An Experimental Study on Drilling Through and Blind Holes on Inconel 718 by Electrical Discharge Machining

M.Sc. Thesis

in

Mechanical Engineering

University of Gaziantep

Supervisor

Assist. Prof. Dr. A. Tolga BOZDANA

by

Tuğba ULUTAŞ

August 2013

REPUBLIC OF TURKEY
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
MECHANICAL ENGINEERING DEPARTMENT

Name of the thesis: An Experimental Study on Drilling Through and Blind Holes on Inconel 718 by Electrical Discharge Machining

Name of the student: Tuğba ULUTAŞ

Exam date: 02.08.2013

Approval of the Graduate School of Natural and Applied Sciences

Assoc. Prof. Dr. Metin BEDİR
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Sait SÖYLEMEZ
Head of Department

This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. A. Tolga BOZDANA
Supervisor

Examining Committee Members	**Signature**
Assoc. Prof. Dr. Oğuzhan YILMAZ	
Assist. Prof. Dr. A. Tolga BOZDANA	
Assist. Prof. Dr. Mehmet KOÇAK	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Tuğba ULUTAŞ

ABSTRACT

AN EXPERIMENTAL STUDY ON DRILLING THROUGH AND BLIND HOLES ON INCONEL 718 BY ELECTRICAL DISCHARGE MACHINING

ULUTAŞ, Tuğba
M.Sc. in Mechanical Engineering
Supervisor: Assist. Prof. Dr. A. Tolga BOZDANA

August 2013, 40 pages

Electrical Discharge Machining (EDM) process has been used for making holes on difficult-to-cut materials in aerospace industry. There are several process parameters affecting performance of EDM operations. Workpiece material, electrode properties (i.e. material and shape of electrode) and type of holes to be drilled (i.e. through or blind) also influence the state of EDM process. Therefore, appropriate machining conditions should be provided for drilling holes in an accurate and effective way.

In this study, an experimental investigation was conducted on making through and blind holes on nickel-based super alloy Inconel 718 (namely IN718). Several holes (Ø2 mm) were drilled at two levels of process parameters (low and high values of current, pulse-on and pulse-off time, capacitance) using two types of brass electrodes (having single and multi-channels). Process performance was analyzed based on Material Removal Rate (MRR) and Electrode Wear Rate (EWR). Diameter and depth of drilled holes were measured in order to evaluate their dimensional accuracy. Surface Roughness (SR) measurements as well as Energy Dispersive X-ray (EDX) analyses were conducted to examine the characteristics of hole surfaces. The results revealed that use of multi-channel electrode and high-level parameters are the most appropriate conditions for drilling through and blind holes in aspects of lower drilling time, better dimensional accuracy, and improved surface quality.

Key Words: Electrical Discharge Machining, Inconel 718, Through/Blind Holes

ÖZ

ELEKTRİKSEL EROZYON PROSESİ İLE INCONEL 718 ALAŞIMINDA AÇIK VE KÖR DELİKLER ÜZERİNE DENEYSEL BİR ÇALIŞMA

ULUTAŞ, Tuğba
Yüksek Lisans Tezi, Makine Mühendisliği Bölümü
Tez Yöneticisi: Yrd. Doç. Dr. A. Tolga BOZDANA

Ağustos 2013, 40 sayfa

Elektriksel Erozyon ile İşleme (EEİ) prosesi, uzay ve havacılık sanayinde işlenmesi zor malzemelerde delik delme için kullanılmaktadır. EEİ performansına etki eden çok sayıda işlem parametreleri vardır. İş parçası malzemesi, elektrot malzemesi ile elektrodun şekli ve deliklerin türü (açık veya kör delik); EEİ şartlarını belirleyen diğer faktörlerdir. Dolayısıyla, deliklerin doğru ve verimli şekilde delinebilmesi için gerekli olan uygun işlem parametrelerinin ve koşullarının sağlanması gerekmektedir.

Bu çalışmada, nikel bazlı süper alaşım malzemesi Inconel 718 (IN718) üzerinde açık ve kör deliklerin delinmesi üzerine deneysel bir araştırma gerçekleştirilmiştir. İki farklı seviyede işlem parametreleri (düşük ve yüksek değerlere sahip akım, vurma ve dinlenme süreleri, kapasitans) ve iki farklı pirinç elektrot (tek ve çok kanallı) kullanılarak 2 mm çapında çok sayıda delik delinmiştir. EEİ performansı, İş Parçası İşleme Hızına (İİH) ve Elektrot Aşınma Oranına (EAO) göre değerlendirilmiştir. Delinen deliklerin boyutsal doğruluk analizleri, delik çapları ve derinlikleri ölçülerek yapılmıştır. Delik yüzeylerinin karakteristik özellikleri, Yüzey Pürüzlülüğü (YP) ve Enerji Dağılımlı X-Işını (EDX) spektroskopi ölçümleri doğrultusunda incelenmiştir. Elde edilen sonuçlar ışığında açık ve kör deliklerin; delme zamanı, boyutsal doğruluk ve yüzey kalitesi açısından en verimli şekilde delinebilmesi için çok kanallı elektrot ve yüksek seviyede işlem parametreleri kullanılması gerektiği tespit edilmiştir.

Anahtar Kelimeler: Elektriksel Erozyon Prosesi, Inconel 718, Açık/Kör Delikler

ACKNOWLEDGMENTS

The author wishes to express her deepest gratitude to her supervisor Assist. Prof. Dr. A. Tolga BOZDANA for his guidance, advice, criticism, encouragements and insight throughout this research.

The author would also like to thank Kürşad GÖV, M. Ali OKKA, and Gültekin ŞAHİNOĞLU for their help and suggestions during implementation of experiments and measurements.

Finally, special thanks to my dearest family and my friends for their moral support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Electrical Discharge Machining (EDM) is one of the most extensively used non-conventional material removal processes (Ho and Newman, 2003). The process is based on the thermoelectric energy created between a workpiece and an electrode submerged in a dielectric fluid (Pham et al., 2004). When workpiece and electrode are separated by a specific small gap (spark gap), a pulsed discharge occurs which removes material from the workpiece through melting and evaporation.

Hole drilling EDM process is a special type in which a rotating tubular electrode is used through which the dielectric fluid flows with a high pressure (Leao et al., 2005). This technique can be used for making holes in a fast and accurate way with a good surface finish. The process is widely used for machining difficult-to-cut materials in automotive, aerospace, and medical industry. Typical applications are making holes in turbine blades, fuel injectors, cutting tool coolant holes, plastic mold vent holes, and other aplications (Sommer, 2004).

There are several process parameters affecting the performance of machining in EDM operations. The workpiece material, the properties of electrode (i.e. material and shape of electrode) and the type of holes to be drilled (i.e. through or blind) also influence the state of EDM process. Therefore, appropriate machining conditions and settings should be accomplished for drilling holes in an accurate and effective way.

1.2 Aims and Objectives

The aim of this study is to conduct an experimental investigation on making holes on an aerospace alloy Inconel 718 (namely IN718). Several through and blind holes will be drilled at different machining conditions using hollow electrodes with single and multi channels. In accordance with this, drilling performance as well as dimensional accuracy and surface characteristics of drilled holes will be evaluated.

1.3 Structure of Thesis

A brief introduction on principle and typical applications of EDM process is given in Chapter 1. The related literature on use of EDM hole drilling process are summarized in Chapter 2 with particular applications. Chapter 3 presents the experimental work and procedure applied for conducting this research. The details on performing experiments as well as the procedure of measurements are explained in this chapter. The results obtained in this study are presented and discussed in Chapter 4 in detail. Finally, conclusions and highlights of the study are reported and further studies are recommended in Chapter 5.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

The origin of EDM dates back to 1770 when English scientist Joseph Priestly discovered the erosive effect of electrical discharges. During 1930s, attempts were made for the first time to machine metals and diamonds with electrical discharges. Erosion was caused by intermittent arc discharges occurring in air between electrode and workpiece connected to a DC power supply. However, these processes were not very precise due to overheating of machining area and may be defined as arc machining rather than spark machining (Ho and Newman, 2003).

Pioneering work on Electrical Discharge Machining (EDM) was carried out in 1943 by two Russian scientists B.R. and N.I. Lazarenko at Moscow University (Lazarenko, 1943). The destructive effect of an electrical discharge was channelized, and a controlled process for machining materials was developed. Resistance-Capacitance (RC) relaxation circuit was introduced in 1950s, which provided the first consistent dependable control of pulse times and also a simple servo control circuit to automatically find and hold a given gap between electrode and workpiece.

In recent years, due to its unique features over traditional techniques, EDM process has been used in many applications, particularly for machining the difficult-to-cut materials. Also, numerous developments in EDM have focused on the production of micro-features (Pham et al., 2004). This has become possible due to the availability of new CNC systems and advanced spark generators that have helped to improve machined surface quality.

This chapter introduces the principle of EDM process, particularly focusing on hole drilling EDM. Process parameters are described, and their effects on performance outputs of process (i.e. rate of material removal from workpiece and rate of wear in electrode material) and quality of machined surfaces (i.e. surface roughness) are presented. Finally, the research on EDM hole drilling applications as well as the gaps in literature are reported.

2.2 Electrical Discharge Machining (EDM)

EDM is the process of machining electrically conductive materials by using precisely controlled sparks that occur between an electrode and a workpiece in the presence of a dielectric fluid (Jameson, 2001). This method is preferred to machine difficult-to-cut materials, particularly aerospace alloys, which cannot be machined easily by means of traditional techniques.

EDM is sometimes called "spark machining" as it removes material from workpiece by producing a rapid series of repetitive electrical discharges. The sparking principle is illustrated in Fig. 2.1. Such electrical discharges are built between the electrode and the workpiece. The small amount of material that is removed from the workpiece is flushed away with a continuously flowing fluid. The repetitive discharges create a set of successively deeper craters in the workpiece until the final shape is produced.

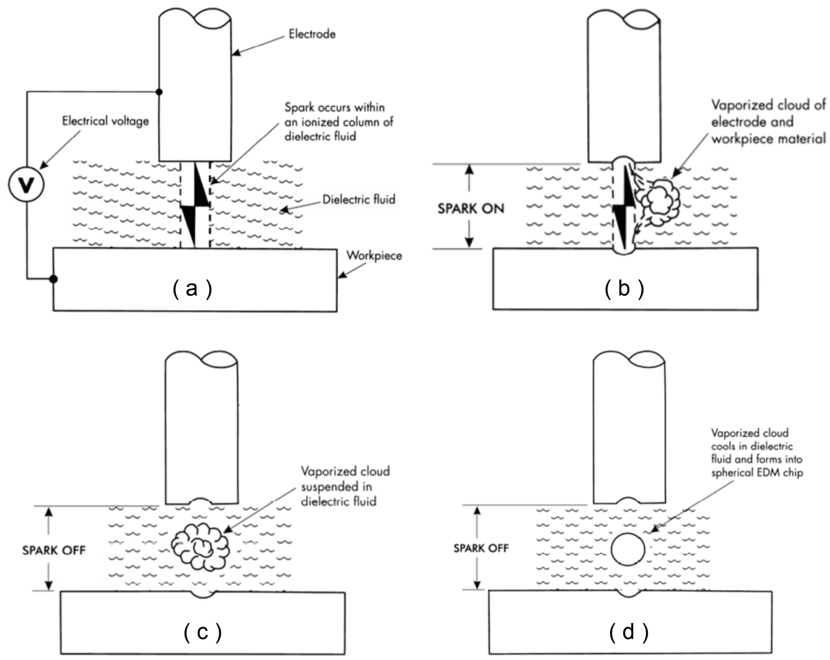

Figure 2.1 Principle of sparking in EDM process (Jameson, 2001)

EDM process has been commonly used in tool and die-making industry. In recent years, this process has also become an integral part of making prototypes and drilling small-scale cooling holes. Such applications are particularly seen in aerospace and electronics industries where production quantities remain low. For this purpose, there are different types of EDM machines for specific applications. Die-sinking EDM machines require an electrode with the exact opposite shape as the one in workpiece. Wire-EDM machines use a continuous wire as the electrode where the sparking takes place from the wire-side of electrode to the workpiece. Hole drilling EDM machines simply incorporate drilling of small-size holes using cylindrical hollow electrodes.

