, (a) 8A, (b) 13A, (c) 18A
The effect of pulse on-time on heat distribution is concluded from Figure 5.5. Pulse on-time is the heating time, so by rising the heating time, temperature and gradient of heat loss diminish in workpiece and cause enlargement of the heat-affected zone. However, this can also be described by the growth of the plasma channel radius with increase of pulse on-time values. In other words, this figure indicates that the gradient of temperature (changing temperature with respect to radius change) would decrease throughout the radius of the workpiece by increasing the pulse on-time. Also, in temperatures around 600 K which is the heat affected zone temperature (not melted or removed zone), we have higher values of radius and it means that we have larger heat affected zone by rising the pulse on-time.

Also, based on equation (3.4), an increase in pulse on-time causes an increase in spark radius. Consequently, the radius of heat affected zone rises simultaneously.

Figure 5.5. The effect of pulse on time on heat distribution
Fig. 5.6 illustrates the temperature profiles when on-time changes in three different processes. Similar to Fig. 5.5 this figure displays that by increasing pulse on-time the highest temperature would decrease, while the heat affected zone increases. This could be explained based on the fact that total input energy of a single spark in EDM process should be distributed throughout the on-time period, so in the case with a constant energy of a single spark, the longer the on-time period, the lower the maximum temperature.

Figure 5.6 Effect of on-time on temperature, (a) 20 µs, (b) 30 µs, (c) 400 µs
5.2. Experimental Results

5.2.1. Parameters Selection and Experiments Design

Selecting the input parameters and performance measures has to be determined before performing the experiments. In order to investigate the performance of EDM-Drilling for PCD, the effect of five machining parameters were studied. Based on the literature review, pre-experimentation work and machine control levels (handbook) of input factors are finalized. The machining parameters and their levels are listed in Table 5.1. Process parameters must be at least in three levels to reflect the true behavior of output parameters of study. Apart from parameters mentioned in Table 5.1, some machining parameters such as off-time (30\(\mu s\)) and capacitance (10\(\mu f\)) were kept constant during experiments in order to optimize the process.

The EDM-Drilling experiments were performed in order to study the effect of process parameters on the output response characteristics (cutting speed). High productivity of EDM-Drilling is achieved with maximum amount of cutting speed. The S/N ratio and average value of the response characteristics for each variable at different levels were calculated from experimental data.

Since it is useful to reduce the cost and time of experiments, Taguchi method was applied as design of experiments (DOE). In order to analyze the influence of parameters on cutting speed, 18 experiments were performed conducting Taguchi (L18) experimental design methodology. Regarding Taguchi experimental design approach Taguchi L18 design of experiment (DOE) was applied because there are one factor with two levels and six factors with three levels in the model. So, degree of freedom (DOF) for the first factor is one and for other factors is two. This gives a total of 13 DOF for seven process parameters selected in this work.
Also, residual error has four DOF. Thus we have a total of 17 DOF for the factors as well as the residual error for the present experiments.

<table>
<thead>
<tr>
<th>Control Factors</th>
<th>Units</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>$V$</td>
<td>L1 40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L2 50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>L3 40</td>
</tr>
<tr>
<td>Spindle Speed</td>
<td>$rps$</td>
<td>0 4 7</td>
</tr>
<tr>
<td>ON-time</td>
<td>$\mu s$</td>
<td>20 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40 40</td>
</tr>
<tr>
<td>Pulse Current</td>
<td>$A$</td>
<td>8 13 18</td>
</tr>
<tr>
<td>Gap Size</td>
<td>$\mu m$</td>
<td>20 30</td>
</tr>
</tbody>
</table>

Table 5.1 Machining Condition in EDM-Drilling

The WEDM experiments were performed in order to study the effect of process parameters on the output response characteristics with the process parameters as given in Table 5.2. The experimental results are collected for cutting speed. 18 experiments were conducted using Taguchi experimental design method and there were two replicates for each experiment to obtain S/N values. To obtain optimum process parameters setting, Taguchi proposed a statistical measure of performance called signal to noise ratio (S/N ratio). All design, plots and statistical analysis are conducted using Minitab statistical software. “Larger the better” formula is applied to calculate the S/N ratio of cutting speed because larger cutting speed amount show the high productivity of EDM-Drilling. Therefore, larger cutting speed and lower cutting time is desire.

