# A Study to Determine the Effects of Wirecut EDM Input Parameters on Material Removal Rate, Surface Roughness and Recast Layer Thickness of NdFeB Magnet.

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# Dedication

To my Beloved Parents,
Without whom none of my success
would have been possible

&

To my Respected Teachers,
Who acted like compass
that activated the magnets of
curiosity, knowledge and wisdom in me

# Declaration

I certified that this research work titled “A Study to Determine the Effects of Wirecut EDM Input Parameters on Material Removal Rate, Surface Roughness and Recast Layer Thickness of NdFeB Magnet” is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledge/referred.

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# **Thesis Abstract (Summary)**

Various techniques employing mechanical, thermal, electrical, chemical, and in some cases a mix of these energies are used in non-conventional machining processes. Wire Electric Discharge Machining (WEDM) is a non-traditional machining technology that removes material by using electricity to generate thermal heat. Every day, the demand for precision in the manufacture of delicate parts grows. Material removal rate, surface finish, and recast thickness are three areas in WEDM that are a focus of research because they are critical in all manufactured parts, especially those made of difficult-to-machine materials such as magnets, tungsten, and ceramics. As a result, this study will concentrate on this topic.

The NdFeB magnet is utilised in this study because it is widely employed in the automobile, defence, aerospace, and hearing devices industries. NdFeB is impossible to machine using traditional production methods. Different sets of machine input settings were used to mill NdFeB magnets on WEDM to see how they affected desired output parameters. In this study, four input parameters, namely voltage, current, pulse-on time, and pulse-off time, are employed in various combinations. The Taguchi method is used to create experimental designs. ANOVA is used for statistical analysis, and the contribution of each input parameter to each output parameter is examined. This made it easier to distinguish between significant and non-significant components. For further mathematical calculations, a regression equation is also established.

The results of the experiments demonstrated that increasing the current and pulse-on duration improves MRR while deteriorating the surface quality and causing a thicker recast layer. Craters appear on the machined surface, and the likelihood of crater formation increases during the WEDM process as the current and pulse-on duration increase. Poor surface smoothness and a thicker recast layer are caused by larger craters on the machined surface. Lowering the EDM machine voltage and reducing the pulse-on time results in a finer surface finish and a smaller recast layer. The pulse on time, current, and voltage have all been found to have a substantial impact on MRR. Recast layer thickness and surface finish. The least influential input parameter in this study is pulse off time.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AJM | Abrasive Jet Machining |
| ANOVA | Analysis of Variance |
| AWJC | Abrasive Water Jet Cutting |
| CNC | Computer Numerical Control |
| DOE | Design of Experiment |
| EB | Electron Beam |
| ECD | Electrochemical De-Burring |
| ECG | Electrochemical Grinding |
| ECM | Electrochemical Machining |
| EDM | Electric Discharge Machining |
| g | Geometrical Accuracy |
| KTDMC | Karachi Tools Dies and Mould Centre |
| $O_V$ | Open Voltage |
| SSNR | Scaled Signal to Noise ratio |
| $S_V$ | Servo Voltage |
| T Off | Pulse OFF time |
| T ON | Pulse ON time |
| $T_p$ | Pulse PEAK time |
| USM | Ultrasonic Machining |
| $V_c$ | Average Cutting speed |
| WEDM | Wire Electric Discharge Machining |
| $W_F$ | Wire Feed |
| WJC | Water Jet Cutting |
| $W_T$ | Wire Tension |

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# Chapter 1

# Introduction to Non Conventional Machining

## 1. Introduction

A group of processes that remove excess material by various techniques involving mechanical, thermal, electrical or chemical energy (or combination of these energies) is defined as non-conventional machining [1-3]. They do not use a sharp cutting tool in conventional sense.

### Classification of Non-Conventional Machining Processes

Nontraditional machining process can broadly be subdivided into four sections:

### Mechanical energy process

Typical form of mechanical process is erosion of work material by a high velocity stream of abrasives or fluid (or both).

### Electrochemical machining process

Electrochemical energy is used to remove the material from workpiece (reverse of electroplating).

### Chemical machining process

Chemical etchants selectively remove material from portions of work part, while other portions are protected by a mask.

### Thermal energy process

Thermal energy usually applied to small portion of work surface causing that portion to be fused and/or vaporized.

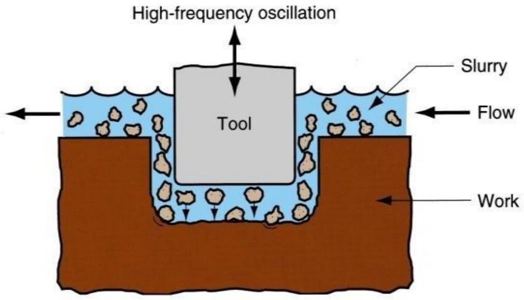
## MECHANICAL ENERGY PROCESS

Few of the important mechanical energy process are appended below:

a. Ultrasonic Machining (USM).
b. Water Jet Cutting (WJC).
c. Abrasive Water Jet Cutting (AWJC).
d. Abrasive Jet Machining (AJM).

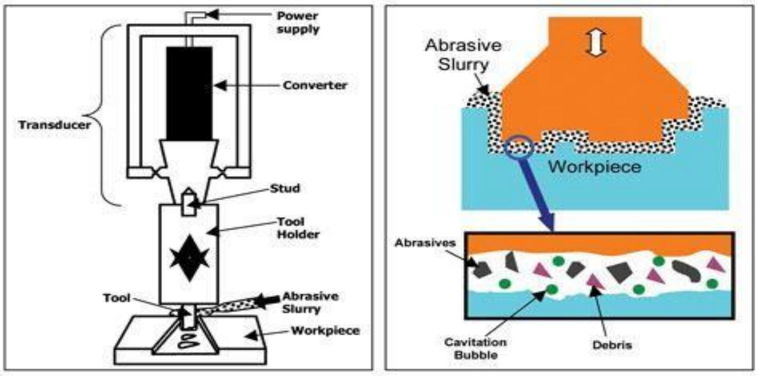
### Ultrasonic machining

In this process abrasives contained in a slurry are driven at high velocity against work by a tool vibrating at low amplitude and high frequency. Oscillation of the tool is perpendicular to work surface. Abrasives accomplish the material removal. In this process tool is fed slowly into the workpiece and shape of tool is formed into the workpiece.



**Schematic of Ultrasonic Machining**

**Figure 1.1**



**Schematic of Ultrasonic Machining**

**Figure 1.2**

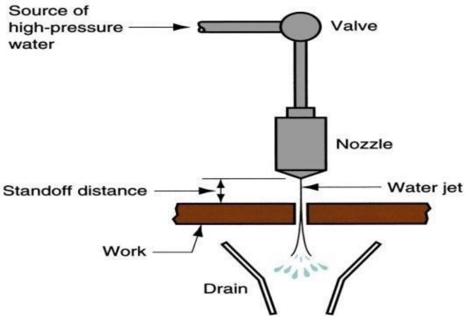
## Applications of ultrasonic machining

Major applications of Ultrasonic Machining are:

a. Hard, brittle work materials such as ceramics, glass, and carbides.
b. Also successful on certain metals such as stainless steel and titanium.
c. Shapes which include non-round holes.
d. Pattern on tool is imparted to a flat work surface i.e. ―Coiningoperations‖.

## Water jet cutting (WJC)

Water jet cutting uses a high pressure, high velocity stream of water which isdirected at work surface for cutting.



**Schematic of Water Jet Cutting**

**Figure 1.3**

## Applications of water jet cutting (WJC)

Water jet cutting is employed to:

a. Cut narrow slits in flat stock such as plastic, textiles, composites, floor tile, carpet, leather and cardboard.
b. Usually automated by CNC or industrial robots to manipulate nozzle along desired trajectory.

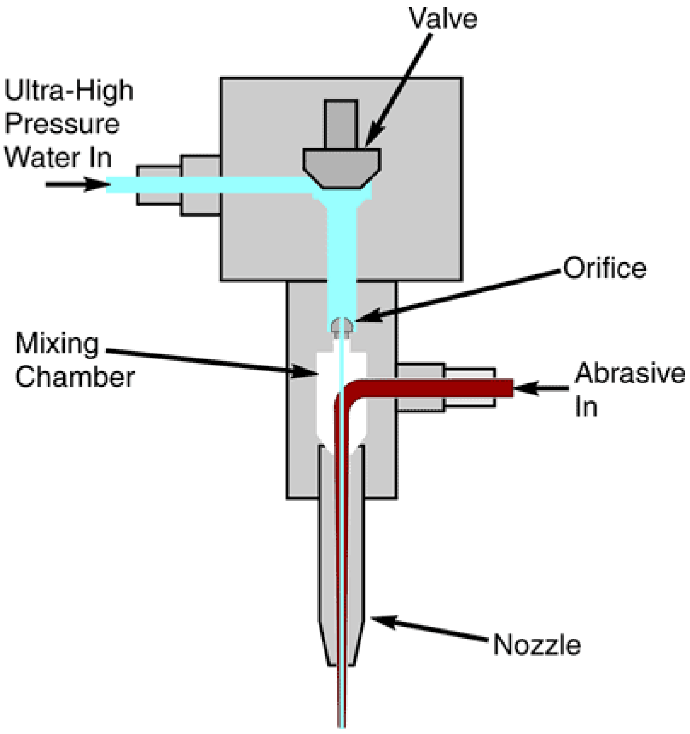
## Advantages of water jet cutting (WJC)

Major advantages of water jet cutting are:

a. No crushing or burning of work surface.
b. Minimum material loss.
c. No environmental pollution.
d. Ease of automation.

## Abrasive water jet cutting (AWJC)

When water jet cutting is used on metals, abrasive particles must be added to jet stream. Abrasives which include aluminum oxide, silicon dioxide, and garnet (asilicate mineral) are added in the water at about 0.25 kg/min (0.5 lb/min) after it exits nozzle. It is usually performed manually by operator who directs the nozzle. AWJC is normally used as a finishing process rather than cutting process.



**Schematic of Abrasive Water Jet Cutting**

**Figure 1.4**

## Applications of abrasive water jet cutting (AWJC)

Applications of abrasive water jet cutting are:

a. De-burring.
b. Trimming.
c. De-flashing.
d. Cleaning.
e. Polishing.

**Abrasive Water Jet Cutting**

**Figure 1.5**

Work materials on which AWJC is employed are thin flat stock of hard, brittle materials (e.g., glass, silicon, mica, ceramics and composites as well).