2.3 Hole Drilling EDM Process

Despite of using the same principle as other EDM techniques, hole drilling EDM process has two distinctive features (Fig. 2.2): a constantly rotating hollow-shape electrode and the pumping of dielectric fluid through this electrode. High flushing pressure of dielectric fluid flowing through the rotating electrode helps in flushing the particles away during machining. The electrode guider keeps the electrode on location and prevents drifting while the rotating electrode is cutting. With the aid of electrode guider and flushing effects on the electrode, this technique can be used for making holes in a fast and accurate way with a good surface finish.

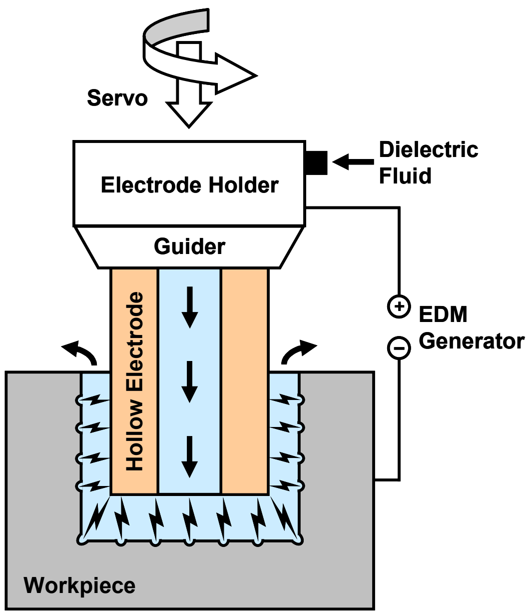

Figure 2.2 Hole drilling EDM process (adopted from Leao et al., 2005)

Use of traditional techniques in drilling holes on aerospace alloys cause problems of tool wear/breakage and slow machining rates, leading to inaccurate hole dimensions and unacceptable surface quality. For this purpose, hole drilling EDM has been recently used to produce cooling holes on aeroengine components such as turbine blades and nozzle guide vanes. The combination of using high pressure (70-100 bar) dielectric pump, the rotation of tubular electrode and the high electrode feed rate (controlled by a fast response servo) make it possible to produce holes at very fast rates. Drilling rates of 1 mm/s can be achieved, and hole size is ranging Ø0.15-3 mm with a length-to-diameter ratio of over 150:1 (Leao et al., 2005).

2.4 Process Parameters

The parameters in hole drilling EDM process can be grouped as controllable (adjustable) and uncontrollable (fixed) parameters,as given in Table 2.1. Controllable parameters, also called machining parameters, are the parameters which can be set or adjusted on EDM machine. Uncontrollable parameters can be selected or defined before the process.

Table 2.1 Controllable and uncontrollable EDM parameters

Controllable Parameters			**Uncontrollable Parameters**		
Name	***Unit***	***Symbol***	***Name***	***Unit***	***Symbol***
Peak current	A	I	Dielectric fluid	-	-
Pulse-on time	μs	t_{on}	Electrode rotation speed	rpm	N
Pulse-off time	μs	t_{off}	Polarity	-	-
Capacitance	μF	C	Voltage	volts	V
			Dielectric flushing pressure	bar	P

Peak current: This is the most important parameter in EDM operation, which states the amount of power used in discharge machining. During each pulse-on time, current increases until it reaches a preset level, which is expressed as "peak current" as seen in Fig. 2.3. Higher currents will improve Material Removal Rate (MRR), but at the cost of high Electrode Wear Rate (EWR) and Surface Roughness (SR).

Pulse-on and pulse-off time: Each sparking cycle during EDM process has pulse-on time (aka pulse duration) and pulse-off time (aka pulse interval). In some EDM machines, "duty factor" or "duty cycle" is specified as the ratio of pulse-on time to the total cycle time. Since all the work is done during pulse-on time, the duration of pulses and the number of cycles per second (frequency) are important. With longer pulse duration, more workpiece material will be melted away. The resulting crater will be broader and deeper than the crater produced by shorter pulse duration, which will cause a rougher surface. The cycle is completed when sufficient pulse interval is allowed before the start of next cycle. Pulse interval will affect speed and stability of the machining. In theory, the shorter the interval, the faster will be the machining operation. On the other hand, if the interval is too short the eroded workpiece material will not be swept away by flow of dielectric fluid, which will cause the next spark to be unstable.

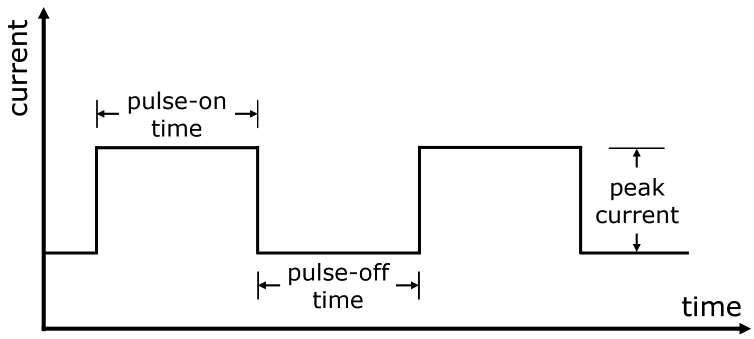

Figure 2.3 Peak current versus pulse-on and pulse-off times (Kumar et al., 2009)

Capacitance: In resistance-capacitor (RC) type discharge pulse generator (Fig. 2.4), the capacitor controls the action of charging and discharging as well as the frequency of discharging. An increase in capacitance results in higher MRR due to larger discharge energy. As capacitance becomes larger, the peak current also increases. This causes the formation of deeper craters, which leads to an increase in MRR and SR as well as slight increase in EWR.

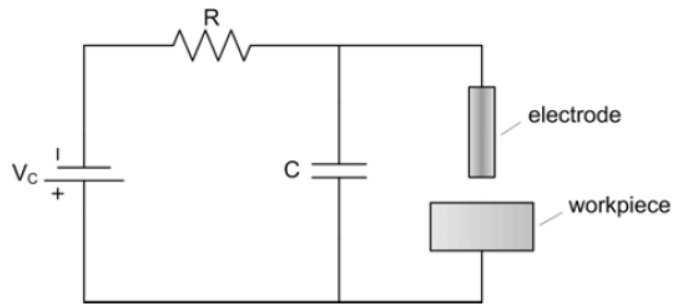

Figure 2.4 RC discharge pulse generation circuit (Jung et al., 2007)

Voltage: Discharge voltage in EDM is related to spark gap and breakdown strength of the dielectric. High voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the cutting action. MRR, EWR, and SR increase by increasing open circuit voltage since the electric field strength increases.

Dielectric fluid: EDM process takes place in the presence of a dielectric fluid. Basic characteristics of dielectric fluid are high dielectric strength and quick recovery after breakdown, effective quenching and flushing ability. MRR and EWR are affected by the type of dielectric and the method of its flushing. It is either a petroleum product or deionised water. Petroleum products are often referred to hydrocarbon fluids as they break down into hydrogen, carbon and other products when they are heated during sparking. Deionised water is free of impurities, and hence it is electrically conductive. The heat of sparking breaks down this water into hydrogen and oxygen. Therefore, deionized water is usually preferred in EDM operations due to its low viscosity and carbon-free characteristics.

Polarity: It can be either positive or negative. The spark creates high temperatures causing material evaporation at both electrode and workpiece. In general, the polarity is determined by experiments, and it is a matter of electrode material, workpiece material, current density and pulse length combinations.

2.5 Research on EDM Hole Drilling

In spite of many studies on EDM process, the studies on application of EDM hole drilling is limited. The research related to hole drilling using EDM process can be grouped with respect to workpiece material, type of electrode, and type of drilled holes. The process has been applied on various metals and alloys, such as aerospace alloys, steels, metal composites, and others. Solid and hollow (single-channel and multi-channel) electrodes have been used in order to drill blind and through holes.

There are a number of works on drilling of holes using EDM process on aerospace alloys, namely IN718 and Ti64. Yılmaz and Okka (2010) have investigated the effect of electrode type in EDM hole drilling. Single-channel and multi-channel tubular electrodes made of copper and brass were used to drill holes (Ø1 mm) on Ti64 and IN718. Deionized water was used as dielectric fluid. Comparisons were made in MRR, EWR, and surface integrity. SEM pictures of EDMed surfaces were performed in order to compare effects of type and material of electrodes on IN718 and Ti64 alloys.

A comparative experimental study on hole drilling of IN718 and Ti64 was performed by Bozdana et al. (2009). Brass and copper electrodes with tubular hollow shape were employed to drill blind and through holes of Ø1 mm. Machining parameters such as discharge current, pulse duration, pulse interval, dielectric fluid, flushing pressure, electrode rotation were kept constant. The changes in magnitudes of MRR and EWR have been compared for two materials. Characterstics of drilled hole surfaces were also examined based on SEM micrographs.

Rajesha et al. (2012) have studied drilling of holes on IN718 with hollow electrode. The experiments were performed using copper electrodes with inner and outer diameter of 9 mm and 12 mm, respectively. Keresone was preferred as dielectric fluid. Process parameters of current, duty factor, discharge gap, and flushing pressure were employed to optimize the process outputs (namely MRR and SR). This optimization was done using Response Surface Methodology (RSM) based on Central Composite Design (CCD). In addition, SEM was used for examining tool wear and sputtered layer deposition.

Kuppan et al. (2008) carried out an experimental investigation on deep micro-hole drilling on IN718. Through holes were drilled using pure electrolytic copper electrode having inner and outside diameter of 0.8 mm and 3 mm, respectively. Through holes were drilled on IN718 workpieces. Based on experimental data, mathematical models using RSM were obtained based on CCD and fractional factorial design of experiments. Input parameters were peak current, pulse-on time, duty factor, and electrode rotation speed while MRR and depth averaged surface roughness (DASR) were the output responses.

Manikandan and Venkatesan (2012) have optimized the machining parameters in micro-EDM of IN718. Brass electrode having diameter of 0.4 mm was chosen. Taguchi’s L9 Orthogonal Array was used for the experimental layout in order to analyze the effect of input parameters (discharge current, pulse-on time, and pulse-off time) on process outputs (MRR, overcut, and EWR).

Analysis of machining characteristics in additive mixed EDM of IN718 was conducted by Kumar et al. (2011). Copper electrode of Ø8.6 mm was chosen as tool electrode, and an oil containing Al additive powder was used as dielectric fluid. Machining parameters were current, pulse-on time, gap voltage, duty factor, and concentration of contamination in dielectric medium. These parameters were used to analyze the variations in output parameters such as MRR, EWR and SR.

Kao et al. (2010) have studied the optimization of hole drilling EDM parameters on machining Ti64 with multiple quality characteristics by Taguchi method. Copper electrode (Ø10 mm) was used to drill several holes with dielectric of kerosene. Input parameters were discharge current, open voltage, pulse duration, and duty factor whereas MRR, EWR, and SR were the response parameters.

A study by Kibria et al. (2010) was conducted to investigate the effect of dielectric on micro-EDM of Ti64. For this purpose, three different dielectric (namely kerosene, boron carbide, and deionized water) were used. Tool electrode was cylindrical tungsten rod of Ø300 µm. Peak current and pulse-on time were considered as varying parameters while other parameters were kept constant. The output responses were MMR, EWR, overcut, and variances at entry and exit regions of holes. After drilling, the drilled hole surfaces were etched to examine the surface topography of holes by means of SEM pictures.

Grey Relational Analysis (GRA) of micro-EDM process was performed by Meena and Azad (2012). Taguchi-based L18 design of experiment was used for modeling the process based on current, pulse width, voltage, and frequency. The responses were MRR, EWR, and OC. The holes were drilled on Ti64 plates using cylindrical tungsten carbide (Ø0.4 mm) electrodes.