The S/N ratio and average value of the response characteristics for each variable at different levels were calculated from experimental data. The analysis of variance (ANOVA) of raw data and S/N data were performed to determine the significant and insignificant variables and to show their effects on the response characteristic. Then, the response curves (main effect) were plotted for raw data and S/N data in order to examine the parametric effects on the response
characteristics. Finally, the optimal values of significant process parameters in terms of mean response characteristics are defined based on analyzing the ANOVA table and response curves.

<table>
<thead>
<tr>
<th># Experiments</th>
<th>Voltage</th>
<th>Spindle speed</th>
<th>On time</th>
<th>Pulse Current</th>
<th>Gap size</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MRR 1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>40</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
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<td>1</td>
<td>40</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>40</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
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<td>40</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>40</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>40</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
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<td>7</td>
<td>1</td>
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<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>40</td>
<td>3</td>
<td>7</td>
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<td>1</td>
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<td>0</td>
<td>3</td>
<td>2</td>
</tr>
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<td>13</td>
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<td>50</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
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<td>50</td>
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<td>4</td>
<td>3</td>
<td>3</td>
</tr>
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<td>50</td>
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<td>4</td>
<td>1</td>
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</tr>
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<td>50</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>50</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.2 Taguchi’s L18 Standard Orthogonal Array
The MRR has been considered as machining performance and it has been done for every procedure during machining. In each experiment, the value of machining parameters was set in machine based on above table. In order to measure the machining time from starting of discharge to the end of machining, a stopwatch was used.
5.2.2. Analysis and Discussion of Results

5.2.2.1. Single Channel Electrode

Tables 5.4 and 5.5, the analysis of ANOVA, show the effect of machining parameters on cutting speed for single channel. The results indicate that machining voltage, spindle speed and pulse current are the significant process parameters because their P-values are less than 0.05. On the other hand, on time and gap-size do not significantly affect the cutting speed values in EDM-Drilling of PCD in both electrode types. The pooled version of ANOVA of the raw data and S/N data for cutting speed is given in the next tables. The P-value of interaction terms are more than 0.05 in pooled ANOVA tables. This indicates there is not any interaction between voltage, spindle speed and pulse current.

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Cutting Speed (mm/min)</th>
<th>S/N Ratio</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>MRR 1</td>
<td>MRR 2</td>
</tr>
<tr>
<td>1</td>
<td>0.521</td>
<td>0.571</td>
</tr>
<tr>
<td>2</td>
<td>0.798</td>
<td>0.768</td>
</tr>
<tr>
<td>3</td>
<td>1.154</td>
<td>1.200</td>
</tr>
<tr>
<td>4</td>
<td>0.800</td>
<td>0.895</td>
</tr>
<tr>
<td>5</td>
<td>1.220</td>
<td>1.312</td>
</tr>
<tr>
<td>6</td>
<td>1.983</td>
<td>2.017</td>
</tr>
<tr>
<td>7</td>
<td>1.380</td>
<td>1.320</td>
</tr>
<tr>
<td>8</td>
<td>2.651</td>
<td>2.552</td>
</tr>
<tr>
<td>9</td>
<td>2.030</td>
<td>1.800</td>
</tr>
<tr>
<td>10</td>
<td>2.133</td>
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</tr>
<tr>
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<tr>
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<tr>
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<td>2.443</td>
<td>2.454</td>
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<tr>
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</tr>
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<td>18</td>
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Table 5.3 Experimental Results
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<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>1</td>
<td>112.353</td>
<td>112.353</td>
<td>112.353</td>
<td>22.75</td>
<td><strong>0.001</strong></td>
</tr>
<tr>
<td>Spindle speed</td>
<td>2</td>
<td>52.252</td>
<td>52.252</td>
<td>26.126</td>
<td>5.29</td>
<td><strong>0.034</strong></td>
</tr>
<tr>
<td>On time</td>
<td>2</td>
<td>22.536</td>
<td>22.536</td>
<td>11.268</td>
<td>2.28</td>
<td>0.164</td>
</tr>
<tr>
<td>Current</td>
<td>2</td>
<td>56.709</td>
<td>56.709</td>
<td>28.354</td>
<td>5.74</td>
<td><strong>0.028</strong></td>
</tr>
<tr>
<td>Gap size</td>
<td>2</td>
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<td>0.938</td>
<td>0.469</td>
<td>0.09</td>
<td>0.91</td>
</tr>
<tr>
<td>Residual Error</td>
<td>8</td>
<td>39.504</td>
<td>39.504</td>
<td>4.938</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>284.292</td>
<td></td>
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</tr>
</tbody>
</table>