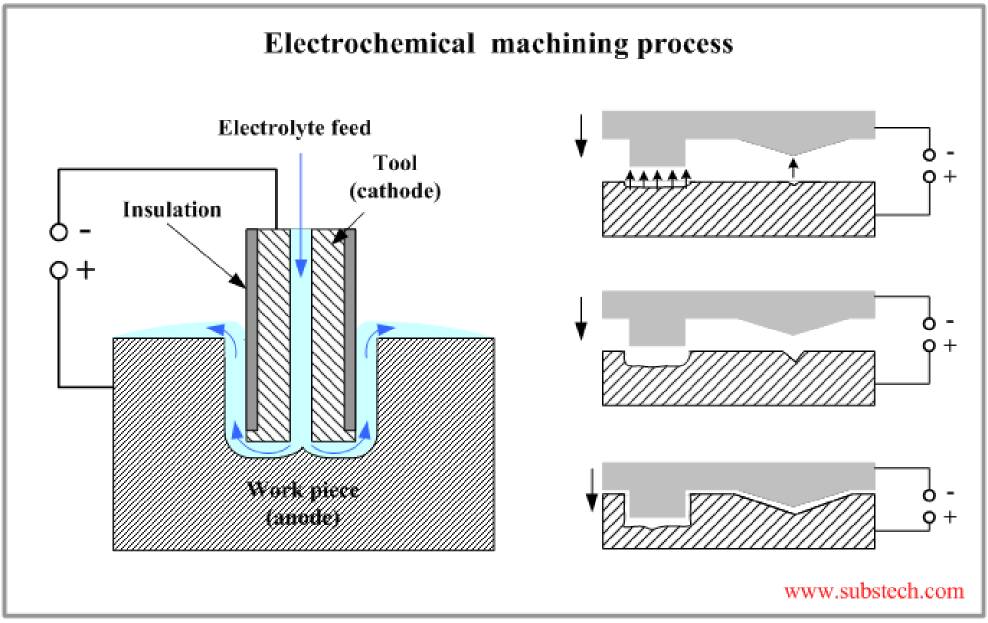
## ELECTROCHEMICAL MACHINING PROCESS

In this process electrical energy is used in combination with chemical reactions to remove material. This process can be explained as a reverse of electroplating. It is important that the work material must be a conductor. This process can be further subdivided into three processes:

a. Electrochemical Machining (ECM).

b. Electrochemical Deburring (ECD).

c. Electrochemical Grinding (ECG).



**Schematic of Electrochemical Machining Process**

**Figure 1.6**

## Electrochemical machining (ECM)

Material is de-plated from anode workpiece (positive pole) and transported to a cathode tool (negative pole) in an electrolyte bath. Electrolyte flows rapidly between two poles to carry off de-plated material so it does not plate onto the tool. Electrode materials usually used are Copper, brass or stainless steel. Tool has an inverse shape of the workpiece. In ECM, material removal by anodic dissolution using electrode (tool) is in close proximity to work but separated by a rapidly flowing electrolyte.

## Electrochemical de-burring (ECD)

This process is an adaptation of ECM to remove burrs or sharp corners on holes in metal parts produced by conventional through-hole drilling.

## Electrochemical grinding (ECG)

This is a special form of ECM in which grinding wheel with conductive bond material augments anodic dissolution of metal part surface.

## Applications and advantages of ECG

Applications of ECG include:

a. Sharpening of cemented carbide tools.

b. Grinding of surgical needles, thin wall tubes and fragile parts.

Advantages of ECG are:

a. De-plating responsible for 95% of metal removal.

b. As machining is mostly by electrochemical action, grinding wheel lastsmuch longer.

## CHEMICAL MACHINING PROCESS

In chemical machining process, material is removed through contact with a strong chemical etchant. Chemical machining process is usually conducted in following steps:

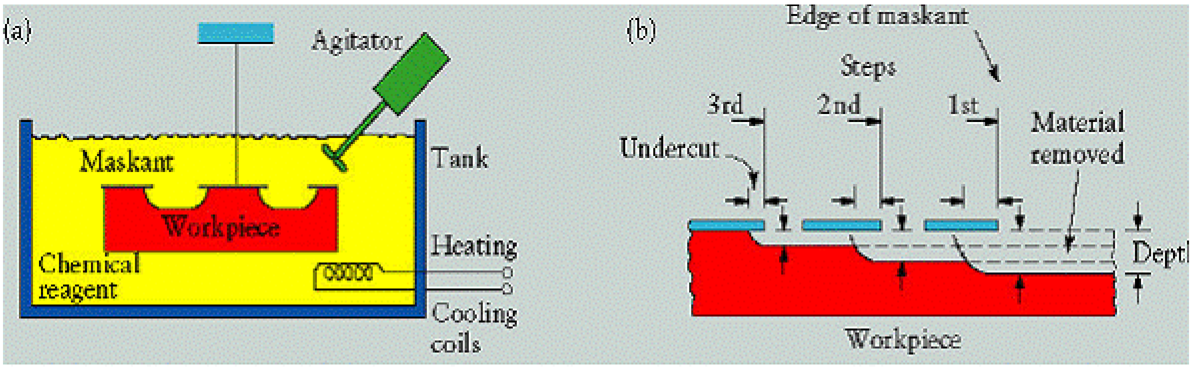
a. Cleaning - to insure uniform etching.

b. Masking - a maskant (resist, chemically resistant to etchant) is appliedto portions of work surface not to be etched.

c. Etching - part is immersed in etchant which chemically attacks those portions of work surface that are not masked.

d. De-masking - maskant is removed.

There are four different sub processes in chemical machining processes, however,all processes, utilize the same mechanism for material removal.



**Schematic of Chemical Machining Process**

**Figure 1.7**

### Chemical milling

In this process, different areas of workpiece are selectively attacked with chemical reagents. Shallow cavities can be produced on plates, sheets and forgings and extrusions.

### Chemical blanking

Chemical blanking is similar to chemical milling. However, the difference is that material is removed by chemical dissolution rather than by shearing. Area of application is burr free etching of printed circuit boards, decorative panels, thin sheet metal stampings as well as production of small and complex shapes.

### Chemical engraving

Chemical engraving is also similar to chemical milling but it is used for engraving letters and name plates.

### Photochemical machining

This process is effective in blanking fragile workpieces and materials. Material is removed using photographic techniques. Applications are electric motor lamination, flat springs, masks for color television, printed circuit cards etc.

## THERMAL ENERGY PROCESSES

Salient of thermal energy nontraditional machining process are as follows:

a. Very high local temperatures.
b. Material is removed by fusion or vaporization.
c. Physical and metallurgical damage to new work surface.
d. In some cases, resulting finish is so poor that subsequent processing is required.

## Types of thermal energy process

Different types of thermal nontraditional process are:

a. Electron beam machining.
b. Laser beam machining.
c. Plasma arc machining.
d. Conventional thermal cutting processes.
e. Electric Discharge Processes.

    (1) Electric discharge machining (Die Sinking).
    (2) Wire Electrical Discharge machining (WEDM).

## Electron beam machining operation

EB gun accelerates a continuous stream of electrons to about 75% of light speed. Beam is focused through electromagnetic lens drastically reducing the diameter. On impinging work surface, kinetic energy of electrons is converted to thermal energy of extremely high density which melts or vaporizes material in a small localized area. It uses high velocity stream of electrons focused on workpiece surface to remove material by melting and vaporization. The main areas of application are:

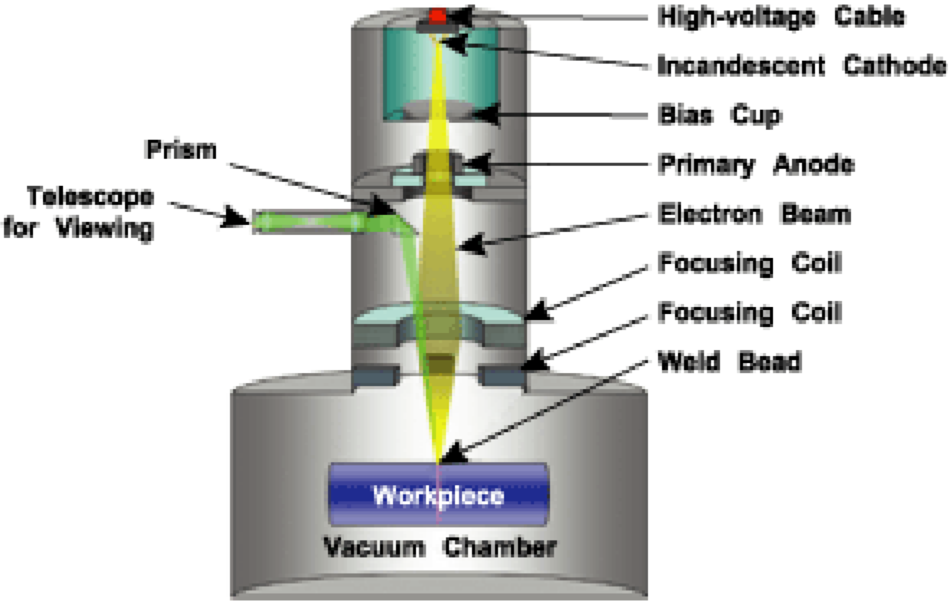
a. Works on any material.
b. Ideal for micromachining.

c. Drilling small diameter holes - down to 0.05 mm (0.002 in).

d. Cutting slots only about 0.025 mm (0.001 in.) wide.

e. Drilling holes with very high depth to diameter ratios.

f. Ratios greater than 100:1.

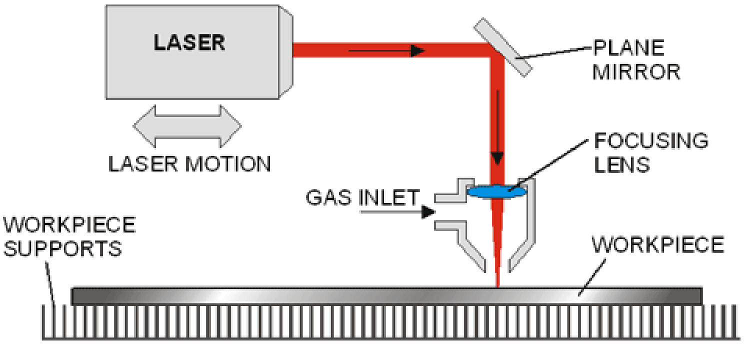


Schematic of Electron Beam Machining Operation

Figure 1.8

**Laser beam machining**

It uses the light energy from a laser to remove material by vaporization and ablation.



Schematic of Laser Beam Machining

Figure 1.9

Laser Beam Machining applications are:

a. Drilling, slitting, slotting, scribing, and marking operations.

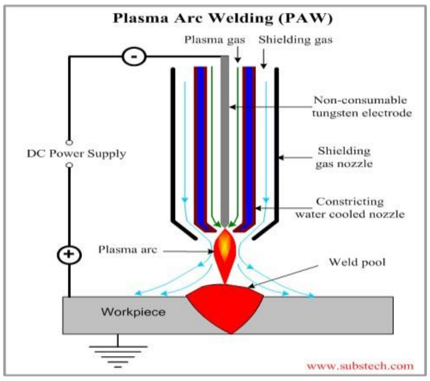
b. Drilling small diameter holes - down to 0.025 mm (0.001 in).

c. Generally used on thin stock.

d. Work materials: metals with high hardness and strength, soft metals, ceramics, glass and glass epoxy, plastics, rubber, cloth, and wood.