Another study on mathematical modeling of micro-EDM of Ti64 was done by Pradhan et al. (2009). Taguchi-based L9 experimental plan was used in this study. Cylindrical brass electrode (Ø500 µm) was used to drill holes at varying machining conditions such as peak current, pulse-on time, flushing pressure, and duty factor. The output responses (MRR, EWR, OC, and taperness) were optimized. In addition, surface characteristics of hole surfaces were analyzed based on SEM micrographs.

Drilling small holes by EDM on TC4 alloy (refers to Ti64 in China) was investigated by Li et al. (2009). Red copper and Cu-W alloy electrodes (Ø0.5 mm) were used. Kerosene was chosen as dielectric fluid. The effect of various parameters (dielectric fluid, flushing pressure, voltage, polarity, current, and capacitance) were considered for improving machining efficiency and decreasing wear of electrode.

Studies on drilling of holes on steel and its alloys are also available in literature. Sameh et al. (2013) have also investigated drilling of microholes on SKD 11 alloy steel. Tungsten electrodes having different diameters (Ø0.3, 0.5, and 1 mm) were used. The holes were drilled by multi-electrodes (i.e. simultaneous drilling with a number of electrodes) where the number of electrodes could be changed. After drilling, SEM images of microholes were compared. Also, process outputs such as MRR and EWR were analysed for various hole diameters.

The process outputs of hole drilling EDM were optimized by Lin et al. (2002) using Grey Fuzzy Logic. A number of holes were drilled on SKD 11 alloy steel with cylindrical copper electrode with diameter of 8 mm using dielectric fluid of kerosene. In this study, pulse-on time, duty factor, and discharge current were determined as input parameters in order to predict output parameters such as MRR, EWR, and SR.

Jung et al. (2007) proposed a new method to estimate the material removal volume and the depth of blind micro-hole drilled on SKD 11. Tungsten carbide electrode (Ø300 μm) was rotated at 200 rpm, and kerosene was used as dielectric. An on-line monitoring of number of discharge pulses was accomplished to provide in-process estimation of material removal and depth of blind hole.

In research of Muthuramalingam and Mohan (2013), the effect of machining parameters on EDM of AISI 202 stainless steel was investigated. Mathematical models for MRR and SR were developed using Taguchi method based on current, gap voltage, and duty factor. Tungsten carbide electrode (Ø4.0 mm) was used, and discharge current was regulated to improve surface finish during the experiment.

Srivastava and Pandey (2012) have studied EDM of high speed steel (M2 grade) using a cryogenically cooled electrode. The holes of Ø7 mm were drilled using a solid cylindrical copper electrode, and liquid nitrogen was applied onto the electrode for cooling during operation. The performance of process was evaluated based on EWR, SR, and shape of electrode.

Öpöz et al. (2009) conducted an experimental work on the geometry of blind microholes drilled by micro-EDM. Their shapes and dimensions were investigated with regard to machining time. Specimens made of plastic mold steel and tungsten carbide tool electrode (Ø300 μm) were used in the experiments. Electrode removal length, depths of blind holes and expansion in diameters of microholes were measured and compared with altering drilling time.

Yu et al. (2002) have conducted an experimental investigation on making through holes with high aspect ratio as well as noncircular complex shaped blind micro holes. This was achieved by planetary movement of tungsten electrode. A rotating electrode was used for drilling of circular micro holes with high aspect ratio whereas an electrode having corresponding hole shape was prepared for blind noncircular micro holes. AISI 304L was the workpiece material, and two dielectric medium (mineral oil and deionized water) were used. Performance characteristics of process (MRR and EWR) were analyzed under different machining conditions.

An experimental investigation on accuracy of blind holes with high aspect ratio was carried out by Puranik et al. (2008). This study explored the relationship between accuracy and depth of micro-EDMed blind holes. The experiments were designed according to L27 orthogonal array, and the mathematical models were generated using Taguchi method. The holes were drilled on pairs of split workpieces made of stainless steel (SS-304) using tungsten electrodes of Ø200 μm. Deionized water was preferred as dielectric fluid. The optimum hole depth with the highest aspect ratio was achieved with good accuracy.

Parametric analysis of dry EDM process was studied by Saha and Choudhury (2009). The experiments, planned based on Central Composite Design (CCD) method, were conducted on EN32 mild steel using a hollow copper electrode through which high-pressure air was pumped. The effect of several process parameters (such as gap voltage, discharge current, pulse-on time, duty factor, air inlet pressure, and spindle speed) on process outputs (namely MRR, EWR, and SR) was analyzed using Response Surface Methodology (RSM) technique. Various channel configurations for the tool electrode were also considered to observe its effect on MRR and SR.

Pham et al. (2007) have studied the influence of various factors on electrode wear of electrodes on drilling blind holes. Specimens made of tool steel (P20), brass (Cu Zn 15), and aluminum (Al 5083) were drilled with hollow and rod electrodes (tungsten carbide with Ø170 μm) at certain sparking conditions. A low-pressure oil was used as dielectric fluid. Input parameters of voltage, current, pulse-on and pulse-off time with constant values were chosen to examine the electrode wear.

EDM hole drilllig of other metals and composites has also been studied by a number of researchers. Experimental work performed by Jahan et al. (2012) reported the impact of various EDM parameters on the surfaces of microholes drilled on cemented carbide (WC-Co) specimens. The electrode was pure tungsten (Ø0.2 and 0.3 mm) with negative polarity. The parameters were gap voltage, resistance, peak current, pulse duration, pulse interval, duty cycle, and electrode rotational speed. The effects of these parameters on MRR, EWR and surface quality of holes were presented.

Taguchi modeling of EDM of tungsten carbide was studied by Lajis at al. (2009). Solid graphite electrode (Ø9 mm) was used to drill holes on square-shape WC plates based on the experiments of L9 orthogonal array. The relationship between input parameters (voltage, peak current, pulse duration, and pulse interval) and output parameters (MRR, EWR, and SR) was analyzed. The machining conditions for optimum process outputs were also determined.

Another study on mathematical modeling of hole drilling EDM process was done by Jeong and Min (2007). This study consists of three phases dealing with simulations of both tool and workpiece, their calculations and the simulation of material removal process. A mathematical model was applied to obtain geometries of both tool and workpiece as well as for calculations of their positions. Materials of workpiece and tool electrode were copper and tungsten carbide (Ø200 µm), respectively. The results of models were verified with experimental trials on drilling blind holes.

Drilling of deep holes with insulated tool electrodes was studied by Ferraris et al. (2013). The holes (Ø0.2 mm) having very high aspect ratio (> 30) were drilled on tungsten carbide workpiece. The tool electrode was also tungsten carbide that was insulated with polymer coating (Parylene C) and ceramic coating (SiCN-SiC). The comparisons in material removal, electrode wear, and dimensions of drilled holes were made based on through and blind holes.

Another study on drilling blind microholes was conducted by Ali et al. (2009). Workpiece and electrode materials were beryllium-copper alloy and tungsten carbide

(Ø300 μm), respectively. This study provided investigations on roundness, taper angle and EWR according to different aspect ratios. Effect of aspect ratio on selected diameter, roundness, and taper angle were examined. Diameters and depths of drilled microholes were measured by SEM.

The machining characteristics of SiC/6025Al composite using rotary EDM were investigated by Mohan et al. (2004). Tool electrode was tubular brass electrodes (having diameter of varying between 1.5 and 3.5 mm) rotating at 270 and 750 rpm. Commercial kerosene was used as dielectric fluid. Various parameters (such as peak current, polarity, volume fraction of SiC reinforced particles, pulse duration, hole diameter of tube electrode, and speed of electrode rotation) were considered. Their effects on MRR, EWR, and SR were discussed.

Grey Relational Analysis (GRA) method was used by Murugesan and Balamurugan (2012) to drill blind hole on 6061 Al alloy (reinforced with 15% SiC) using multi-hole electrode. The tool electrode was an electrolytic copper rod (Ø12 mm) with an array of Ø2 mm holes. Taguchi-based L18 experiments were chosen to determine the effect of machining parameters (polarity, discharge current, pulse-on and pulse-off times, and pressure of dielectric) on process outputs (machining time, electrode wear, and surface roughness). The machining conditions were obtained for drilling a blind hole with optimum process outputs.

2.6 Literature Gap

Table 2.2 presents the summary of works conducted on EDM hole drilling process. Workpiece material, hole type (through or blind holes), and electrode type (solid or hollow electrode with single and multi channels) for each reference are also given.

As discussed in Section 2.5, there are several works on EDM hole drilling process. Such works have focused on experimental investigation, mathematical modelling, and/or optimization of process outputs. Many researchers were dealing with EDM performance outputs (such as MRR and EWR) or surface characteristics of drilled holes (i.e. surface roughness and topography). However, only few studies examined the dimensional analysis of drilled holes, particularly blind holes.

In addition, among those works, the effect of using multi-channel electrode has not been come across. Use of solid or single-channel electrode causes problems related with geometry and surface properties of blind holes due to insufficient flushing effect of dielectric. Therefore, there is still a need for a comprehensive experimental work in order to observe dimensional and surface characteristics of blind holes.

Table 2.2 Summary of research on EDM hole drilling process

		Hole Type		Electrode Type		
Reference	**Workpiece Material**	**Thru**	**Blind**	**Solid**	**Single**	**Multi**
Ali et al. (2009)	Beryllium-copper alloy		X	X		
Bozdana et al. (2009)	- IN718 - Ti64	X	X		X	
Ferraris et al. (2013)	WC	X	X		X	
Jahan et al. (2012)	WC-Co	X		X		
Jeong & Min (2007)	Copper		X	X		
Jung et al. (2007)	SKD 11 alloy steel		X	X		
Kao et al. (2010)	Ti64	X		X		
Kibria et al. (2010)	Ti64	X		X		
Kumar et al. (2011)	IN718	X		X		
Kuppan et al. (2008)	IN718	X			X	
Lajis et al. (2009)	WC	X		X		
Li et al. (2009)	Ti64 (TC4)	X		X		
Lin et al. (2002)	SKD11 alloy steel	X		X		
Manikandan & Venkatesan (2012)	IN718	X		X		
Meena and Azad (2012)	Ti64	X		X		
Mohan et al. (2004)	SiC/6025Al composite	X			X	
Murugesan & Balamurugan (2012)	Al alloy (with SiC)		X			X
Muthuramalingam & Mohan (2013)	AISI 202 stainless steel	X		X		
Öpöz et al. (2009)	Plastic mold steel		X	X		
Pham et al. (2007)	- P20 tool steel - Cu Zn 15 - Al 5083		X	X	X	
Pradhan et al. (2009)	Ti64	X		X		
Puranik et al. (2008)	SS-304 stainless steel		X	X		
Rajesha et al. (2012)	IN718	X			X	
Saha & Choudhury (2009)	EN32 mild steel	X			X	X
Sameh et al. (2013)	SKD 11 alloy steel	X		X		
Srivastava & Pandey (2012)	HSS (M2 grade)	X		X		
Yılmaz & Okka (2010)	- IN718 - Ti64	X			X	X
Yu et al. (2002)	AISI 304L steel	X	X	X		

This study presents an experimental investigation on drilling through and blind holes on IN718 using single and multi channel electrodes. The effect of process parameters and type of electrode has been analyzed on performance outputs of process as well as dimensional accuracy and surface characteristics of drilled holes. The presented work is original and useful in related literature, and it may provide a reference for industrial applications.

CHAPTER 3

EXPERIMENTAL WORK and PROCEDURE

3.1 Introduction

This chapter presents the experimental work and procedure. The material properties of specimens and electrodes are given. The procedure of drilling holes with specified EDM parameters is described in detail.

3.2 Workpiece and Electrode Materials

The workpiece material was Inconel 718 (namely IN718). It is a nickel-based super alloy with specific chemical composition, which is given in Table 3.1. In spite of poor machinability and low mechanical properties, this material is preferred in aerospace applications due to specific thermal and physical properties.