Table 5.4 Analysis of Variance for SN ratios

<table>
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<tr>
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<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
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</thead>
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<tr>
<td>Voltage</td>
<td>1</td>
<td>3.3291</td>
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<td>3.32906</td>
<td>26.9</td>
<td><strong>0.001</strong></td>
</tr>
<tr>
<td>Spindle speed</td>
<td>2</td>
<td>1.3622</td>
<td>1.3622</td>
<td>0.68109</td>
<td>5.5</td>
<td><strong>0.031</strong></td>
</tr>
<tr>
<td>On time</td>
<td>2</td>
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<td>0.359</td>
<td>0.17948</td>
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</tr>
<tr>
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<td>2.1173</td>
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<td><strong>0.01</strong></td>
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<tr>
<td>Gap size</td>
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<td>0.1422</td>
<td>0.07109</td>
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</tr>
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<td>0.9902</td>
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<td></td>
<td></td>
</tr>
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<td>Total</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</table>

Table 5.5 Analysis of Variance for Means

<table>
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<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>1</td>
<td>3.32906</td>
<td>3.32906</td>
<td>3.32906</td>
<td>28.36</td>
<td>0.006</td>
</tr>
<tr>
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<td>1.36217</td>
<td>0.68109</td>
<td>5.69</td>
<td>0.054</td>
</tr>
<tr>
<td>Current</td>
<td>2</td>
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<td>0.1422</td>
<td>0.07109</td>
<td>0.57</td>
<td>0.585</td>
</tr>
<tr>
<td>Voltage*Spindle speed</td>
<td>2</td>
<td>0.02760</td>
<td>0.02760</td>
<td>0.01380</td>
<td>0.12</td>
<td>0.894</td>
</tr>
<tr>
<td>Voltage*Current</td>
<td>4</td>
<td>0.25631</td>
<td>0.25631</td>
<td>0.06408</td>
<td>0.54</td>
<td>0.720</td>
</tr>
<tr>
<td>Spindle speed*Current</td>
<td>4</td>
<td>0.47848</td>
<td>0.47848</td>
<td>0.11962</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.6 Pooled Analysis of Variance for SN ratios

<table>
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<th>Adj SS</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>1</td>
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<td>3.32906</td>
<td>3.32906</td>
<td>27.83</td>
<td>0.006</td>
</tr>
<tr>
<td>Spindle speed</td>
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<td>0.72895</td>
<td>0.72895</td>
<td>0.36448</td>
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<td>0.157</td>
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<td>Current</td>
<td>2</td>
<td>0.02760</td>
<td>0.02760</td>
<td>0.01380</td>
<td>0.12</td>
<td>0.894</td>
</tr>
<tr>
<td>Voltage*Spindle speed</td>
<td>2</td>
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<td>0.06408</td>
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<td>0.720</td>
</tr>
<tr>
<td>Voltage*Current</td>
<td>4</td>
<td>0.47848</td>
<td>0.47848</td>
<td>0.11962</td>
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</tr>
<tr>
<td>Spindle speed*Current</td>
<td>4</td>
<td>0.47848</td>
<td>0.47848</td>
<td>0.11962</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7 Pooled Analysis of Variance for Means
The following table includes ranks based on delta statistics, which compare the relative magnitude of effects. Voltage has the maximum influence on cutting speed followed by the current and spindle speed. In fact, voltage has the highest importance for cutting speed among other significant parameters.