## Plasma arc cutting

In plasma arc cutting (Plasma is a superheated, electrically ionized gas with temperatures about 10,000°C to 14,000°C (18,000°F to 25,000°F). Plasma arc generated between electrode in torch and anode workpiece. Plasma flows through water cooled nozzle that constricts and directs stream to desired location. It uses plasma stream operating at very high temperatures to cut metal by melting.



**Schematic of Plasma Arc Cutting**

**Figure 1.10**

## Electric discharge processes

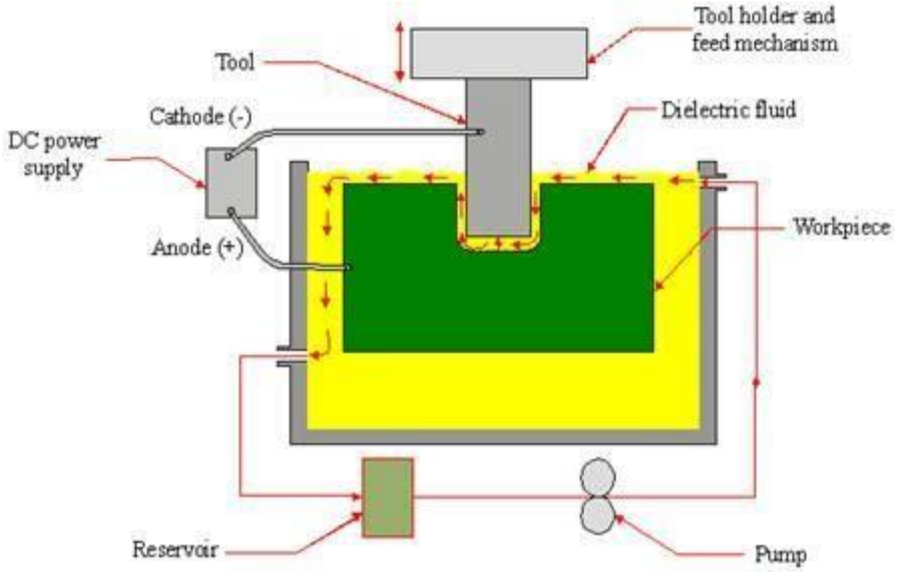
In electric discharge process, metal is removed by a series of discrete electrical discharges (sparks) causing localized temperatures high enough to melt or vaporize the metal. It is primarily used only on electrically conducting work materials. The two main processes are:

a. Electric Discharge Machining (Die Sinking).

b. Wire Electric Discharge machining (WEDM).

## Electric discharge machining operation (EDM)

It is one of the most widely used nontraditional processes. The shape of finished work surface produced is same as the shape of electrode tool. In this process, sparks occur across a small gap between tool and work. It requires a dielectric fluid, which creates a path for each discharge as fluid becomes ionized in the gap.



**Schematic of Electric Discharge Machining**

**Figure 1.11**

Work material considerations in EDM are:

a. Work materials must be electrically conducting. However, with newresearch, conductive material is coated over ceramics and can also be cut.

b. Hardness and strength of work material are not driving factors in EDM.

c. Material removal rate depends on melting point of work material.

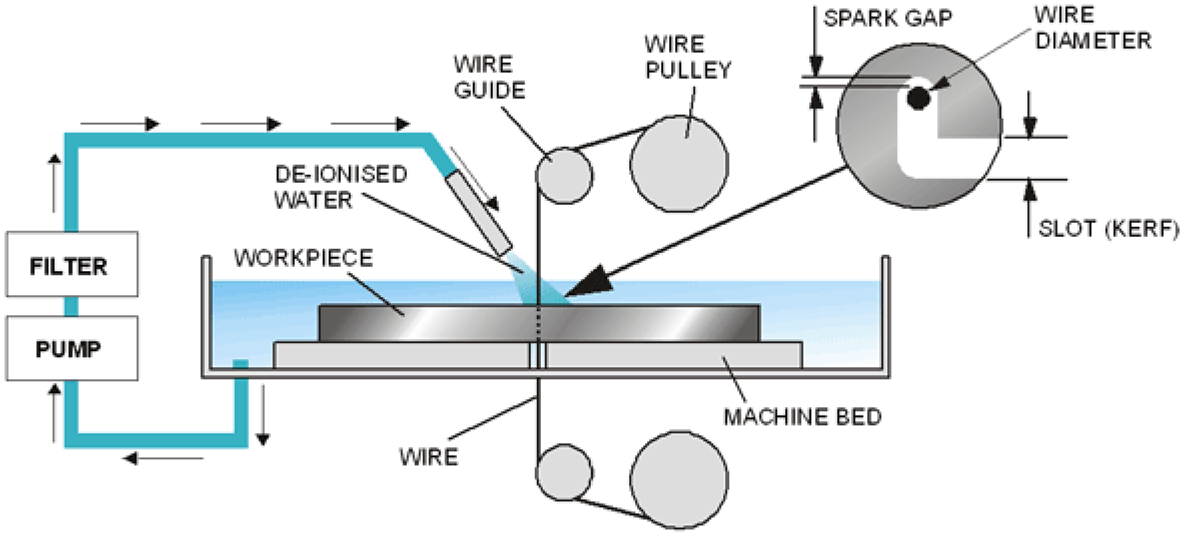
Areas of application of EDM are:

a. Molds for plastic injection molding, extrusion dies, wire drawing dies, forging and heading dies and sheet metal stamping dies.

b. Delicate parts not rigid enough to withstand conventional cutting forces, hole drilling where hole axis is at an acute angle to surface and machining of hard metals.

## Wire electric discharge machining

Work is fed slowly past wire along desired cutting path, like a band saw operation. CNC is used for motion control of workpiece. Dielectric is required, using nozzles directed at tool work interface. Special form of WEDM uses small diameter wire as electrode to cut a narrow kerf in work. WEDM process is also explained in detail as a separate topic in the subsequent paragraphs.



**Schematic of Wire Electric Discharge Machining**

**Figure 1.12**

## BASICS OF WIRE ELECTRIC DISCHARGE MACHINING

WEDM can best be understood by drawing its analogy from a band saw [4]. A band saw uses a motor to drive a blade; the blade has sharp teeth that can chip off metal using force and friction. There are three major variables in using a band saw:

a. Size of teeth (teeth per inch).
b. Speed of blade (meters per minute).
c. Feed of work (Kg of force).

Band saw blade has teeth and under mentioned are results depending upon the cutting speed.

| SLOW | CUTTING SPEED | FAST |
|---|---|---|
| Smoother | SURFACE FINISH | Rough |
| Small | CHIP SIZE | Large |
| 24 teeth/inch | CUTTER INTENSITY | 2 teeth/inch |
| >.020 inch | WIDTH OF CUT | >.080 inch |

When WEDM is compared with band saw, WEDM has ―Teeth‖ that are sparks. Under mentioned are the results depending upon the frequency of sparks:

| SLOW | CUTTING SPEED | FAST |
|---|---|---|
| Micron | SURFACE FINISH | Rough |
| Small | CHIP SIZE | Large |
| approx 5 amps | SPARK INTENSITY | approx 600 amps |
| .0002 inch | LENGTH OF SPARK | .003 inch |

**Spark energy**

Spark energy determines the size of ―chip‖ that is removed from the workpiece. Higher settings would ensure faster cutting speed, rough surface finish and larger chips. Lower settings provide slower cutting speeds, smoother surface finish and smaller chips. For best results lower spark energy settings with higher spark cycle settings will reduce the chip size and give better flushing of the cutting chips. This could lead to faster cutting.

Band saw blade speed is variable and so is the Wire EDM spark cycle. Sparking rates are expressed in the terms ―Cycle‖, ―Frequency‖ and ―On — Off Time‖. All of these terms give sparks (chips) per second**.**

**Spark cycle**

Spark cycle is microseconds between sparks. (ON time + OFF time). Selecting a spark microsecond cycle time determines the following:

a. Thicker parts, smaller cycle number (lot of room to fit in a lot of sparks).
b. Thinner parts, larger cycle number (no room to fit in a lot of sparks).
c. Poor flushing conditions, larger number (less chips to flush away).

Spark cycle can be controlled by following methods:

a. Automatic selection of standard number from technology tables.
b. Manual override of settings.
c. Change of settings in program.
d. Automatic changing of cycle using T-Auto control (changes cycle as machine sees the change of part thickness).

If flushing conditions are poor, it is recommended to use a larger spark cycle, which makes fewer chips per minute.

### Gap or servo voltage

Band saw uses feed of workpiece for example 10 kg feed or 50 Kg feed. Wire EDM also uses feed of workpiece i.e. 80 volt gap or 30 volt gap. Gap is defined as the electrical voltage between cutting wire and the workpiece which can be defined as a physical distance. Wire EDM machines allow to set traveling speed in terms of mm/min, cm/hour or with adaptive controls in terms of gap voltage.

### Feed rate controls

The feed rate determines how fast you cut your workpiece. Feed Rate Settings can be conducted by utilizing one of the following methods:

a. Manual input.
b. Automatic input from technology tables.
c. Automatic settings based on target gap voltage.

### Removing the chips

Band saw blade pulls the chips we make through the cut. They are disposed under the work table. Wire EDM does not have a blade to pull the chips through the cut. Wire EDM uses high pressure flushing with dielectric water to wash away the chips. It is careful to place the high pressure flushing nozzle close to the work to be successful in cutting your work. Dielectric water at up to 300 psi comes out of the nozzles to surround the cutting wire and flush away the chips.

The top and bottom nozzles use up to 300 psi of flushing pressure to quickly move the chips out of the cutting area. The dielectric water and chips meet the middle of the cut where the chips move around the wire, and out the path that was already cut. This gives you a darkened area in the middle of your part. If the dark area is aboveor below the centerline, it means the top and bottom nozzles are not balanced.

## Spark dynamics in rough cut

Spark dynamics in a WEDM is an important phenomenon and need to be clearly defined:

a. When the wire is close enough to the part, a spark can form and jumpfrom the wire.
b. The spark hits the workpiece.
c. The spark is very hot and it melts a small section of the workpiece anda small section of the cutting wire.
d. The spark finishes and the melted sections of the workpiece and wire become cooled by the dielectric water. Two chips are formed by each spark.
e. This process is repeated based on the spark cycle up to 250,000 timesa second i.e. one spark at a time.
f. As a result, the cutting wire is damaged so much that further tension cannot be applied on the wire as it will break. Low wire tension causes wire drag and lower accuracy.

## Rough and skim cuts (First cut and second cut)

By cutting the part twice, workpiece accuracy is improved. First cut is called a rough cut. Rough cut removes the entire diameter of the cutting wire plus the spark gap. The second cut is called a skim cut, because it only removes a small amount of material.