Table 3.1 Chemical compositions of IN718 (wt. %) (Bozdana et al., 2009)

Ni : 50-55	Co : 1.00 (max)	Mn : 0.35 (max)
Cr : 17-21	Ti : 0.65-1.15	Cu : 0.30 (max)
Fe : Balanced	Al : 0.20-0.80	C : 0.08 (max)
Nb : 4.75-5.50	Si : 0.35 (max)	B : 0.06 (max)
Mo : 2.80-3.30		

Tubular brass electrodes having single and multiple channels (Fig. 3.1) were used in drilling operations. The electrodes have an outside diameter and a length of 2 mm and 400 mm, respectively. Table 3.2 presents the geometrical properties of electrodes. The number of channels is a significant parameter in EDM hole drilling as the flushing characteristics of electrode is influenced by the channel area through which the dielectric fluid is flowing (Yılmaz and Okka, 2010). The efficiency of using single and multiple channel electrodes are discussed in the next chapter.

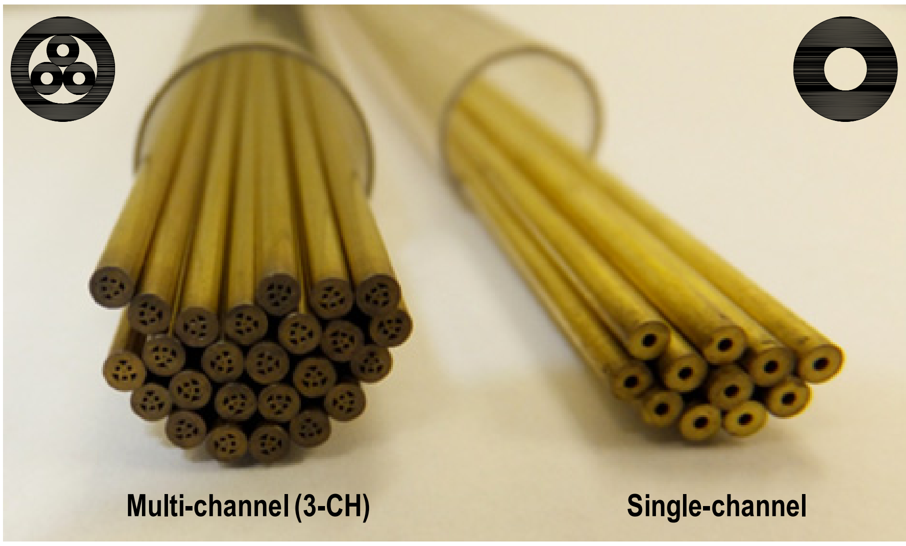

Figure 3.1 Brass electrodes with single and multiple channels

Table 3.2 Geometrical properties of electrodes

	Single-channel	*Multi-channel*
Outside Dia. (mm)	2.0	2.0
Sparking Area (mm^2)	2.821	2.713
Channel Area (mm^2)	0.320	0.428
Flushing Force (N)	3.20	4.28
Electrode length (mm)	400	400

Brass electrode is commonly preferred in machining of IN718 due to its desirable thermal and electrical properties (Bozdana et al., 2009; Manikandan and Venkatesan, 2012; Yılmaz and Okka, 2010), as given in Table 3.3.

Table 3.3 Material properties of workpiece and electrode (MatWeb)

Property	*IN718*	*Brass*
Density (g/cm^3)	8.19	8.48
Melting point (ºC)	1260 - 1336	900 - 940
Electrical resistivity (µΩ-cm)	125	4.70
Thermal conductivity (W/m-ºK)	11.4	159
Specific heat capacity (J/g-ºC)	0.435	0.380

3.3 Experimental Setup and Procedure

The experiments were performed on JS EDM AD-20 hole drilling EDM machine. Specifications of this machine are given in Fig. 3.2.

JS AD-20 EDM

X / Y AXIS TRAVEL	300 x 200 mm (11.8" x 7.9")
Z1 / Z2 AXIS TRAVEL	345 mm (13.6")
WORK TABLE	480 x 210 mm (18.9" x 8.3")
X / Y / Z AXIS DRO RESOLUTION	0.005 mm (0.000196")
ELECTRODE GUIDE TRAVEL	150 mm (5.9")
HEIGHT OF WORK TABLE TO GUIDE	80 ~ 210 mm (3.1" ~ 8.3")
MAX. WORKPIECE WEIGHT	200 kg
MACHINE WEIGHT (N.W)	600 kg
OVERALL DIMENSIONS (L x W x H)	1000 x 1020 x 2070 mm (39.4" x 40.2 " x 81.5")
MAX. MACHINING CURRENT	30 A
MAX. POWER CONSUMPTION	4 KVA
INPUT VOLTAGE	220 / 380 / 415 / 440 V

Figure 3.2 Specifications of JS AD-20 EDM machine

The experimental procedure is shown in Fig. 3.3. The holes were drilled on block specimens with dimensions of 6 x 11 x 35 mm. Before drilling operations, flat surfaces (top, bottom and side faces) of specimens were ground and polished to obtain good surface finish. Two specimens were clamped together and the holes were drilled on the mating interface, as illustrated in Fig. 3.4. After drilling, the specimens were separated to perform geometrical and surface measurements on the mating face of specimens.

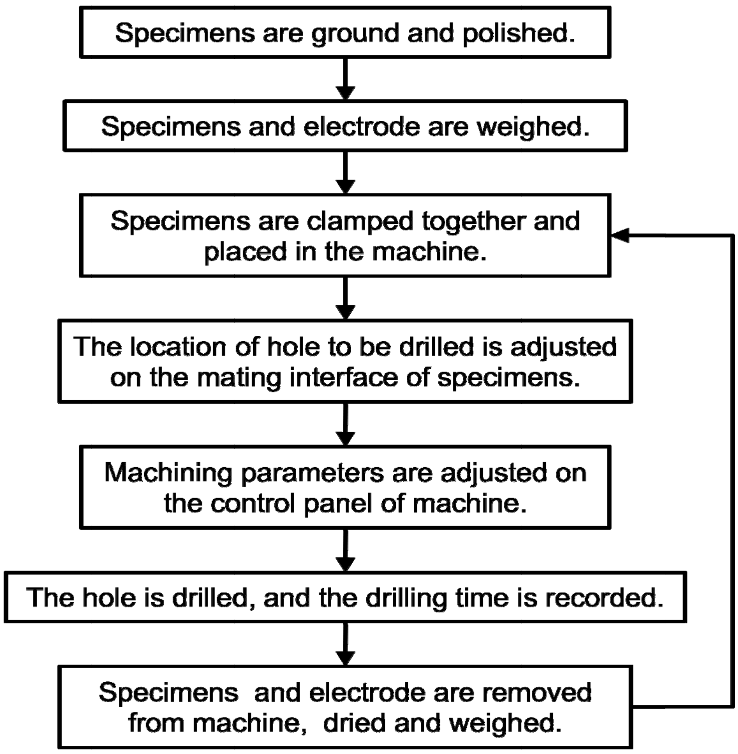

Figure 3.3 Experimental procedure

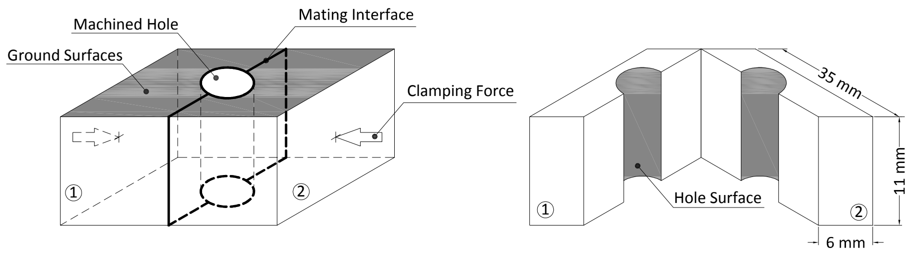

Figure 3.4 Sketch of specimens and drilled holes

The components of EDM machine are shown in Fig. 3.5. The vertical movement of electrode is controlled by servo control, and the coordinate display shows the axis movements. The dielectric fluid is filtered and pumped through hollow electrode during operation. Machine settings are selected on the control panel. Current and voltage were measured using an oscilloscope whereas the values of pulse-on time, pulse-off time, and capacitance were specified by machine manufacturer.

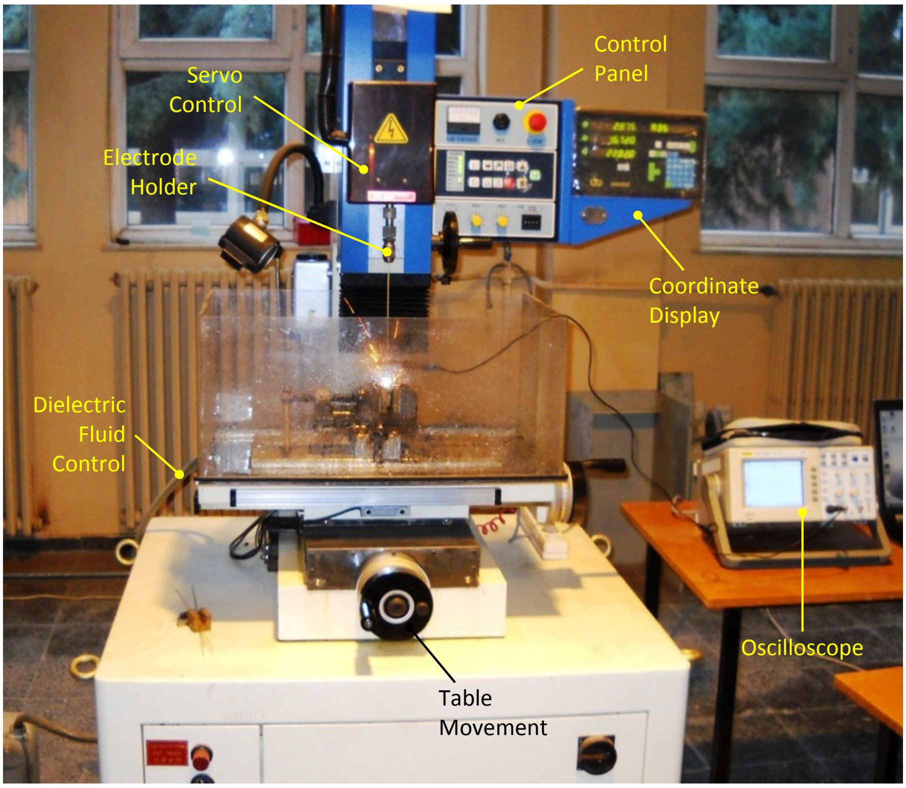

Figure 3.5 Components of JS AD-20 EDM machine

The initial weights of specimen and electrode were weighed using a digital scale with 1 mg accuracy. After drilling of each hole, both specimen and electrode were removed from the machine, cleaned using alcohol, dried using compressed air before weighing on the digital scale.

Electrode wear occurs at inner and outer surfaces of the electrodes during drilling. Therefore, the electrode consumption in weight was considered in calculation of Electrode Wear Rate (EWR). In addition, before drilling of each hole, the worn end of electrode was cut away. After that, the tip of electrode was ground and made flat. This enabled drilling of each hole with a fresh (new) electrode.

In this study, one through hole and five blind holes at different depths were drilled. The depths of blind holes were determined incrementally based on the drilling time of the through hole. This is due to the reason that the depth of a blind hole during drilling operation cannot be determined visually. The hole depth can be estimated by observing real time progress of the electrode on the coordinate display of EDM machine during drilling operation. However, this would be misleading due to electrode wear (loss in electrode). This wear occurs not only in length, but also in diameter of the electrode, which is not uniform under all drilling conditions. Therefore, an accurate estimation for the hole depth cannot be done based on dimensional characteristics of electrode and/or hole shape.

For this reason, the depth of each blind hole was proportioned with the drilling time. Firstly, the through hole (11 mm in depth) was drilled, and the drilling time was recorded. After that, the depth of each blind hole was incremented with respect to the time for drilling each blind hole. Finally, all blind holes were drilled according to these drilling times, as illustrated in Fig. 3.6. The incremental depths for blind holes and the corresponding drilling times are given Table 3.4.