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage</th>
<th>Spindle speed</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.387</td>
<td>1.447</td>
<td>1.552</td>
</tr>
<tr>
<td>2</td>
<td>2.247</td>
<td>1.901</td>
<td>1.599</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>2.105</td>
<td>2.302</td>
</tr>
<tr>
<td>Delta</td>
<td>0.860</td>
<td>0.658</td>
<td>0.750</td>
</tr>
<tr>
<td>Rank</td>
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<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.8 Response Table for Means

It is seen from Figures 5.7 and 5.8 that there is not any interaction between the process parameters in affecting the cutting rate since the responses at different levels of process parameters for a given level of parameter value are almost parallel.

Figures 5.9 and 5.10 are plotted based on the results achieved from machining of PCD by single channel electrode. It is observed from Figures 5.3 and 5.4 that the cutting speed increases with the increase of voltage, spindle speed and pulse current. An increase in pulse current and voltage results in growth of discharge energy, causing to produce surface craters of greater size, and therefore MRR will enhance. According to the Figures the MRR rose when spindle rotates and also continues to rise with the increase of spindle speed. This is due to the effective flushing of the rotary electrode. The rotation of electrode imparts a whirl and effectively flushes the gap. It can be seen that the raw data and S/N data analysis suggest the first level of voltage, spindle speed and pulse current to achieve the maximum value of cutting speed in EDM-Drilling process of PCD.
Figure 5.7 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

Figure 5.8 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)
Figure 5.9 Effects of Process Parameters on Cutting Speed (S/N Data)

Figure 5.10 Effects of Process Parameters on Cutting Speed (Raw Data)
5.2.2. Solid Electrode

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Cutting Speed (mm/min)</th>
<th>S/N Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MRR 1</td>
<td>MRR 2</td>
</tr>
<tr>
<td>1</td>
<td>0.401</td>
<td>0.423</td>
</tr>
<tr>
<td>2</td>
<td>0.498</td>
<td>0.492</td>
</tr>
<tr>
<td>3</td>
<td>0.943</td>
<td>1.012</td>
</tr>
<tr>
<td>4</td>
<td>1.032</td>
<td>1.022</td>
</tr>
<tr>
<td>5</td>
<td>1.012</td>
<td>1.031</td>
</tr>
<tr>
<td>6</td>
<td>1.678</td>
<td>1.671</td>
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<td>7</td>
<td>0.978</td>
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<td>8</td>
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<td>1.856</td>
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<td>9</td>
<td>1.681</td>
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<td>1.182</td>
</tr>
<tr>
<td>12</td>
<td>1.632</td>
<td>1.602</td>
</tr>
<tr>
<td>13</td>
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<tr>
<td>14</td>
<td>2.130</td>
<td>2.141</td>
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<td>2.209</td>
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<tr>
<td>17</td>
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<td>18</td>
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<td>1.872</td>
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</table>

Table 5.9 Experimental Results

Tables 5.10 and 5.11, the analysis of ANOVA, show the effect of machining parameters on cutting speed for single channel. The results indicate that machining voltage, spindle speed and pulse current are the significant process parameters because their P-values are less than 0.05. On the other hand, on time and gap-size do not significantly affect the cutting speed values in EDM-Drilling of PCD in both electrode types. The pooled version of ANOVA of the raw data and S/N data for cutting speed is given in the next tables. The P-value of interaction terms are more than 0.05 in pooled ANOVA tables. This indicates there is not any interaction between voltage, spindle speed and pulse current.
### Table 5.10 Analysis of Variance for SN ratios

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
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<td>107.006</td>
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<td>78.907</td>
<td>39.453</td>
<td>9.09</td>
<td>0.009</td>
</tr>
<tr>
<td>On time</td>
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<td>17.834</td>
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<tr>
<td>Current</td>
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<td>48.938</td>
<td>24.469</td>
<td>5.64</td>
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<tr>
<td>Gap size</td>
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<td>6.731</td>
<td>3.365</td>
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<td>0.492</td>
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<tr>
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<td>34.706</td>
<td>4.338</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
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<td>294.122</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 5.11 Analysis of Variance for Means