The rough cut has to remove a lot of metal, so the highest flushing pressure possible to remove the chips is applied. The skim cut removes only a small amount ofmaterial and a lower flushing pressure can be used to remove a smaller amount of chips. The low flushing pressure does not deflect the wire and allows better part accuracy.

The large sparks used in the rough cut along with the large cutting area gives a weak cutting wire. Rough cuts require low wire tensions. The smaller sparks used in the skim cut along with a small cutting area gives a strong cutting wire. Skim cuts canuse highest wire tensions for better tolerance.

**Wire center drags**

It is like pulling a rope from two ends. This is caused by the laws-of-physics. Salient features in this regard are appended below:

| WIRE STAYS STRAIGHT WHEN | WIRE DRAGS BEHIND WHEN |
|---|---|
| Smaller sparks | Larger sparks |
| High wire tension | Low wire tension |
| Low flushing pressure | High flushing pressure |
| Shorter distance between nozzles | Longer distance between nozzles |
| Larger gap voltage | Smaller gap voltage |

**Flushing near edge**

Flushing water bounces off the part edge instead of injecting into the spark cutting zone. If flushing pressure is too high, this area will be dry. When a spark dischargesin this dry area, the wire will weld and break. The dielectric flushing water is required to cool the wire and flush away chips. When the flushing pressure is too high, water bounces off the part corner and leaves part of the workpiece dry. When a spark occurs without dielectric, wire is broken. A flat surface gives you tight nozzle contact for the best chip flushing. When the work piece is not flat on top and/or bottom, the ability to flush out chips is poor. The only way to cut this part is to slow down and cut at efficiency of the flushing conditions.

# CHAPTER 2
# LITERATURE REVIEW

## 2. INTRODUCTION

WEDM is a non-conventional process which has established itself over a period of time [5]. It is used to manufacture parts which have complex silhouette and contours. WEDM is considered as an offshoot of conventional EDM process in which an electrode is used to commence the process with the help of a spark.

The difference between WEDM and EDM is that, in WEDM process an electrode is used. The electrode is a wire which is continuously moving between the two wire spools. This wire is thin and manufactured from different materials such as copper, brass and tungsten. The diameter could vary between 0.5 - 03 mm. This small diameter provides the capability of machining small corner radii. The two spools in addition to holding the wire are also a means of providing the requisite tension to the wire. Wire is held in tension using a mechanical device because tension in the wire ensures a reduction in probability of manufacturing out of tolerance piece.

During the machining procedure, material is wrinkled to the fore of wire. Workpiece and the wire do not get in touch with each other and therefore, there are no mechanical stresses experienced during WEDM process. Due to aforementioned reasons, WEDM method has the capability to remove material from workpiece which have high strength and are temperature resistive. One of the applications of WEDM is that due to this method when material is removed from heat treated steels, there is elimination of geometrical change. WEDM made its debut in the late 1960s. The basis reason for transformation of WEDM from EDM was the need to find an alternative of the machined electrode which is used by the EDM.

It was in 1974, that the optical line follower method was used to manage manufacturing of parts shape without the intervention of machinist [6]. However, by 1975, WEDM popularity increased sharply in the industry. The main reason for gaining popularity was that by this time the industry had developed a better understanding of WEDM process [7].

WEDM process received a major breakthrough when WEDM was integrated with the CNC machines. Integration of the two versatile processes brought a major revolution in the machining industry. The first major utility of WEDM was machining of through holes in parts which was possible due to wire electrode. Areas of application of WEDM include fabrication of form tools, parts used in the aeronautical industry, medical field, fixtures gauges, stamping, extrusion tools and dies.

## WEDM PROCESS AND ITS VARIATIONS

WEDM is an offshoot of EDM and therefore both have many similarities including the erosion effect. In WEDM, number of sparks occurs between the wire and workpiece. These sparks erode the material, dielectric fluid which is constantly injected into the machining region is present between the wire and workpiece [8].

Electrical energy is used by WEDM to generate a conduit of plasma amid anode and cathode [9]. This energy is converted into thermal energy [10]. Temperature near the workpiece are about 8000-12000$^{o}$C [11]. Temperature can reach as high as 20,000$^{o}$C [12]. These high temperatures produces great amount of heat which melts the material on surface of anode and cathode. When the power supply is switchedoff, the plasma channel breaks [13]. This results in an abrupt decrease of temperature, which allows the flowing dielectric fluid to wash out liquefied elements of workpiece from anode and cathode as an infinitesimal fragments.

All functional characteristics of EDM process and WEDM process are not identical. WEDM uses a thin wire as an electrode while EDM uses a pre-shaped electrode.The dielectric fluids used in both processes are also different. In WEDM, deionised water is used due to low viscosity and rapid cooling rate while in EDM hydrocarbon, oil is used in the sparking zone as it reduces the electrode wear.

Cutting rate achieved for WEDM is 300 mm$^2$/min when the thickness of workpiece is 50 mm for tool steel ($D_2$). In case of 150 mm thick aluminum workpiece, cutting rate up to 7500 mm2/min can also be achieved. Surface quality which can be achieved by WEDM is 0.04-0.25 µRa.

## WEDM APPLICATIONS

WEDM has number of avenues for its application. Salient avenues are explained in the ensuing paragraphs.

### Modern tooling application

Number of materials which are selected as modern tools are machined by WEDM. Numerous researchers have conducted research on the machining performance of WEDM in the field of cutting silicon and removing material from compacting dies manufactured by sintered carbide [14-15].

Comparisons are also conducted between WEDM and laser cutting process for NdFeB and soft magnetic material used in small sized system [16]. The findings were that WEDM has a better dimensional accuracy and surface finish. The only demerit was WEDM‘s slow cutting speed.

### Advanced ceramic materials

Common methodology to machine advanced ceramics is lapping, grinding and machining by diamond [17]. However, WEDM has developed as one of the most promising substitute. One of the requirements for EDM or WEDM operation to undertake is that the material should be electrically conductive. However, both EDM and WEDM have conducted machining on non conducting materials by making a coating of conductive particles on surface of workpiece. Similar methodology has also been adopted for insulating ceramic materials such as $ZnO_2$ and $Al_2O_3$ whereas both these material are also not good electrical conductors [18].

### Modern composite materials

In modern composite materials, number of different material removal processes is used. Among these, many available options, WEDM is also considered to be inexpensive and efficient method. In modern composite materials, numerous studies have been carried out for MMC, reinforced liquid crystal polymers and carbon fibers to make a comparison between WEDM and laser cutting [19-20]. Results of these studies had indicated that WEDM is a superior form of machining, when it comes to cutting edge quality, process parameter control and damages that take place on the surface. The area where laser cutting outmaneuvers

WEDM is material removal rate for all composite materials which were tested.

## MAJOR AREAS OF WEDM RESEARCH

Research in numerous areas pertaining to WEDM has been conducted. These areas can be bifurcated into two portions. First area comes under the heading of WEDM process optimization while the second area is WEDM process monitoring and control.

### WEDM process optimization

In the contemporary world, most efficient machining strategy is controlled by finding the different factors which affect the WEDM and thereafter, identifying the best machining condition.

### Process parameter design

In order to determine the optimal machining performance, determination of the different process parameters is important as same play an important role. Few of the important WEDM characteristics against which its performance is measured are cutting rate, material removal rate and surface finish. In the ensuing paragraphssame are briefly explained.

### Factors affecting performance measure

WEDM is not a simple machining process and neither controlled by a singular process parameter. Various process parameters are simultaneously affecting the WEDM and any slight change in one parameter affect the overall performance related to roughness and cutting rate significantly [21].

Suziki et al [22] had studied in past that reduction in discharge energy yields a better surface roughness. Luo [23] proved that the machining rate could be increased provided energy is increased and wire is also not broken. Several researchers [24] have also studied the relationship between performance measures, cost, machining accuracy and wire tool performance. It has also been proved that the parameter provided in the manufactures handbook are only for common grade steel while setting for more advanced materials has to be achieved by experimentation [25].

### Effect of process parameters on cutting rate

In order to investigate the significant factor and its relationship with other factor, various types of tools have been used to find a relationship. Konda et al [26] conducted study and distributed the factor into five classes. The five different classes are component geometry, machine characteristics, workpiece material, dielectric flied and adjustable machining parameters. Furthermore, he used D.O.E methodology for his experiments and validated his results using the signal to noise ratio technique.

### Effect of machining parameters on material removal rate

Scott et al [27] developed a factorial design and undertook number of experiments to find out the optimum combination for WEDM. As per finding, the factors which had the predominant effect are pulse frequency, pulse duration and discharge current while dielectric flow rate, wire speed and wire tension have the least effect on material removal rate and surface finish.

### Effect of process parameters on surface finish

Surface finish is one of the important areas of study in WEDM and number of researchers have exclusively studied the effect of various parameters on surface finish in WEDM.

Gokler and Ozanozgu [28] conducted research to find out the desired cutting and offset parameter to find the desired surface roughness while keeping the dielectric flushing and wire speed constant.

Tosun et al [29] also conducted the research for finding out an optimum combination for achieving good surface roughness. As per finding, an increase in three factors i.e.wires speed, pulse duration and open circuit voltage increases the surface roughness while an increase in dielectric fluid pressure decreases surfaceroughness.

### Process modeling

Mathematical models have also been developed to find a relationship between process variables and performance of the process. Spedding and Wan [30] formulated a mathematical model to forecast three process parameters i.e. cutting rate, surface finish and surface waviness with quite a large number of input factors and different levels. Han et al [31] formulated a simulation system which precisely imitates the working of WEDM.

## WEDM PROCESS MONITORING AND CONTROL

In WEDM, control systems are vital for monitoring and control of the process. In the ensuing paragraphs, important features of control systems are discussed.

### Fuzzy control systems

Kinoshita et al [32] examined the effect of four factors i.e. electrical parameters, winding speed, wire tension and wire feed rate on the condition of distance between the wire and workpiece when there is disturbance in the system due to some unexpected conditions. As a result of this study, number of algorithms were developed which can be used for developing controls for EDM and WEDM.

### Wire inaccuracy adaptive control system

One of the most problematic issues of WEDM is the breakage of wire. Various studies have been conducted in the past to find a solution and to formulate an online method which could identify the abnormal machining characteristic and stop the breaking of wire.

### Wire breakages

Kinoshita et al [33] has identified that a sharp rise is observed in the pulse frequency.This rise occurs for 5-40 ms and after that the wire breaks. In order to resolve this, a monitoring and control system was formulated, which can control the pulse generator and servo system and switches it off. However, this arrangement does have negative effects on the machining effectiveness.

Number of researchers [34-35] have concluded that the breakage of wire is due to concentration of discharge of electricity at a singular point. This concentration of temperature at a single point results in an increased localized temperature which results in breakage of wire.

### Wire lag and wire vibration

Wire lag and wire vibration are the two phenomena due to which the wire does not move on the programmed path. This failure results in geometrical inaccuracies of the parts manufactured by WEDM.