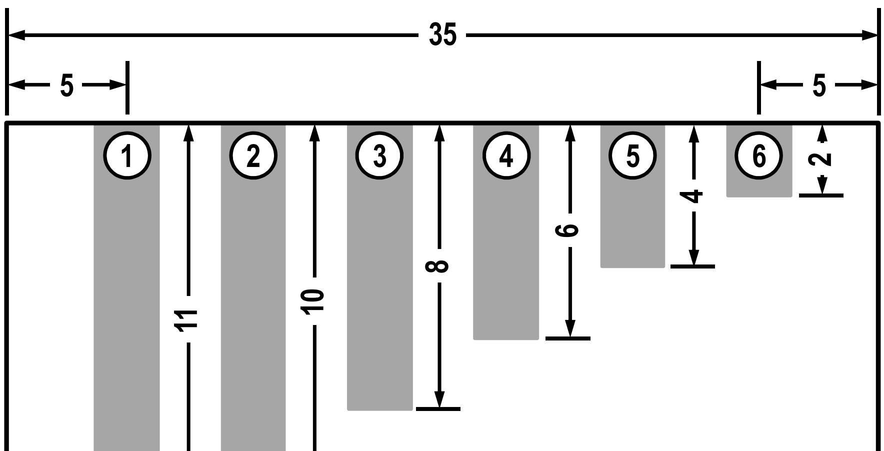

Figure 3.6 Sketch of through and blind holes

Table 3.4 Incremental hole depths and corresponding drilling times

Hole No.	***Hole Type***	***Hole Depth (mm)***	***Drilling Time (s)***
1	Through	11	t
2	Blind	10	t * (10/11)
3	Blind	8	t * (8/11)
4	Blind	6	t * (6/11)
5	Blind	4	t * (4/11)
6	Blind	2	t * (2/11)

The depths of hole #2 and hole #6 are quite significant. Hole #2 has a depth that is very near the bottom end of specimen while hole #6 is very shallow. This would enable the analysis of dimensional accuracy of such blind holes after drilling.

Table 3.5 shows the machining parameters and settings used in drilling operations. In this study, two sets of machining parameters (5-5-5-5 and 9-9-9-9) were chosen, which are the highest and the lowest machine settings for machining IN718 (Okka, 2010). In addition, the drilling operations were performed at such settings using two electrode types (single-channel and multi-channel). Therefore, this has provided four set of experiments, as as given in Table 3.6.

Table 3.5 Machining parameters and settings

Adjustable parameters		
	Settings	***Values***
Peak Current (I)	5, 9	8.2 A, 12 A
Pulse-on Time (T_{on})	5, 9	27 µs, 44 µs
Pulse-off Time (T_{off})	5, 9	16 µs, 26 µs
Capacitance (C)	5, 9	1100 µF, 1476 µF
Fixed Parameters		
Voltage	27 V	
Dielectic Fluid	Deionized water	
Dielectic Pumping Pressure	100 Bar	
Electrode Rotation Speed	200 rpm	
Polarity	Negative (electrode)	

As seen from Table 3.6, in each set of drilling operation, machining settings and electrode type were changed while all other parameters were kept constant. This would enable to examine the dimensional accuracy and surface characteristics of through and blind holes drilled at different set of experimental conditions. The holes drilled at different set of experiments are given in Fig. 3.7.

Table 3.6 Set of experiments

Set of Experiment	*Machine Settings*	*Electrode Type*
#1	5-5-5-5	Single-channel
#2	5-5-5-5	Multi-channel
#3	9-9-9-9	Single-channel
#4	9-9-9-9	Multi-channel

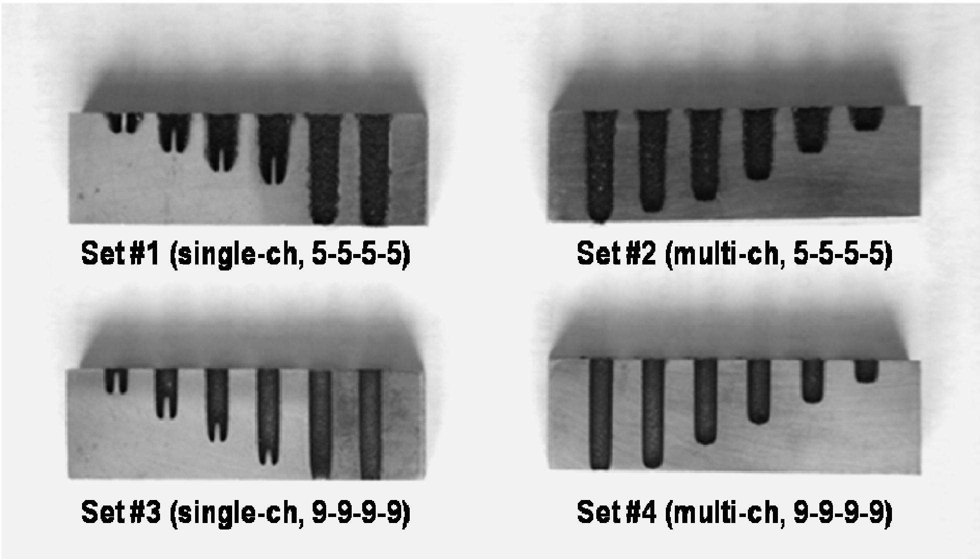

Figure 3.7 Specimens with drilled holes at different set of experiments

3.4 Procedure for Measurements

In EDM operations, Material Removal Rate (MRR) is a measure of machining characteristics, and it is directly related to the amount of removed material from the surface within machining time. It was calculated by the following formula:

$$\text{MRR (mg/min)} = \frac{\text{loss in specimen weight}}{\text{drilling time}} \qquad \text{Eq. 3.1}$$

Electrode Wear Rate (EWR) is generally calculated as ratio of electrode consumption in length to drilling time. However, as mentioned in Section 3.3, the electrode wear cannot be considered based on length. Therefore, EWR was determined according to the loss in electrode weight with respect to the drilling time as follows:

$$\text{EWR (mg/min)} = \frac{\text{loss in electrode weight}}{\text{drilling time}} \qquad \text{Eq. 3.2}$$

The pictures of hole surfaces were taken by JEOL JSM-6390LV Scanning Electron Microscope (SEM). After that, the dimensional analyses of holes (such as hole diameter, hole length, etc.) were performed using a 3D SEM imaging software (Alicona MeX). In addition, composition analyses on the hole surfaces after drilling were performed by Energy Dispersive X-ray (EDX) spectroscopy. This was done in order to evaluate the effect of chemical interaction between electrode and workpiece materials during EDM process.

The roughness of hole surfaces were measured on Mitutoyo SJ-401 using a cut-off length of 0.8mm. The measurements were performed on through holes in each set of experiment at different regions of hole surface (namely at entrance, middle, and exit regions). This was done to observe the surface quality at different regions of holes.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results obtained after experimental works described in Chapter 3. The holes after drilling operation were analyzed in terms of EDM process performance, dimensional properties, and surface characteristics. The results have been presented and compared in each section, and the reasons of such findings have been discussed in detail.

4.2 Machining Performance Analyses

Tables from 4.1 through 4.4 show MRR and EWR values for all sets of experiments. As described in Chapter 3, loss in weight of specimens and electrodes were calculated. The drilling time for each hole was also recorded. Then, MRR and EWR values were determined using Eq. 3.1 and Eq. 3.2, respectively.

Regardless of level of process parameters (i.e. low-level vs. high-level), MRR and EWR values for multi-channel electrode are greater than those for single-channel electrode. Due to the cross-sectional geometry of multi-channel electrode, sparking occurs more uniform and intense as compared with single-channel electrode. This results in higher amount of material removal from both workpiece and electrode during machining, which leads to higher MRR and EWR values.

In case of comparison between low-level and high-level parameters (i.e. 5-5-5-5 vs. 9-9-9-9), there is considerable difference in MRR and EWR values. Regardless of type of electrode, high-level parameters exhibit greater MRR and EWR values than low-level parameters. This is due to the reason that current and capacitance values are higher, which leads to higher amount of material removal from both workpiece and electrode.

Table 4.1 MRR and EWR values for set of experiment #1

Hole No.	Drilling Time (s)	Loss in Weight (g)		MRR (mg/min)		EWR (mg/min)	
		Specimen	Electrode	Value	Dev. (%)	Value	Dev. (%)
1	381	0.424	0.051	66.772	-11.53	8.031	4.13
2	346	0.388	0.049	67.283	-12.39	8.497	-1.43
3	277	0.264	0.039	57.184	4.48	8.448	-0.84
4	208	0.202	0.031	58.269	2.67	8.942	-6.74
5	139	0.133	0.020	57.410	4.10	8.633	-3.05
6	70	0.061	0.009	52.286	12.66	7.714	7.92
Ave.				**59.867**		**8.378**	

Table 4.2 MRR and EWR values for set of experiment #2

Hole No.	Drilling Time (s)	Loss in Weight (g)		MRR (mg/min)		EWR (mg/min)	
		Specimen	Electrode	Value	Dev. (%)	Value	Dev. (%)
1	316	0.365	0.085	69.304	6.98	16.139	-7.18
2	287	0.339	0.080	70.871	4.87	16.725	-11.07
3	230	0.295	0.057	76.957	-3.29	14.870	1.25
4	173	0.227	0.042	78.728	-5.67	14.566	3.26
5	115	0.141	0.026	73.565	1.26	13.565	9.91
6	58	0.075	0.014	77.586	-4.14	14.483	3.82
Ave.				**74.502**		**15.058**	

Table 4.3 MRR and EWR values for set of experiment #3

Hole No.	Drilling Time (s)	Loss in Weight (g)		MRR (mg/min)		EWR (mg/min)	
		Specimen	Electrode	Value	Dev. (%)	Value	Dev. (%)
1	100	0.323	0.101	193.800	7.45	60.600	-2.81
2	90	0.308	0.095	205.333	1.94	63.333	-7.45
3	73	0.265	0.072	217.808	-4.02	59.178	-0.40
4	54	0.196	0.050	217.778	-4.00	55.556	5.75
5	36	0.129	0.033	215.000	-2.68	55.000	6.69
6	18	0.062	0.018	206.667	1.30	60.000	-1.79
Ave.				**209.398**		**58.944**	

Table 4.4 MRR and EWR values for set of experiment #4

Hole No.	Drilling Time (s)	Loss in Weight (g)		MRR (mg/min)		EWR (mg/min)	
		Specimen	Electrode	Value	Dev. (%)	Value	Dev. (%)
1	77	0.303	0.099	236.104	0.40	77.143	-2.74
2	70	0.288	0.096	246.857	-4.14	82.286	-9.59
3	56	0.224	0.071	240.000	-1.25	76.071	-1.32
4	42	0.170	0.047	242.857	-2.45	67.143	10.58
5	28	0.107	0.035	229.286	3.27	75.000	0.11
6	14	0.053	0.017	227.143	4.18	72.857	2.96
Ave.				**237.041**		**75.083**	

Drilling times versus losses in weight of specimen and electrode for all sets of experiments are shown in Fig. 4.1 and Fig. 4.2, respectively. As seen from graphs, drilling time and material loss vary proportionally. There exist slight deviations in the curves without sharp peaks, and hence this relationship can be expressed as linear with very good fitness levels (i.e. high R^2 values). Therefore, the amount of material loss in workpiece and electrode can be estimated reliably based on drilling time.