<table>
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<tr>
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<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
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</thead>
<tbody>
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<td>107.006</td>
<td>107.006</td>
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<td>0.001</td>
</tr>
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<td>0.005</td>
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<td>48.938</td>
<td>24.469</td>
<td>14.36</td>
<td>0.015</td>
</tr>
<tr>
<td>Voltage*Spindle speed</td>
<td>2</td>
<td>31.258</td>
<td>31.258</td>
<td>15.629</td>
<td>9.17</td>
<td>0.032</td>
</tr>
<tr>
<td>Voltage*Current</td>
<td>2</td>
<td>11.646</td>
<td>11.646</td>
<td>5.823</td>
<td>3.42</td>
<td>0.136</td>
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<tr>
<td>Spindle speed*Current</td>
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<td>9.548</td>
<td>2.387</td>
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<td>0.43054</td>
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<td>Total</td>
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<td>4.91485</td>
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### Table 5.12 Pooled Analysis of Variance for SN ratios

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<th>Adj SS</th>
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<td>78.907</td>
<td>39.453</td>
<td>15.45</td>
<td>0.013</td>
</tr>
<tr>
<td>Current</td>
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<td>48.938</td>
<td>48.938</td>
<td>24.469</td>
<td>14.14</td>
<td>0.015</td>
</tr>
<tr>
<td>Voltage*Spindle speed</td>
<td>2</td>
<td>31.258</td>
<td>31.258</td>
<td>15.629</td>
<td>9.17</td>
<td>0.032</td>
</tr>
<tr>
<td>Voltage*Current</td>
<td>2</td>
<td>11.646</td>
<td>11.646</td>
<td>5.823</td>
<td>3.42</td>
<td>0.136</td>
</tr>
<tr>
<td>Spindle speed*Current</td>
<td>4</td>
<td>9.548</td>
<td>9.548</td>
<td>2.387</td>
<td>1.40</td>
<td>0.376</td>
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</tbody>
</table>

### Table 5.13 Pooled Analysis of Variance for Means

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
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<td>Spindle speed</td>
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<td>1.15530</td>
<td>0.57765</td>
<td>15.45</td>
<td>0.013</td>
</tr>
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<td>1.05749</td>
<td>1.05749</td>
<td>0.52874</td>
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<td>0.015</td>
</tr>
<tr>
<td>Voltage*Spindle speed</td>
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<td>0.25206</td>
<td>0.25206</td>
<td>0.12603</td>
<td>3.37</td>
<td>0.139</td>
</tr>
<tr>
<td>Voltage*Current</td>
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<td>0.19284</td>
<td>0.19284</td>
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<td>2.58</td>
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<tr>
<td>Spindle speed*Current</td>
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<td>0.08557</td>
<td>0.02139</td>
<td>0.57</td>
<td>0.699</td>
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<td>0.14954</td>
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</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>4.91485</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
The following table includes ranks based on delta statistics, which compare the relative magnitude of effects. Voltage has the maximum influence on cutting speed followed by the spindle speed and current. In fact, voltage has the highest importance for cutting speed among other significant parameters.

<table>
<thead>
<tr>
<th>Level</th>
<th>Voltage</th>
<th>Spindle speed</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.120</td>
<td>1.100</td>
<td>1.258</td>
</tr>
<tr>
<td>2</td>
<td>1.790</td>
<td>1.591</td>
<td>1.311</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>1.674</td>
<td>1.797</td>
</tr>
<tr>
<td>Delta</td>
<td>0.670</td>
<td>0.574</td>
<td>0.539</td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

*Table 5.14 Response Table for Means*

It is seen from Figures 5.11 and 5.12 that there is not any interaction between the process parameters in affecting the cutting rate since the responses at different levels of process parameters for a given level of parameter value are almost parallel.

Figures 5.13 and 5.14 are plotted based on the results achieved from machining of PCD by single channel electrode. It is observed from Figures 5.13 and 5.14 that the cutting speed increases with the increase of voltage, spindle speed and pulse current. An increase in pulse current and voltage results in growth of discharge energy, causing to produce surface craters of greater size, and therefore MRR will enhance. According to the Figures the MRR rose when spindle rotates and also continues to rise with the increase of spindle speed. This is due to the effective flushing of the rotary electrode. The rotation of electrode imparts a whirl and effectively flushes the gap. It can be seen that the raw data and S/N data analysis suggest the first level of voltage, spindle speed and pulse current to achieve the maximum value of cutting speed in EDM-Drilling process of PCD.
Figure 5.11 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

Figure 5.12 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)
Figure 5.13 Effects of Process Parameters on Cutting Speed (S/N Data)