D.F. Dauw et al [36-37] has indicated that forces which act on the wire are mechanical forces due to gas bubbles produced during the erosion mechanism, hydraulic forces present due to flushing medium, electro dynamic forces and electrostatic forces which act on the wire due to spark generation. Static deflection in the shape of lag effect has been studied in detail by a number of researchers.

### Self tuning adaptive control systems

During the recent years, WEDM research has led to formulation of strategies which dictate the variation of power while machining workpiece of varying density. Research in this field has been conducted as it has been concluded that a change in thickness profile of workpiece is a cause of breaking the wire [33].

## RESEARCH ON WIRE LAG AND ITS EFFECT IN WEDM

EDM process takes places under a dielectric medium with a voltage drop which is typically about 20 volt [38]. Wire electrical discharge machining (WEDM) works on the same methodology, only major difference between EDM and WEDM is that in WEDM the electrode is a conducting wire. Wire electrical discharge machining (WEDM) has many applications but is primarily used for contour cutting. In order to have good contour cutting, the item to be machined is moved in horizontal plane.The movement in horizontal plane is CNC controlled and is a relative motion between electrode (wire) and workpiece. CNC control is primarily to achieve higher accuracy.The electrical wire which acts as electrode is perishable and is, therefore, continuously fed in order to ensure a constant diameter.

In present times, requirement from WEDM is to improve dimensional accuracy despite the fact that it is a process which has a higher accuracy index than other contemporary process which are being presently used [39]. The major determinate which affects the accuracy in WEDM is wire lag [40]. This wire lag is due to various forces which act on the wire and bend it. Although the forces which act on wire are minute but the wire has a big slenderness ratio, because it is quite long and has a very small diameter.

### Description of wire lag

In order to determine the accuracy, two types of studies need to be conducted simultaneously i.e. vibration and static deflection. Lots of studies have been conducted on wire vibration but little research is done on static deflection of wire [41- 43].

Wire lag in WEDM is due to host of reasons. One of the reasons is increase in the cutting speed i.e. when cutting speed is increased, the wire lag also increases and with decrease in speed wire lag also decreases. However, the effects of wire lag come into play when a change in the direction of wire takes place. The analogy that can be drawn to understand these phenomena is that of a car when it turns. Thefront wheel and rear wheel does not travel in same path. This effect is also termedas the back wheel effect [44]. In case of WEDM, wire guide is like front wheel while electrode deflected position is back wheel.

It is pertinent to mention that although position of the wire is controlled by wire guides, however, actual cutting takes places at a certain distance behind the wire guides. Due to above stated reason, it is not possible to have an exact corner; rather what is achieved is a rounded corner.

Study has been conducted both experimental and mathematical on the subject and only variable having direct relationship with the corner error identified is wire speed.If the wire speed is more, a profound corner error is obvious; however, at slow speeds cover error is not appreciable. However, so far very little is known about the combined effects of variables on corner error.

### Effect of wire lag

There is no mathematical model for a given entering speed which can be utilized to determine the corner error. WEDM is in use since 1969 and speed of the cutting process increases twice every four year. However, it is not possible to accrue benefits from this increase in speed due to restrictions associated with wire lag. Although size of error may be as small as few hundred microns, however, it is not acceptable in many places which require extreme precision.

## USING WEDM FOR IMPROVED CORNER CUTTING ACCURACY OF THIN PARTS

### Geometrical inaccuracies

O. Dodun et al [45] conducted research for improving cutting accuracy of thin parts. WEDM is a process which is used for achieving straight surfaces by using an electrode which is a thin wire traveling as per designed program. Wire (electrode) is attached between two points at a certain distance. Main credential of this process is that material removal rate does not depend upon material hardness. At instances, WEDM is the only available means for removal of material in a suitable time frame in a cost-effective manner for high strength modern materials which are also resistiveto temperature [46-48].

Gather U [49] has indicated that geometrical accuracy is an important aspect to be monitored in this process. It is defined as the deviation between the manufactured part and the limitation imposed on design of the manufactured part.

There are various causes of geometrical inaccuracy [45]. However, dominant reason is force implied on the wire. It is pertinent to mention that the efficiency and accuracy of the machined parts is not only dependent upon vibration of the electrode (wire), deflection and risk of rupture but also on the machining parameter which governs the machining processes. Few of the machining parameters which affect the efficiency and accuracy of the machined part is potential drop, working liquid viscosity and pulse voltage.

The forces which are implied on the wire are pulling force that keep the wire straight, the forces due to flushing of liquid, (hydraulic force) and the two forces produced by the spark generation i.e. the electromagnetic and electrostatic forces.

Geometrical inaccuracy in case of corner error is mainly due to following four factors:

**Wire deflection**

Wire is being held at a distance by two clamps with a certain force. However, it is not possible to apply unlimited force because excessive force would break the wire (electrode) and the process will stop. When the machining operation commence, forces acting on the wire tends to pull it backward. However, during this process the wire tends to move it in backward direction. As per design process, tensile forces are applied to compensate the force which tends to pull the wire in the backward direction. However, unlimited tensile force cannot be applied as same will break the wire.

**Changes in direction of wire motion**

The movement in WEDM is not in a singular direction, it changes its motion as per machining requirement. Whenever there is a change of direction, the deflection in the wire also increases. The change in deflection is primarily due to the reason that loading pattern on the wire changes. The loading pattern changes primarily as equilibrium of the machining process is changed as per changes in the direction. The major factors that changes the equilibrium is forces in the flushing system and material removal process.

### Intensification in electric field

During the machining process, there is an intensification of electric field near the corner crest. Due to change in magnitude of the electric field, there is a change in the material removal rate.

### Material removal rate increase

During the machining process near the corner, it is difficult to dissipate all the heat generated due to electric sparking. This difficultly results in increase of material removal rate near the corner. These phenomena should be seen in direct relationship with the above mentioned phenomena of intensification in the electric field. As per authors, in most of the studies conducted, primary reason for geometrical inaccuracy is wire deviation from the programmed path.

### Improvement in geometrical inaccuracies

In order to improve the geometrical corner accuracy, research work has been conducted in the past [50-57]. Area of focus has been vast but not limited to online methodology, offline methodology, use of optical sensor, use of fuzzy logic circuits and expert systems, change in feed rate and pulse off time at the corners. In addition to the methodology enumerated in the above paragraphs, mathematical models have also been used to estimate the corner error. Taguchi method has also been used to study the influence of various parameters on the wire lag phenomenon in order to study geometrical accuracy. This helped in finding the optimum parameter for different machining situations.

## OPTIMISATION OF GEOMETRICAL INACCURACY DUE TO WIRE LAG PHENOMENON

Spedding et al [58] has indicated that as newer composite materials have been invented during the last few decades, limitations of conventional machining has surfaced. This limitation has come to light as requirement for machining of more complex shapes has raised.

Under prevailing circumstances, WEDM usage in the manufacturing industry has increased during the last 30 years. Its area of application includes but not limited to aerospace and automotive industry.

The main reason for growth in EDM is that sometimes it is the only available solution for machining complex profiles on high strength materials which are also temperature resistive. Furthermore, WEDM has proved itself to be having satisfactory accuracy and surface finish for most of operations.

Although many facets of WEDM have improved tremendously over the years, however, room for improvement dose exists. Keeping in view the tight range of tolerance desired by various industries, it is an established fact that in a WEDM operation high MRR and good SF cannot be achieved at the same time [59].

Numerous researchers have conducted research in this field all over the world to achieve a satisfactory answer. One of the answers to this problem is to first make a rough cut which is followed by two or three trim cuts depending upon the requirement of the customers. However, in order to study the phenomenon, it is mandatory that two important phenomena be studied together. The two phenomena are vibrational behavior and static deflection of wire.

A lot of study has been conducted in the field of wire vibration but very little research is conducted in the area of wire lag which is very important for achieving precision. Furthermore, the studies conducted have not taken into account the full spectrum of machine variables.

Efforts have therefore been made to find the effects of machine variables on three important aspects i.e. average cutting speed ($V_c$), surface finish characteristics and the geometrical accuracy (g) which are caused by wire lag. Puri et al [59] employed on L $27(3)^{13}$ orthogonal array using the Taguchi's method to facilitate in identification of fundamental factors that influence the average cutting speed ($V_c$) surface finish and geometrical inaccuracy. It is proved that in order to get good productivity and satisfactory level of surface finish, it is mandatory that a rough cut be made initially and after that at least one trim cut is made. Therefore, the machining operation is envisaged in a manner that after an initial cut, another cut i.e. trim cut is also made.A total of thirteen machine parameters were chosen to study their effects and each factor was planned to have three levels. Control factors for rough cut were pulse off time (T Off), pulse peak current (Tp) and pulse on time (T On). The factor for trim cut were feed velocity, dielectric flow rate, wire cutting speed, off set of wire, pulse on time, pulse peak current, wire tension, pulse peak voltage, wire feed velocity and corresponding duty factor.

During experiments, typical wire cut EDM machine model supercut 734 was used. The material used was a typical die steel with a thickness of 28 mm and the electrode was brass wire of diameter 250 µm.

After conducting the experiment, data was analysed and signal to noise ratio was calculated followed by ANOVA. It was established that for average cutting speed, ($V_c$) pulse on time, pulse off time and pulse peak current are significant factors during a rough cut while pulse on time and cutting speed are significant factors for trim cut. In case of surface roughness, pulse peak current was significant factor for rough cut while pulse on time, pulse peak voltage, servo spark gap set voltage, dielectric flow rate, wire tool offset and a constant cutting speed were significant factors during trim cut. For geometrical inaccuracy due to wire lag (g) pulse on time, pulse off time and pulse peak current are significant factors in case of a rough cut while pulse peak voltage, wire tension, servo spark gap set voltage, wire tool offset and cutting speed are significant factors during a trim cut.

## SALIENT OF RESEARCH IN RELEVANT FIELD OF WEDM

J.A. Sanchez et al. [65] studied the corner geometry generated by the successive cuts (roughing and finishing). Errors at different zones of the corner are identified and related to the material removed during each cut. According to him, limitation of cutting speed allows a certain control on the amount of material actually removed by the wire. Discussed the influence of different aspects such as work thickness, corner radius and number of trim cuts. Main conclusion is that a corner accuracy optimization procedure must consider the errors generated by the previous cuts.

Chin-Teng Lin et al [66] develops a control strategy based on fuzzy logic so that the machining accuracy at corner parts for wire-EDM can be improved. The fuzzy rules based on the wire-EDM‘s physical characteristics, experimental data and operator‘s experience are constructed, so that the reduced percentage of sparking force can be determined by a multi-variables fuzzy logic controller. The objective of the total control is to improve machining accuracy at corner parts, but still keeping the cutting feedrate at fair values. As a result of experiments, machining errors of corner parts, especially in rough-cutting, can be reduced to less than 50% of those in normal machining, while the machining process time increases not more than 10% of the normal value.