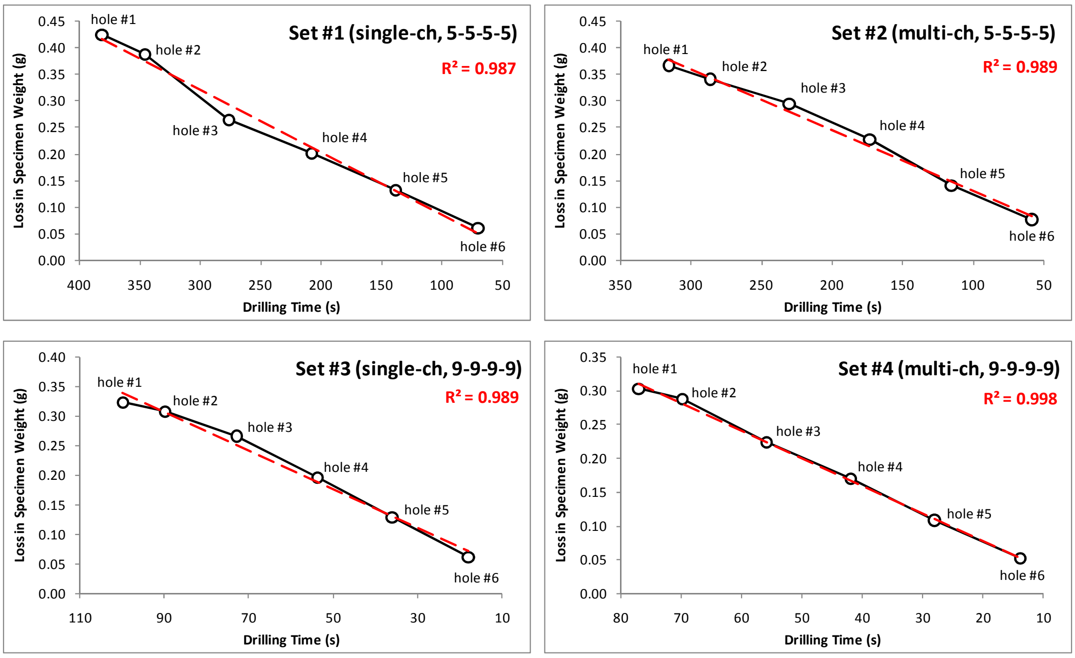

Figure 4.1 Drilling time vs. loss in specimen weight

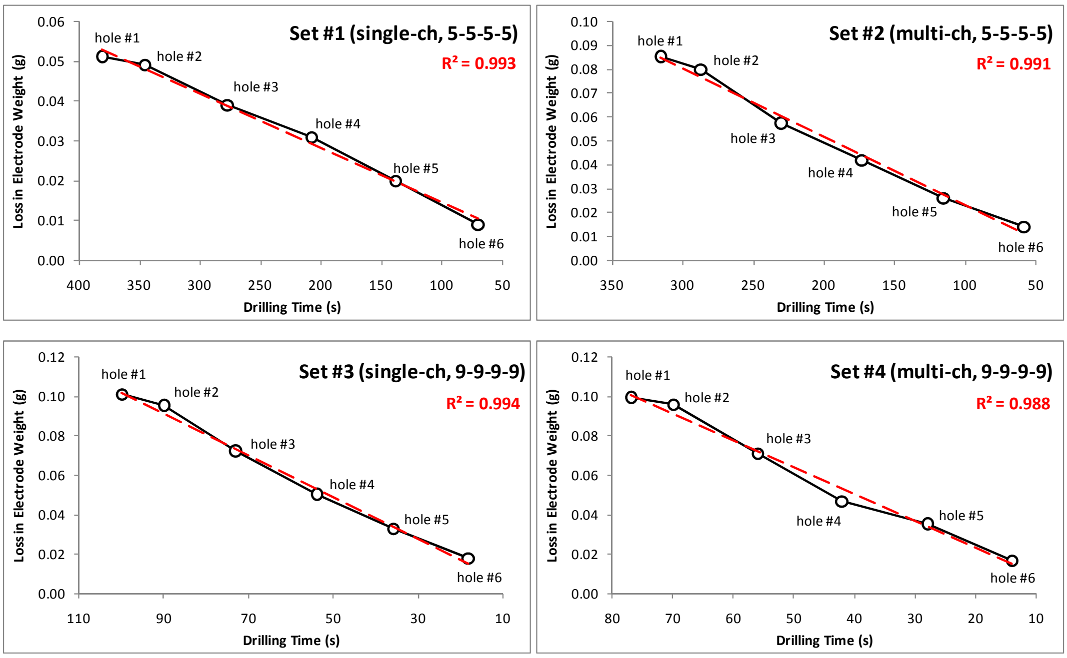

Figure 4.2 Drilling time vs. loss in electrode weight

Reliability of MRR and EWR values can also be verified through Table 4.1-4.4. The percentage of deviation of MRR and EWR value for each hole was calculated based on their average values within each set of experiment. The results show that MRR and EWR values are consistent within about 10% of deviation. This consistency can be seen through Fig. 4.3-4.4.

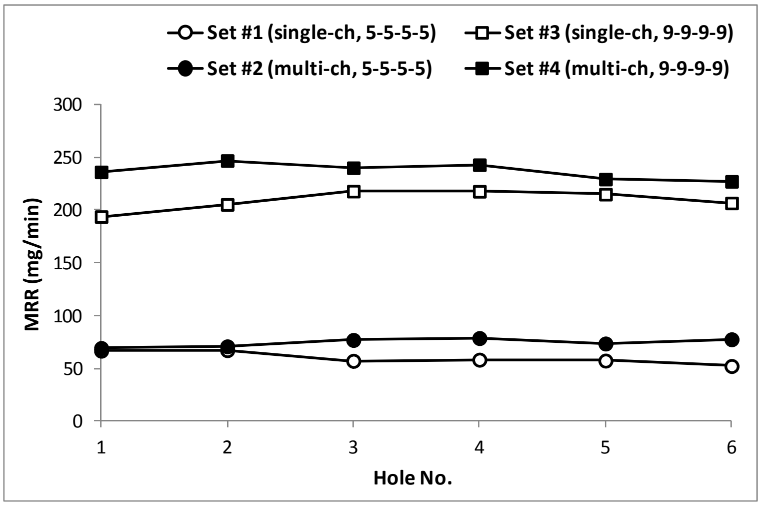

Figure 4.3 MRR for all sets of experiment

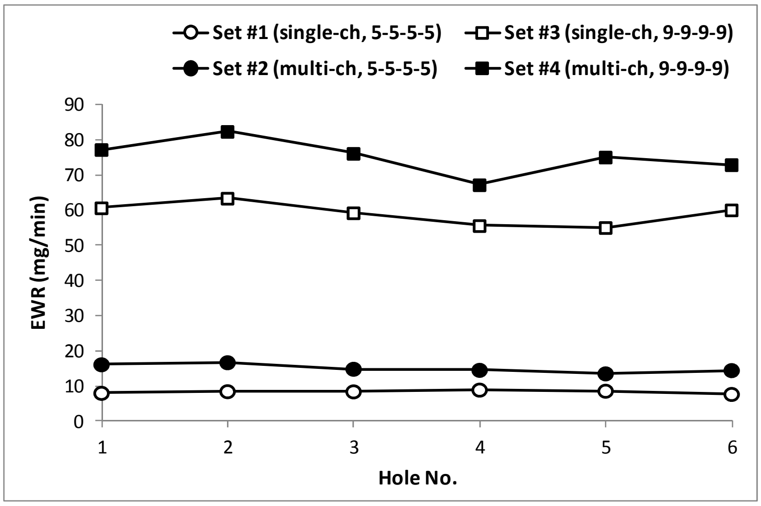

Figure 4.4 EWR for all sets of experiment

4.3 Dimensional Analyses

The pictures of holes in all sets taken by SEM are given in Fig. 4.5-4.8. The depths of blind holes as well as the diameter of through holes (at entrance and exit regions) were measured using a 3D SEM imaging software (Alicona MeX).

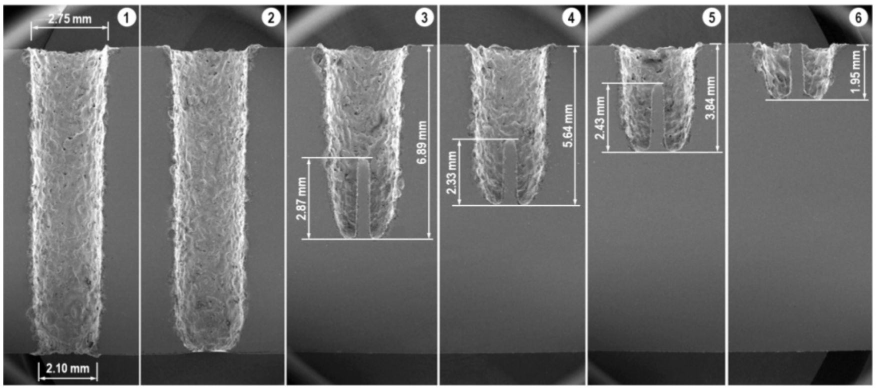

Figure 4.5 SEM pictures of hole surfaces in set of experiment #1

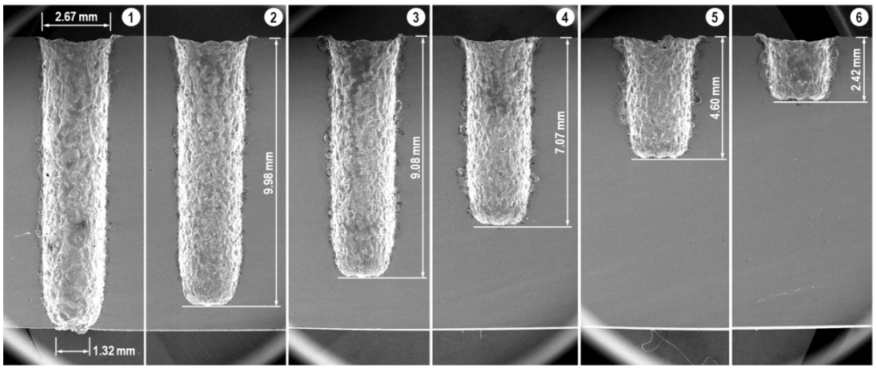

Figure 4.6 SEM pictures of hole surfaces in set of experiment #2

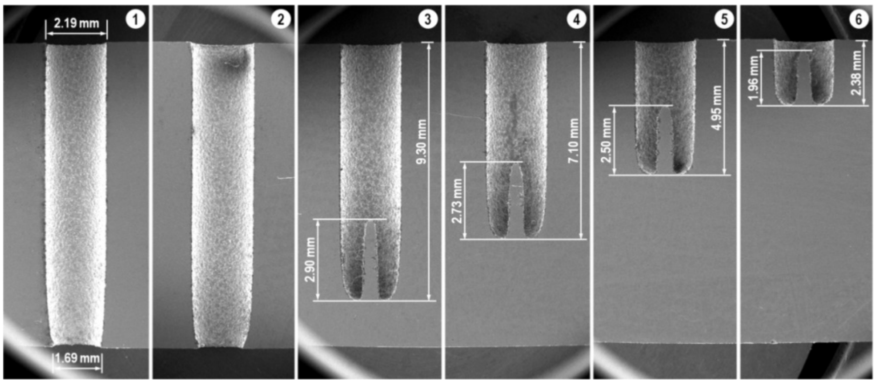

Figure 4.7 SEM pictures of hole surfaces in set of experiment #3

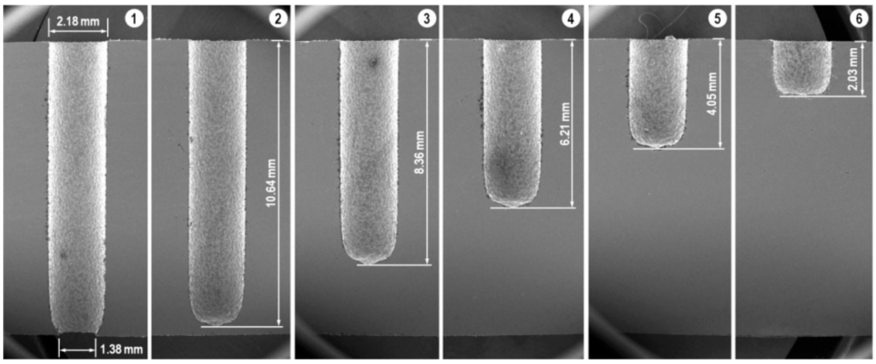

Figure 4.8 SEM pictures of hole surfaces in set of experiment #4

As seen from Fig. 4.5 and 4.7, a spike (core) occurs at the center of blind holes when single-channel electrode was used. On the contrary, no spike is observed at holes drilled by multi-channel electrodes as seen in Fig. 4.6 and 4.8. This is due to the reason that the spark gap is not sufficient to remove the core at the center of drilled hole when using single-channel hollow electrode. Machining takes place only along the side surfaces of electrode whereas no erosion occurs in the vicinity of center region at the bottom side of electrode (Saha & Choudhury, 2009). On the other hand, in case of using a multi-channel electrode, the sparking between workpiece and electrode is uniform at any region of machining. Therefore, no spike or core occurs as illustrated in Fig. 4.9.