Figure 5.14 Effects of Process Parameters on Cutting Speed (Raw Data)
5.2.2.3. Effect of Electrode Type on MRR

Material removal rate is an important performance measure and several researchers explored several ways to improve it. Several researchers have tried to improve MRR using alternate types of electrode design. The most popular attempt in this way was performed by Mohan in 2004 to investigate the effect of electrode type on machining of Al–SiC metal matrix composites using rotary tube electrode. The results showed that the electrode tube hole has a positive impact on MRR [51, 52]. Based on the obtained results on Figure 5.15 it is obvious that the single channel electrode has higher values of cutting speed (MRR) in comparison with solid electrode. The existence of channel causes the dielectric fluid flows through it, leading to have more efficient flushing over the EDM process.

Figure 5.15 Effect of electrode on MRR
Chapter 6

Conclusion & Recommendations

6.1. Conclusion

In this study, an experimental investigation and finite element simulation of Electro Discharge Machining-Drilling (EDM-Drilling) of Polycrystalline Diamond (PCD) is performed. In order to determine the effect of five process parameters including voltage, spindle speed, pulse on-time, pulse current and gap size on cutting speed, several experiments have been done. ANSYS finite element simulation has been applied to calculate the temperature distribution on the workpiece. The effect of current and pulse on-time in EDM-Drilling process on heat distribution along the radius and depth of the workpiece has been obtained. Based on the results and analysis, the following conclusions can be drawn:

- In numerical simulation, by investigating the effects of pulse current and on-time, the results showed that current is the major influencing parameter in thermal analysis which is in an agreement with experimental result.

- By increasing the pulse current there would be a significant rise in distributed temperature. Increasing in current value leads to have high level of energy densities. We can also conclude from the obtained ANSYS figures that area influenced by heat flux would be increased by increasing the current, which can be explained by the growth of the plasma channel's radius. It is clear that the top surface temperature goes on increasing with increase in current. This is because, the current is a function of the
heat energy transferred to the workpiece. The larger the current, the greater the heat energy generated and transferred to the workpiece. In addition, the discharge energy increases by increasing the current. Also, the distribution of temperature follows the shape of Gaussian curve. As expected, farther the distance from the workpiece center, lower the temperature.

- Pulse on-time is the heating time, so by rising the heating time, temperature and gradient of heat loss diminishes in workpiece and cause enlargement of the heat-affected zone. However, this can also be described by the growth of the plasma channel radius with increase of pulse on-time values. In other words, the gradient of temperature (changing temperature with respect to radius change) would decrease throughout the radius of the workpiece by increasing the pulse on-time. Also, in temperatures around 600 K which is the heat affected zone temperature (not melted or removed zone), we have higher values of radius and it means that we have larger heat affected zone by rising the pulse on-time.

- It is found that voltage, pulse current and spindle speed have the significant impact on MRR in machining of PCD with both electrode types.

- By increasing voltage, pulse current and spindle speed, MRR was improved. An increase in pulse current and voltage results in growth of discharge energy, causing to produce surface craters of greater size, and therefore MRR will enhance. According to the Figures the MRR rose when spindle rotates and also continues to rise with the
increase of spindle speed. This is due to the effective flushing of the rotary electrode. The rotation of electrode imparts a whirl and effectively flushes the gap.

- The single channel electrode results in higher cutting speed compared with solid electrode. The existence of channel causes the dielectric fluid flows through it, leading to have more efficient flushing over the EDM process.

6.2. Recommendations

- In this study the effect of single channel and solid copper electrode on machining performance of PCD was investigated. One extension of this study might be analysis of influence of multi-channel electrode on EDM-Drilling. Also, another aspect that could be done in future is investigation of different electrode materials in EDM-Drilling process.

- The effect of five process parameters including voltage, spindle speed, pulse on-time, pulse current and gap size on cutting speed were analyzed. It may be more practical to investigate the impact of other machining parameters such as injection pressure or pulse off time on EDM-Drilling of PCD.

- Thermal simulation of single spark was done using finite element method (ANSYS). The heating source was assumed to be fixed. To study the effect of rotational heating source (rotational electrode), developing codes in finite elements is required to obtain the more realistic results. Also, voltage is the parameter that can be studied in thermal simulation.
References