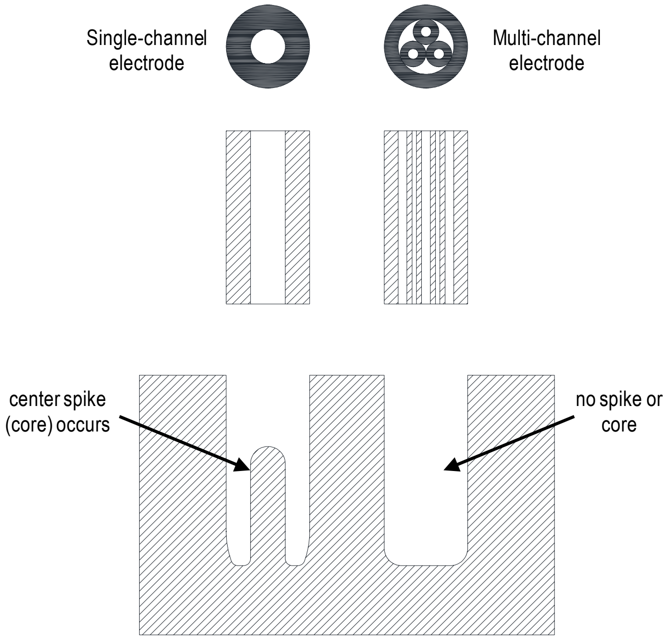

Figure 4.9 Effect of electrode type on geometry of blind holes (Sommer, 2004)

As mentioned in Chapter 3, the depth of blind hole #2 (i.e. 10 mm) is significant as it is very near the bottom end of specimen. After drilling with single-channel electrode, this hole was observed as a through hole as seen from Fig. 4.5 and 4.7. On the other hand, this is not true in case of multi-channel electrode (Fig. 4.6 and 4.8). This is due to flushing effect in single-channel electrode. The dielectric fluid flows through this single channel causing a cavity in the middle of the hole. This cavity propagates until the bottom end of specimen so that the hole becomes a through hole.

Table 4.5 and Fig. 4.10 present expected (planned) versus actual (measured) depths of blind holes. As seen from results, there are deviations from expected values in all hole depths. However, the least deviation is observed in set #4 (i.e. the holes drilled at high-level parameters using multi-channel electrode).

Table 4.5 Expected vs. measured hole depths

Hole No.	Expected Depth (mm)	Measured Depth (mm) Set #1	Dev. (%)	Set #2	Dev. (%)	Set #3	Dev. (%)	Set #4	Dev. (%)
2	10.00	11.00	-10.0	9.98	0.2	11.00	-10.0	10.64	-6.4
3	8.00	6.89	13.9	9.08	-13.5	9.30	-16.3	8.36	-4.5
4	6.00	5.64	6.0	7.07	-17.8	7.10	-18.3	6.21	-3.5
5	4.00	3.84	4.0	4.60	-15.0	4.95	-23.8	4.05	-1.3
6	2.00	1.95	2.5	2.42	-21.0	2.38	-19.0	2.03	-1.5

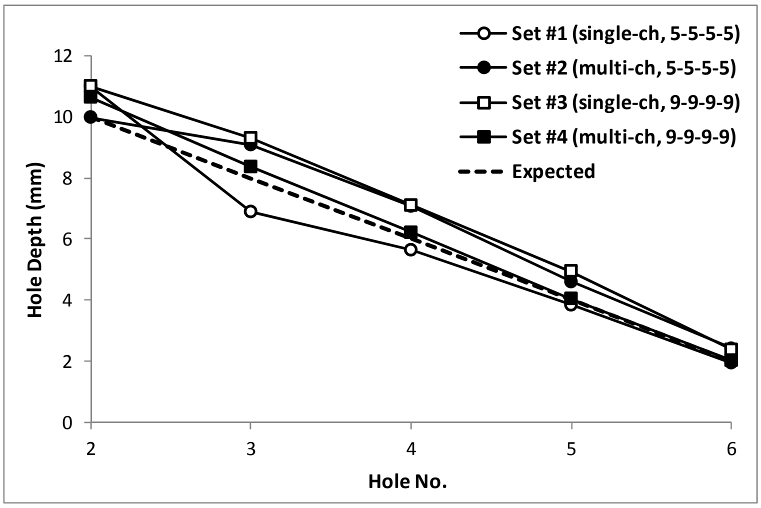

Figure 4.10 Expected vs. measured hole depths

The diameter of through holes at entrance and exit regions was also measured as given in Table 4.6. The entrance diameter of holes is always larger than the electrode diameter. This is called “overcut”, which occurs due to the nature of EDM process. The sparking occurring on the side surfaces of electrode causes erosion on the walls of drilled holes, which results in an enlargement in hole diameter.

Table 4.6 Hole diameters at entrance and exit regions

Set of Exp.	Electrode Dia. (mm)	Hole Entrance Dia. (mm)	Overcut (%)	Hole Exit Dia. (mm)
#1	2.0	2.75	37.5	2.10
#2	2.0	2.67	33.5	1.32
#3	2.0	2.19	9.5	1.69
#4	2.0	2.18	9.0	1.38

As seen from Table 4.6, there is a considerable overcut in holes drilled at low-level parameters (i.e. sets #1 and #2). This may be related to low machining rate when low-level parameters are used. The machining takes place at a slower rate in case of low levels of peak current and capacitance, which results in an excessive amount of machining (i.e. overcut).

On the other hand, the exit diameter of holes (with an exception of through hole in set #1) is smaller than the electrode diameter. This is also a common problem in EDM process, which occurs due to the difficulties with sparking and flushing in the vicinity of exit region. When a small opening (crater) occurs near the bottom end of specimen, sparking is insufficient and flushing is non-uniform due to the irregular shape of this crater. Although the machining continues at this region, there is a slight increase in diameter of hole. This problem can be overcome by placing a very thin piece of material under the bottom end of specimen. The machining will continue to take place, and hence exit region of the hole will have a straight geometry.

4.4 Surface Analyses

Table 4.7 presents the results of roughness measurements performed on through holes in each set of experiment. As mentioned in Chapter 3, the measurements were performed at three different regions of holes (i.e. entrance, middle, and exit regions). The results reveal that use of multi-channel electrode produces hole surfaces with lower roughness (i.e. improved surface quality). This is due to the reason that flushing effect of multi-channel electrode is stronger than that of single-channel electrode. This enables the dielectric fluid to wash particles away from the machining zone during drilling operation. Thereby, the machined surface is free of particles, which results in a smoother surface.

Table 4.7 Surface roughness values at different regions of hole surface

Set of Exp.	**Hole No.**	**Surface Roughness (Ra, µm)**			
		Entrance	***Middle***	***Exit***	***Average***
#1	1 (thru)	12.77	11.06	9.59	11.14
#2	1 (thru)	6.30	5.79	6.98	6.35
#3	1 (thru)	4.14	3.73	3.38	3.75
#4	1 (thru)	2.88	2.82	3.61	3.10

This is more considerable for holes drilled at high-level machining parameters. It is known that peak current and capacitance are the most effective parameters in EDM process on the surface quality of machined surfaces (Okka, 2010). Increase in these parameters leads to decrease in surface roughness values. As seen from Table 4.7, the surfaces of holes drilled at high-level parameters have lower roughness values regardless of electrode type.

In general, the lowest roughness values were observed on the hole surface obtained in set #4 (i.e. the hole drilled at high-level settings using multi-channel electrode). This is due to higher flushing rate of dielectric fluid in multi-channel electrode and higher settings of peak current and capacitance.

Fig. 4.11 shows the graphs of EDX spectroscopy performed on surfaces of through hole in each set of experiment. The chemical composition of each surface is given in Table 4.8. The sampling area was chosen on through holes only, and the size of sampling area was kept identical in order to make a reliable comparison. The results prove that the chemical composition on surface of workpiece material was altered after drilling operation.

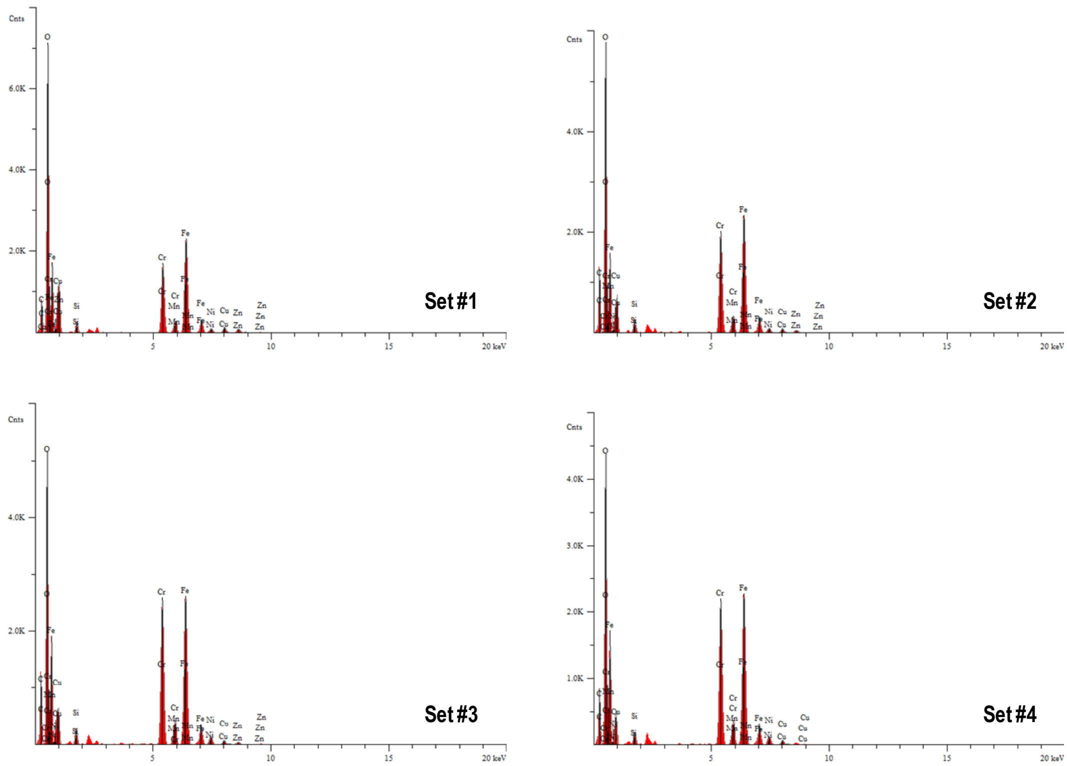

Figure 4.11 EDX graphs of through hole surfaces in all sets

Table 4.8 Chemical composition of through hole surfaces in all sets

Set of Exp.	Weight of Element (%)								
	C	**O**	**Si**	**Cr**	**Mn**	**Fe**	**Ni**	**Cu**	**Zn**
#1	7.574	31.632	1.008	14.450	0.935	32.533	2.578	4.739	4.473
#2	11.539	27.715	1.053	17.403	0.933	33.374	2.318	3.024	2.642
#3	10.949	23.327	0.966	20.931	1.120	35.035	3.224	2.496	1.950
#4	8.710	23.670	0.947	21.711	1.249	37.500	3.489	2.723	---

The effect of certain elements (such as O and Cu+Zn) is of great importance. Considering the existence of O, it is inevitable that burning has occurred on surfaces due to the nature of EDM process. Burning is slightly more dominant in case of machining at low-level parameters.

In addition, the existence of Cu+Zn is also significant as it represents the existence of electrode material (i.e. brass) on the hole surface. This means that the particles from electrode were not washed away, and hence they have stuck onto workpiece material. Therefore, there exists particles of brass on hole surface. In this respect, the worst surface (i.e. the highest amount of Cu+Zn) was obtained in set #1 (i.e. the surface drilled at low-level settings using a single-channel electrode).

4.5 Summary

The experimental results obtained in this study have been presented and discussed in this chapter. The findings with possible reasons have been given. The conclusions drawn from this study are summarised in the next chapter.

CHAPTER 5

CONCLUSIONS AND FUTURE WORKS

5.1 Summary

This study aims an experimental investigation on drilling small holes on IN718 using hollow electrodes. For this purpose, through holes (with diameter of Ø2 mm and depth of 11 mm) were drilled on block specimens made of IN718. For drilling these holes, two levels of process parameters (i.e. low and high-level settings of current, pulse-on and pulse-off time, and capacitance) and two types of electrode (namely single and multi-channel brass electrodes) were used. Based on the drilling time of these through holes, a series of blind holes having different depths were planned and drilled within each set of experiment.

The effect of process parameters and type of electrode was analyzed on performance outputs of process (i.e. MRR and EWR) as well as dimensional accuracy (i.e. geometry and dimensions of holes) and surface characteristics (i.e. SR and EDX analyses) of drilled holes. The results obtained for each set of experiment have been compared, and possible reasons of such findings have been discussed.

5.2 Conclusions

The highlights of this study are given in the following sections based on the aspects of process performance, dimensional properties and surface characteristics.

5.2.1 Process Performance

The performance outputs (MRR and EWR) were obtained based on material losses in workpiece and electrodes with respect to drilling times. The comparisons made in each set of experiment have revealed following conclusions:

- The results of both MRR and EWR for each set of experiment are consistent within 10% of deviation. Hence, the amount of material loss in both workpiece and electrode can be estimated reliably based on drilling time.
- In comparison with single-channel electrode, higher MRR and EWR values were obtained in drilling of holes using multi-channel electrode.
- Regardless of electrode type, MRR and EWR values obtained at high-level parameters are considerable higher than those at low-level parameters.

5.2.2 Dimensional Properties

After drilling, SEM pictures of hole surfaces were taken and dimensional analyses were performed using a dedicated 3D imaging software. Diameter of through holes (at entrance and exit regions) and depth of blind holes in each set of experiment were measured. The remarks in this section are as follows:

- Using single-channel electrode in drilling of blind holes causes a spike (core) occurring at the center of hole. Such problem has been overcome by using multi-channel electrode.
- Regardless of electrode type, there is a considerable overcut (up to %37.5) in diameter of holes drilled at low-level process parameters. This has been reduced (down to %9.5) in case of drilling at high-level parameters.
- Blind holes close to the bottom side of workpiece have become through holes in case of using single-channel electrode. On the other hand, such holes were drilled accurately with a specified hole depth using multi-channel electrode.
- There are deviations between expected (planned) and actual (measured) depths of blind holes in all set of experiments.

5.2.3 Surface Characteristics

Surface roughness measurements were performed on different regions (at entrance, middle, and exit regions) of through hole surfaces. In addition, EDX analyses were done to investigate the modifications in the chemical composition of hole surfaces after drilling operations. The followings are the concluding remarks:

- Under all machining conditions, use of multi-channel electrode results in surfaces with lower roughness as compared with single-channel electrode. This is more significant in case of drilling at high-level process parameters.

- EDX analyses showed that there exists oxygen on all surfaces. This states that burning occurs on hole surface during process, which is slightly more dominant in case of drilling at low-level parameters.
- EDX results also reveal the existence of copper and zinc on hole surfaces, which proves the existence of electrode material (i.e. brass) stuck on surface of holes. This is quite considerable on the surface drilled at low-level parameters using single-channel electrode.

Based on the conclusions, use of multi-channel electrode and high-level parameters are the most appropriate conditions for drilling through and blind holes. Such holes can be drilled effectively and reliably in aspects of lower drilling time, better dimensional accuracy, and improved surface quality.

5.3 Further Studies

This study can be extended in the following aspects:

- Drilling holes on different materials, particularly difficult-to-cut alloys
- Using electrodes with different channel configurations
- Optimizating the combination of machining parameters and electrode type

REFERENCES

Ali, M. Y., Hamad, M. H., Karim, A. I. (2009). Form characterization of microhole produced by microelectrical discharge drilling, *Materials and Manufacturing Processes*, **24**, 683-687.

Bozdana, A. T., Yılmaz, O., Okka, M. A., Filiz, İ. H. (2009). A comparative experimental study on fast hole EDM of Inconel 718 and Ti-6Al-4V, *5th International Conference and Exhibition on Design and Production of Machines and Dies/Molds*, Kuşadası, Turkey.

Ferraris, E., Castiglioni, V., Ceyssens, F., Annoni, M., Lauwers, B., Reynaerts, D. (2013). EDM drilling of ultra-high aspect ratio micro holes with insulated tools, *CIRP Annals - Manufacturing Technology*, **62**, 191-194.

Ho, K. H., Newman, S. T. (2003). State of the art electrical discharge machining (EDM), *International Journal of Machine Tools and Manufacture*, **43**, 1287-1300.

Jahan, M. P., Wong, Y. S., Rahman, M. (2012). Experimental investigations into the influence of major operating parameters during micro-electro discharge drilling of cemented carbide, *Machining Science and Technology*, **16**, 131-156.

Jameson, E. C. (2001). Electrical Discharge Machining. Dearborn, Michigan: Society of Manufacturing Engineers (SME).

Jeong, Y. H., Min, B. K. (2007). Geometry prediction of EDM-drilled holes and tool electrode shapes of micro-EDM process using simulation, *International Journal of Machine Tools and Manufacture*, **47**, 1817-1826.

Jung, J. W., Ko, S. H., Jeong, Y. H., Min, B. K., Lee, S. J. (2007). Estimation of material removal volume of a micro-EDM drilled hole using discharge pulse monitoring, *International Journal of Precision Engineering and Manufacturing*, **8(4)**, 45-49.

Kao, J. Y., Tsao, C. C., Wang, S. S., Hsu, C. Y. (2010). Optimization of the EDM parameters on machining Ti–6Al–4V with multiple quality characteristics, *International Journal of Advanced Manufacturing Technology*, **47**, 395-402.

Kibria, G., Sarkar, B. R., Pradhan, B. B., Bhattacharyya, B. (2010). Comparative study of different dielectrics for micro-EDM performance during microhole machining of Ti-6Al-4V alloy, *International Journal of Advanced Manufacturing Technology*, **48**, 557-570.

Kumar, A., Maheshwari, S., Sharma, C., Beri, N. (2011). Analysis of machining characteristics in additive mixed electric discharge machining of nickel-based super alloy Inconel 718, *Materials and Manufacturing Processes*, **26**, 1011-1018.

Kumar, S., Singh, R., Singh, T. P., Sethi, B. L. (2009). Surface modification by electrical discharge machining: a review, *Journal of Materials Processing Technology*, **209**, 3675-3687.

Kuppan, P., Rajadurai, A., Narayanan, S. (2008). Influence of EDM process parameters in deep hole drilling of Inconel 718, *International Journal of Advanced Manufacturing Technology*, **38**, 74-84.

Lajis, M. A., Radzi, H. C. D. M., Amin, A. K. M. N. (2009). The Implementation of Taguchi method on EDM process of tungsten carbide, *European Journal of Scientific Research*, **26(4)**, 609-617.

Leao, F. N., Pashby, I. R., Cuttell, M., Lord, P. (2005). Optimisation of EDM fast hole drilling through evaluation of dielectric and electrode materials, *Proceedings of 18th International Congress of Mechanical Engineering (COBEM)*, Ouro Preto, MG.

Li, M. S., Chi, G. X., Wang, Z. L., Wang, Y. K., Dai, L. (2009). Micro electrical discharge machining of small hole in TC4 alloy, *Transactions of Nonferrous Metals Society of China*, **19**, 434-439.

Lin, C. L., Lin, J. L., Ko, T. C. (2002). Optimisation of the EDM process based on the orthogonal array with fuzzy logic and grey relational analysis method, *International Journal of Advanced Manufacturing Technology*, **19**, 271-277.

Manikandan, R., Venkatesan, R. (2012). Optimizing the machining parameters of micro-EDM for Inconel 718, *Journal of Applied Sciences*, **12(10)**, 971-977.

MatWeb: Material Property Data. 1996. Available at: http://www.matweb.com. Accessed: 18.07.2013.

Meena, V. K., Azad, M. S. (2012). Grey relational analysis of micro-EDM machining of Ti-6Al-4V alloy, *Materials and Manufacturing Processes*, **27**, 973-977.

Mohan, B., Rajadurai, A., Satyanarayana, K. G. (2004). Electric discharge machining of Al-SiC metal matrix composites using rotary tube electrode, *Journal of Materials Processing Technology*, **153-154**, 978-985.

Murugesan, S., Balamurugan, K. (2012). Optimization by Grey Relational Analysis of EDM parameters in machining Al-15% SiC MMC using multihole electrode, *Journal of Applied Sciences*, **12(10)**, 963-970.

Muthuramalingam, T., Mohan, B. (2013). Influence of discharge current pulse on machinability in electrical discharge machining, *Materials and Manufacturing Processes*, **28**, 375-380.

Okka, M. A. (2011). An experimental investigation of Electrical Discharge Machining (EDM) fast hole drilling of Inconel 718 and Ti-6Al-4V, MSc thesis. University of Gaziantep, Turkey.

Öpöz, T. T., Ekmekci, B., Erden, A. (2009). An experimental study on the geometry of microholes in microelectric discharge machining, *Materials and Manufacturing Processes*, **24**, 1236-1241.

Pham, D. T., Dimov, S. S., Bigot, S., Ivanov, A., Popov, K. (2004). Micro-EDM: Recent developments and research issues, *Journal of Materials Processing Technology*, **149**, 50-57.

Pham, D. T., Ivanov, A., Bigot, S., Popov, K., Dimov, S. (2007). An investigation of tube and rod electrode wear in micro EDM drilling, *International Journal of Advanced Manufacturing Technology*, **33**, 103-109.

Pradhan, B. B., Masanta, M., Sarkar, B. R., Bhattacharyya, B. (2009). Investigation of electro-discharge micro-machining of titanium super alloy, *International Journal of Advanced Manufacturing Technology*, **41**, 1094-1106.

Puranik, M. S., Joshi, S. S. (2008). Analysis of accuracy of high-aspect-ratio holes generated using micro-electric discharge machining drilling, *Proceedings of IMechE - Part B: Journal of Engineering Manufacture*, **222**, 1453-1464.

Rajesha, S., Sharma, A. K., Kumar, P. (2012). On electro discharge machining of Inconel 718 with hollow tool, *Journal of Materials Engineering and Performance*, **21(6)**, 882-891.

Saha, S. K., Choudhury, S. K. (2009). Experimental investigation and empirical modeling of the dry electric discharge machining process, *International Journal of Machine Tools and Manufacture*, **49**, 297-308.

Sameh, H., Okada, A., Uno, Y. (2013). Improving the productivity of electrical discharge machining process by using multi-thin electrodes, *Machining Science and Technology*, **17**, 110-128.

Sommer, C. (2004). Complete EDM Handbook. Advance Publishing (TX).

Srivastava, V., Pandey, P. M. (2012). Performance evaluation of electrical discharge machining (EDM) process using cryogenically cooled electrode, *Materials and Manufacturing Processes*, **27**, 683-688.

Yılmaz, O., Okka, M. A. (2010). Effect of single and multi-channel electrodes application on EDM fast hole drilling performance, *International Journal of Advanced Manufacturing Technology*, **51**, 185-194.

Yu, Z. Y., Rajurkar, K. P., Shen, H. (2002). High aspect ratio and complex shaped blind micro holes by micro EDM, *CIRP Annals - Manufacturing Technology*, **51(1)**, 359-362.