M. N. Islam et al [67] present the experimental and analytical results of an investigation into dimensional accuracy achievable in WEDM. Three techniques i.e. traditional analysis, Taguchi method, and Pareto ANOVA analysis are employed to determine the effects of six major controllable machining parameters: the discharge current, pulse duration, pulse gap frequency, wire speed, wire tension, and dielectric flow rate on three key dimensional accuracy characteristics of the prismatic component, dimensional errors, flatness errors, and perpendicularity errors of corner surfaces. Subsequently, the input parameters are optimized in order to maximize the dimensional accuracy at corner.

Nihat Tosun et al. [68] applied Taguchi and ANOVA methods to determine optimal machining parameters for minimum Kerf and maximum Material Removal Rate (MRR) on AISI 4140 Steel. The experimental study was conducted under varying machining parameters named as pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. Based on Taguchi and ANOVA methods, it was inferred that highly effective parameters on both the kerf and the MRR are open circuit voltage and pulse duration whereas; wire speed and dielectric flushing pressure are less effective factors. Conclusion of the study is that the corner radius to be produced in WEDM operations is limited by the kerf.

## PROBLEM STATEMENT

Wire Electric Discharge Machining (WEDM) has gained wide applications after the introduction of CNC machines and is utilized for manufacturing parts in high tech field such as medical and aeronautical fields which require precision and accuracy. Furthermore, requirement of accuracy in manufacturing of these intricate parts is increasing with every day. Magnets are consider impossible to machine through conventional manufacturing techniques dur to its brittleness. One of the areas in WEDM which is focal area of research is to machine brittele, hard amd low toughness materials. Material removal rate, Surface finish and recast layer thickness has significant importance in manufactured parts especially biomedical applications like MRI etc.Research work is available on various aspects of MRR,SF and RLT such as wire lag, segmentation of corner error, corner error simulation etc. However, little research has been reported on MRR,SF and RLT while machining NdFeB magnet as workpiece, where as it is one of the most widely used materials for energy generating/stroring devices, medical devices and automobile industry. The main aim of this thesis will be to identify the effects of various machine control variables and angle size on MRR,SF and RLT in wire electric discharge machining while machining NdFeB magnet.

# CHAPTER 3

# DESIGN OF EXPERIMENT, EXPERIMENTATION AND ANALYSIS

## DESIGN OF EXPERIMENT

Researcher‘s paramount goal is to acquire sufficient data that can facilitate in understanding the scientific phenomenon [69]. The experiments are used to study effects of parameters as they are set at various levels. There are three broad experimental methods.

### Trial and error approach

Trial and error approach is a set of experiments where each experiment gives some understanding. Measurements are to be made after every experiment so that analysis of observed data will decide about the next experiment. Usually such methodology does not make much headway. Therefore, such experimental process ends well before number of experiments reaches a double digit. The data drawn is insufficient to draw any significant conclusions and usually key problem remains unsolved.

### Design of experiment

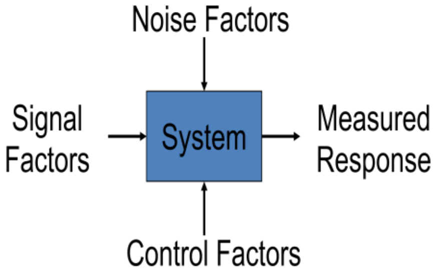
D.O.E is a well planned set of experiments. All parameters of interest are varied over a specified range. It is a comprehensive approach to obtain systematic data. Mathematically speaking, such a complete set of experiments gives the desired results. However, number of experiments and resources (materials and time) required is prohibitively large.

### Taguchi method

Taguchi method is based on orthogonal arrays which give much reduced variancefor the experiments with optimum settings of control parameters. The main advantage of Taguchi's method is that it reduces the prohibitively large requirementof experiments and resources. The main disadvantage is that instead of designing experiment to investigate the potential interaction, captioned method prefer to use three level factors to estimate the curvature.

## BRIEF DESCRIPTION OF TAGUCHI METHOD

In order to understand the Taguchi method, understanding of two factors is imperative i.e. control factor and noise [70]. Control factors are the design factors that are to be set at optimal levels to improve quality and reduce sensitivity to noise, examples are dimensions of parts, type of material, etc. Noise factors represent the noise that is expected in production or in usage; examples are operating temperature, dimensional variation, etc.



**Schematic of system depicting noise and control factors**
**Figure 3.1**

Taguchi's method guides in selecting combinations of various factor levels (control and noise both). This selection enables to determine the output characteristics and thereby calculate the performance statistic. Each experiment consists of setting the design parameters and associated setting of noise factors. For control factors that are quantitative, three levels are necessary to estimate the quadratic (or nonlinear) effects, if any.

## ANOVA (ANALYSIS OF VARIANCE)

ANOVA is a statistical technique which is widely used for analyzing the data of experiments. ANOVA uses null hypothesis for formulating the results. It is possible to determine the significant factors in a data utilizing this method. It is tedious tounderstand and conduct mathematical modeling for ANOVA. However, softwares are available which facilitate in determining the significant factors.

## EXPERIMENTATION

NdFeB magnet (Density 7.5 gm/cm3, thermal capacity 0.67 c(J/kg) resistance 156 (µΩ.cm) are used in experiments. Four machine controllable variables were selected and controlled for four levels. The machine variables were pulse on time, pulse off time, voltage and current. Table 3.1 outlines the four machine control parameters with their levels. The levels to be used were carefully selected keeping in view the pre-experimental runs and literature review. Main interruption experienced during pre-experimental runs was breakage of wire. Therefore, focused attention was directed to ensure uninterrupted execution of experimental runs.

**TABLE 3.1**

**Four MACHINE VARIABLES**

| **Factors** | **UNITS** | **LEVEL 1** | **LEVEL 2** | **LEVEL 3** | **LEVEL 4** |
|---|---|---|---|---|---|
| Voltage | Volt | 60 | 70 | 80 | 90 |
| Pulse on time | µSec | 1.4 | 1.6 | 1.8 | 2 |
| Pulse off time | µSec | 8 | 10 | 12 | 14 |
| Current | Ampere | 10 | 12 | 14 | 16 |

### Taguchi orthogonal array

Literature survey revealed that number of previous researchers has used Taguchi's orthogonal arrays in their research on WEDM with success. Therefore, Taguchi's orthogonal array L16 was utilized for current research. Orthogonal Array is tabulated as Table 3.2.

**TABLE 3.2**

**Taguchi Orthogonal Array**

| Run | OPEN VOLTAGE (Volts) | Current (Ampere) | PULSE on Time (Micro Sec) | PULSE off Time (Micro Sec) |
|---|---|---|---|---|
| 1 | 60 | 16 | 1.8 | 8 |
| 2 | 60 | 14 | 2 | 12 |
| 3 | 60 | 12 | 1.4 | 10 |
| 4 | 60 | 10 | 1.6 | 14 |
| 5 | 70 | 16 | 2 | 10 |
| 6 | 70 | 14 | 1.8 | 14 |
| 7 | 70 | 12 | 1.6 | 8 |
| 8 | 70 | 10 | 1.4 | 12 |
| 9 | 80 | 16 | 1.4 | 14 |
| 10 | 80 | 14 | 1.6 | 10 |
| 11 | 80 | 12 | 1.8 | 12 |
| 12 | 80 | 10 | 2 | 8 |
| 13 | 90 | 16 | 1.6 | 12 |
| 14 | 90 | 14 | 1.4 | 8 |
| 15 | 90 | 12 | 2 | 14 |
| 16 | 90 | 10 | 1.8 | 10 |

## Measurements

In this thesis there were three requirements for measurement i.e. Material removal rate, surface roughness and recast layer thickness. Measurement procedure for each is explained in details in the successive paragraphs.

### Material Removal Rate:

In WEDM material removal rate can not be predefined and the depth of cut is not independent from input parameters. In all experiments cutting time is noted down. By using Formula i.e mentioned below MRR is calculated.

MRR (mm3/min)= [(Height of work piece x width of cut x wire diameter)/ machining time]

$$MRR= [(Hx\ Wx0.25)/\ t]$$

In this research height of the work piece is 25mm and cut width is 5mm. Only time is variable which is determined through experiments. Machining time (t) depends on input parameters.

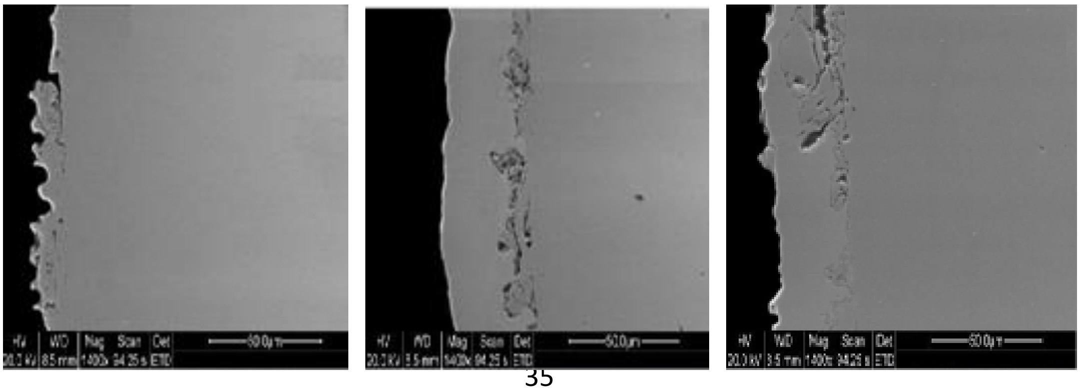
### Surface Finish:

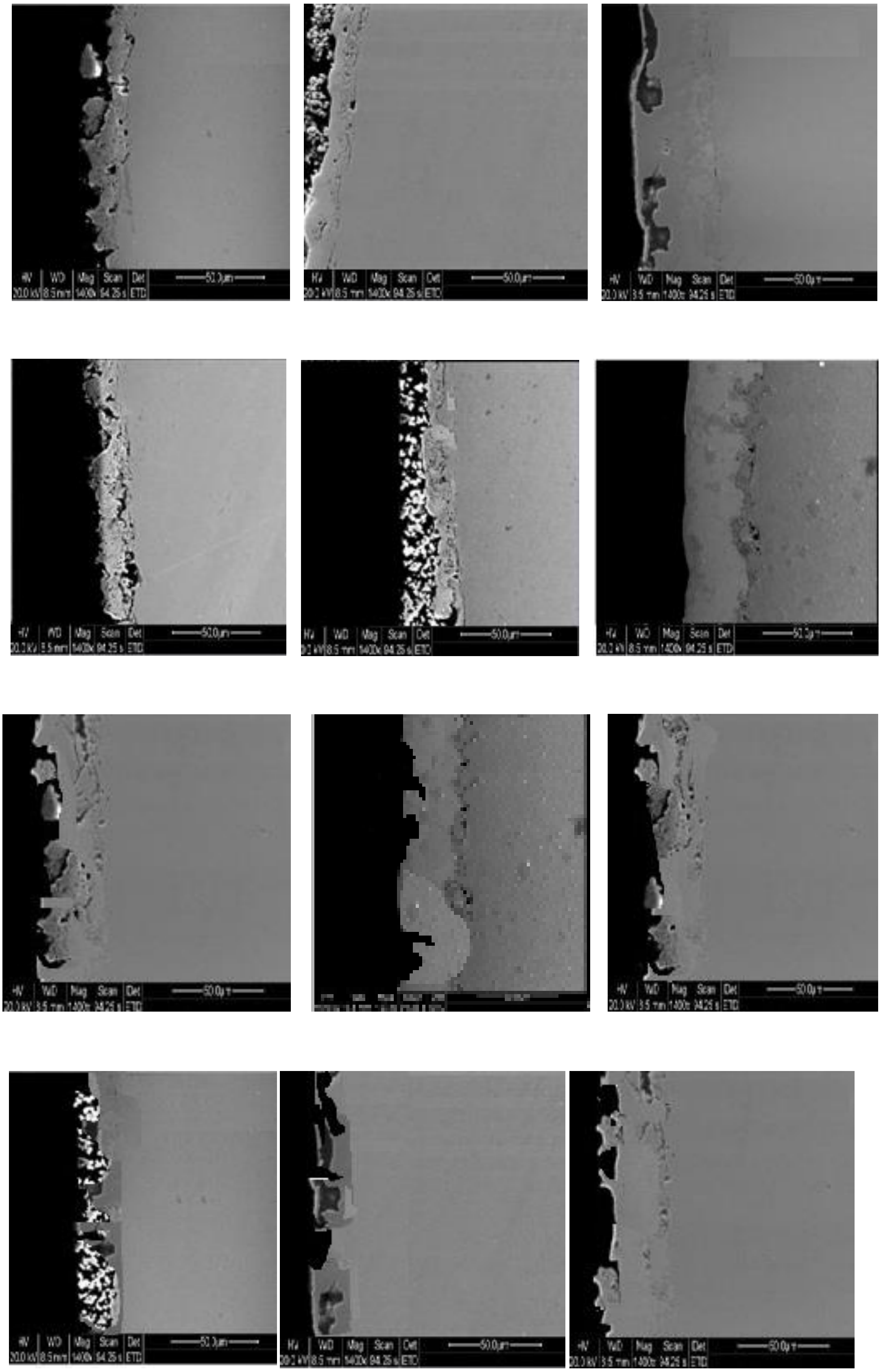
Surface finish is analyzed utilizing the Surface Roughness Tester by Mitutoyo, Japan. The surface finish is very much dependant on the input parameters.

### Recast Layer Thickness:

Scanning electron microscopy was performed using an FEI Quantum 400 with an backscatter detector for topography, and backscatter detector for compositional analysis. Representative images of the recast layer at magnifications varying from 40x-3500x were taken for at least two samples per sample group. Backscatter images were used to confirm the boundary between parent material and recast layer. Recast layer thicknesses were calculated using these images. is measured by the “Infinity Analyze”.

The Infinity Analyze Camera was utilized to capture the photos of the work pieces and then Infinity Analyze software was utilized to measure the recast layer thickness.





**Measurement of Recast Layer Thickness**
**Figure 3.3.1-15**

## TABLE 3.3

## Material Removal Rate Measurements

| RUN | READING1 (mm3/min) | READING 2 (mm3/min) | AVERAGE (mm3/min) |
|---|---|---|---|
| 1 | 6.944 | 6.923 | 6.934 |
| 2 | 6.410 | 6.399 | 6.404 |
| 3 | 5.319 | 5.306 | 5.312 |
| 4 | 4.167 | 4.187 | 4.177 |
| 5 | 7.143 | 7.113 | 7.128 |
| 6 | 6.250 | 6.211 | 6.231 |
| 7 | 5.208 | 5.188 | 5.198 |
| 8 | 4.5008 | 3.987 | 4.378 |
| 9 | 6.579 | 6.559 | 6.569 |
| 10 | 6.098 | 6.110 | 6.104 |
| 11 | 3.846 | 3.826 | 5.454 |
| 12 | 5.435 | 5.473 | 4.984 |
| 13 | 6.757 | 6.770 | 6.763 |
| 14 | 5.952 | 5.968 | 6.454 |
| 15 | 3.704 | 3.691 | 5.960 |
| 16 | 5.256 | 5.506 | 5.170 |

**TABLE 3.4**

**Surface Roughness Measurements**

| RUN | READING 1 (µm) | READING 2 (µm) | AVERAGE (µm) |
|---|---:|---:|---:|
| 1 | 2.87415 | 2.86225 | 2.8682 |
| 2 | 2.58745 | 2.56475 | 2.5761 |
| 3 | 1.805325 | 1.80291 | 1.8041175 |
| 4 | 1.152101 | 1.14921 | 1.1506555 |
| 5 | 2.78745 | 2.76659 | 2.77702 |
| 6 | 2.45325 | 2.4901 | 2.471675 |
| 7 | 1.97512 | 1.94329 | 1.959205 |
| 8 | 1.5025 | 1.4859 | 1.4942 |
| 9 | 2.99579 | 2.95589 | 2.97584 |
| 10 | 1.92036 | 1.89658 | 1.90847 |
| 11 | 1.451051 | 1.42158 | 1.4363155 |
| 12 | 1.98156 | 1.95326 | 1.96741 |
| 13 | 3.01238 | 3.00239 | 3.007385 |
| 14 | 1.96589 | 1.92875 | 1.94732 |
| 15 | 1.7101051 | 1.69856 | 1.70433255 |
| 16 | 1.95854 | 1.99486 | 1.9767 |

## TABLE 3.5

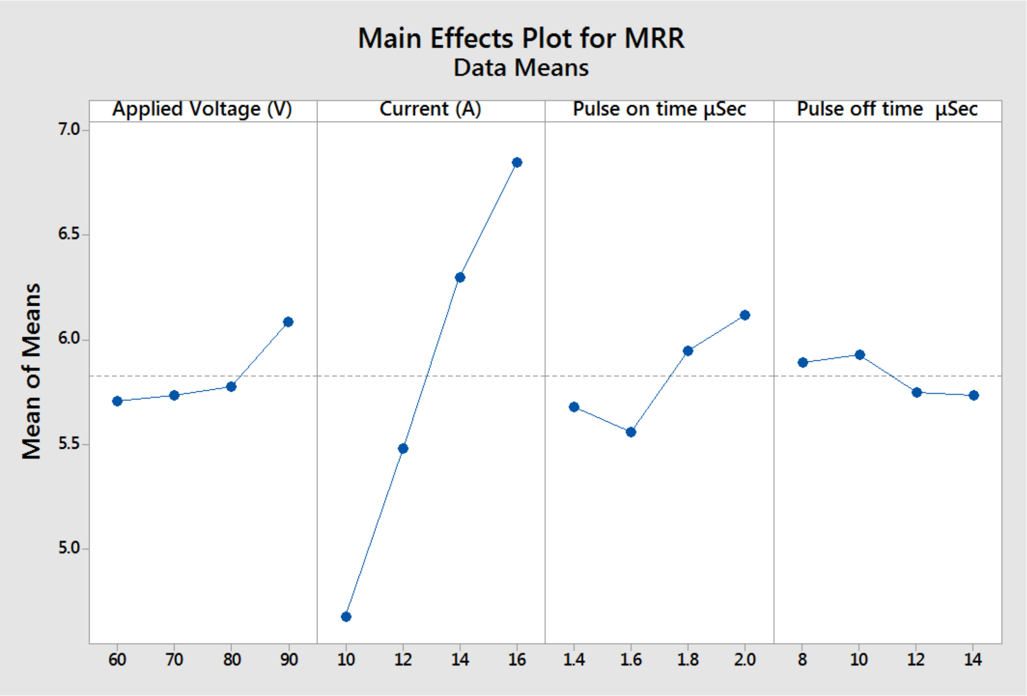
## Recast Layer Thickness Measurements

| RUN | READING 1 (µm) | READING 2 (µm) | AVERAGE (µm) |
|---|---|---|---|
| 1 | 13.4786 | 13.4625 | 13.4706 |
| 2 | 13.9125 | 14.0547 | 13.9836 |
| 3 | 12.0000 | 11.9957 | 11.9978 |
| 4 | 12.4286 | 12.4758 | 12.4522 |
| 5 | 14.2148 | 13.9986 | 14.1067 |
| 6 | 13.5486 | 13.5401 | 13.5444 |
| 7 | 13.3561 | 13.3209 | 13.3385 |
| 8 | 13.2560 | 13.2355 | 13.2458 |
| 9 | 14.0256 | 14.0104 | 14.0180 |
| 10 | 14.1986 | 14.2065 | 14.2026 |
| 11 | 15.6591 | 15.6623 | 15.6607 |
| 12 | 15.8952 | 15.9016 | 15.8984 |
| 13 | 17.8695 | 17.9460 | 17.9078 |
| 14 | 17.0259 | 16.9856 | 17.0058 |
| 15 | 18.0025 | 18.0128 | 18.0077 |
| 16 | 17.9978 | 17.9689 | 17.9834 |

## ANALYSIS

Experiments are conducted according to the Taguchi's design of experiments and the results are mentioned in Table 3.3 - 3.5. These results are fed into software i.e Minitab, main effects were analyzed and ANOVA for all output parameters are conducted. Contribution of each input parameter on individual output parameter is analyzed; this helped in differentiating between significant factors and non significant factors. Regression equation is also developed for further mathematical calculations:

### General Linear Model: MRR(mm3/min)



Relationship between input Parameters to MRR

**Figure 3.6.1.1**

**Table 3.6**

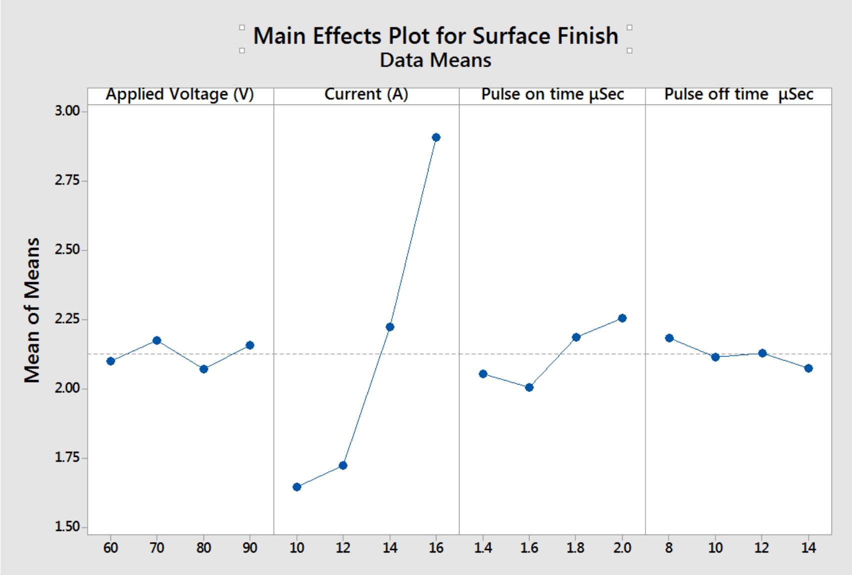
**Analysis of Variance for MRR**

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| Applied Voltage (V) | 3 | 0.1416 | 0.73% | 0.1416 | 0.04720 | 0.07 | 0.972 |
| Current (A) | 3 | 14.9098 | 76.72% | 14.9098 | 4.96993 | 7.42 | 0.067 |
| Pulse on time µSec | 3 | 0.1056 | 0.54% | 0.1056 | 0.03520 | 0.05 | 0.981 |
| Pulse off time µSec | 3 | 2.2697 | 11.68% | 2.2697 | 2.0083 | 1.13 | 0.461 |
| Error | 3 | 2.0083 | 10.33% | 0.75657 | 0.66943 | | |
| Total | 15 | 19.4350 | 100.00% | | | | |

**Regression Equation**

MRR(mm3/min) = 5.585 + 0.125 Applied Voltage (V)_60 + 0.065 Applied Voltage (V)_70- 0.096 Applied Voltage (V)_80 - 0.093 Applied Voltage (V)_90 - 0.796 Current (A)_10 - 1.066 Current (A)_12 + 0.592 Current (A)_14 + 1.270 Current (A)_16 -0.123 Pulse on time µSec_1.4 - 0.028 Pulse on time µSec_1.6 + 0.064 Pulse on time µSec_1.8 + 0.087 Pulse on time µSec_2.0 + 0.300 Pulse off time µSec_8 + 0.443 Pulse off time µSec_10 - 0.332 Pulse off time µSec_12 - 0.411 Pulse off time µSec_14

**General Linear Model: Surface Finish**



Relationship between input Parameters to Surface Finish

Figure 3.6.2

Table 3.7

Analysis of Varience for Surface Finish

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| Applied Voltage (V) | 3 | 0.02856 | 0.56% | 0.02856 | 4.03731 | 0.04 | 5.00 |
| Current (A) | 3 | 4.03731 | 79.82% | 0.16045 | 0.02470 | 0.20 | 0.03 |
| Pulse on time µSec | 3 | 0.16045 | 3.17% | 0.80686 | 0.00952 | 0.989 | 0.109 |
| Pulse off time µSec | 3 | 0.02470 | 0.49% | 1.34577 | 0.05348 | 0.891 | 0.991 |
| Error | 3 | 0.80686 | 15.95% | 0.00823 | 0.26895 | | |
| Total | 15 | 5.05788 | 100.00% | | | | |

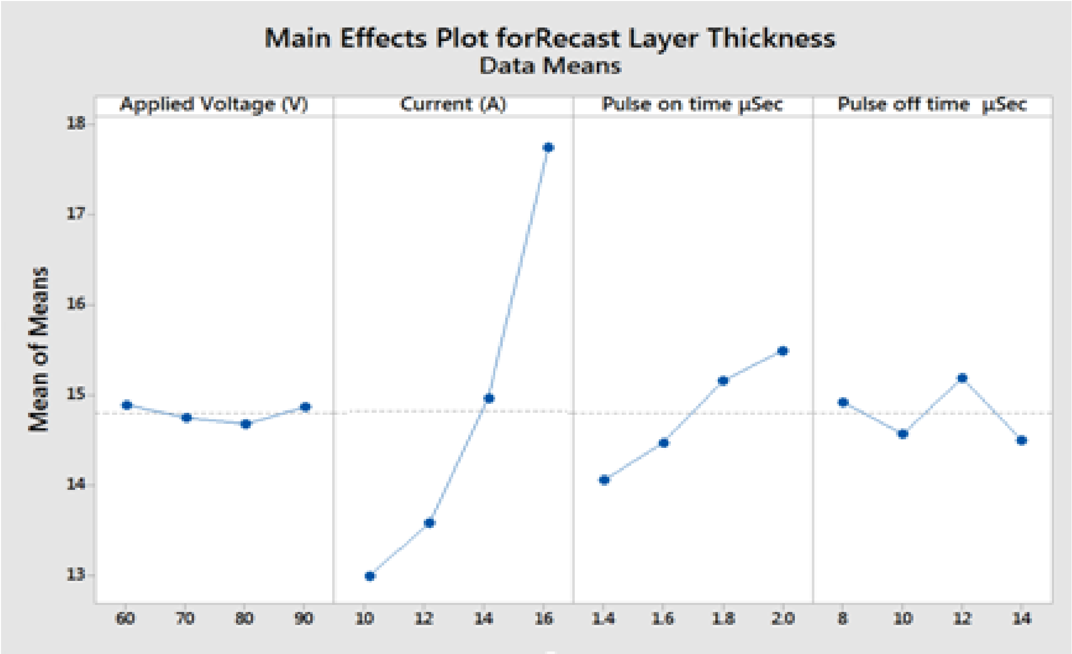
**Regression Equation**

Surface Finish(Ra) µm = 2.133 - 0.029 Applied Voltage (V)_60 + 0.046 Applied Voltage (V)_70 - 0.046 Applied Voltage (V)_80 + 0.028 Applied Voltage (V)_90 - 0.485 Current (A)_10 - 0.398 Current (A)_12 + 0.098 Current (A + 0.784 Current (A)_16 - 0.066 Pulse on time µSec_1.4 - 0.118 Pulse on time µSec_1.6 + 0.051 Pulse on time µSec_1.8 + 0.133 Pulse on time µSec_2.0

+ 0.066 Pulse off time µSec_8- 0.015 Pulse off time µSec_10 + 0.005 Pulse off time µSec_1- 0.056 Pulse off time µSec_14

**General Linear Model: Recast Layer Thickness**

**Analysis of Variance**



Relationship between input Parameters to Recast Layer Thickness

**Figure 3.6.3**

Table 3.8

**Analysis of Variance for Recast Layer Thickness**

| **Source** | **DF** | **Seq SS** | **Contribution** | **Adj SS** | **Adj MS** | **F-Value** | **P-Value** |
|---|---|---|---|---|---|---|---|
| Applied Voltage (V) | 3 | 53.8021 | 89.27% | 53.8021 | 17.9340 | 1912.19 | 0.000 |
| Current (A) | 3 | 0.1223 | 0.20% | 0.1223 | 0.0408 | 4.35 | 0.129 |
| Pulse on time µSec | 3 | 5.0590 | 8.39% | 5.0590 | 1.6863 | 179.80 | 0.001 |
| Pulse off time µSec | 3 | 1.2577 | 2.09% | 1.2577 | 0.4192 | 44.70 | 0.005 |
| Error | 3 | 0.0281 | 0.05% | 0.0281 | 0.0094 | | |
| Total | 15 | 60.2692 | 100.00% | | | | |

**Regression Equation**

Recast Layer Thickness (RL) µm = 14.8043 - 1.8494 Applied Voltage (V)_60 - 1.2105 Applied Voltage (V)_70 + 0.1403 Applied Voltage (V)_80+ 2.9196 Applied Voltage (V)_90 + 0.0901 Current (A)_10 - 0.0499 Current (A)_12 - 0.1329 Current (A)_14 + 0.0928 Current (A)_16 - 0.7275 Pulse on time µSec_1.4 + 0.3667 Pulse on time µSec_1.8 + 0.7019 Pulse on time µSec_2.0 + 0.1346 Pulse off time<µSec_8 - 0.2015 Pulse off time<µSec_10 + 0.3699 Pulse off time<µSec_12 - 0.3030 Pulse off time<µSec_14 - 0.3411 Pulse on time µSec_1.6

**Optimization**

As optimization is in the scope of this thesis, calculation for optimum response was also conducted in order to assess the improvement achieved. In order to calculate optimum response, calculation for optimum level combination is the first step. Using Minitab-17 optimum level combination is derived. Optimum level combination Level is tabulated in Table 3.9

**TABLE 3.9**

**Optimum level combination**

| **Combination** | **FACTORS** | | | |
|---|---|---|---|---|
| | **Voltage (V)** | **Current(A)** | **Pulse on Time** | **Pulse off Time** |
| 1 | 60 | 14 | 1.6 | 10 |
| 2 | 60 | 14 | 1.4 | 10 |

**PREDICTED VALUE**

According to the optimum level combinations predicted values of each response is tabulated:

**TABLE 3.10**

**PREDICTED RESPONSE**

| **Combination** | **MRR** | **Surface Finish** | **Recast layer Thickness** |
|---|---|---|---|
| 1 | 6.71908 | 2.06899 | 12.3035 |
| 2 | 6.61737 | 2.11793 | 11.8951 |

## Confirmatory runs

Confirmatory runs were conducted to reconfirm the predicated results. Confirmatory results are tabulated in Table 3.12. Results of confirmatory run are in line with the perceived results as tabulated in Table 3.11. Therefore, it is concluded that design of experiment furnished logical results.

**TABLE 3.12**

**CONFIRMATORY RUN**

| Combination | MRR | Surface Finish | Recast layer Thickness |
|---|---|---|---|
| 1 | 6.70569 | 2.07028 | 12.4019 |
| 2 | 6.59647 | 2.19568 | 12.0041 |

# CHAPTER 4

# CONCLUSIONS AND RECOMMENDATIONS

## CONCLUSIONS

In this study, different wirecut EDM input parameters i.e current, voltage, pulse on time and pulse off time are used to determine their effect on MRR, surface finish and recast layer of NdFeB magnet. Brass wire having diameter of 0.25mm is used as an electrode. Taguchi design of experiments technique is utilized for the experiments. For the statistical analysis ANOVA by Minitab-17 is used. The following conclusions were drawn based on the study.

- Increasing the current and pulse-on duration improves MRR while deteriorating the surface quality and causing a thicker recast layer.
- Craters appear on the machined surface, and the likelihood of crater formation increases during the WEDM process as the current and pulse-on duration increase. Poor surface finish and a thicker recast layer are caused by larger craters on the machined surface.
- Lowering the EDM machine voltage and reducing the pulse-on time results in a finer surface finish and a smaller recast layer.
- The pulse on time, current, and voltage have all been found to have a substantial impact on MRR. Recast layer thickness and surface finish The least influential input parameter in this study is pulse off time.

## RECOMMENDATIONS

The research findings, combined with other mathematical models, will provide an appropriate guideline for selecting result parameter settings for machining NdFeB magnet on EDM to achieve the requisite MRR, surface finish and Recast Layer thickness.

# REFERENCES

**[1]** Fundamentals of Modern Manufacturing, Materials, Processes and Systems. Third Edition. Mikell P Grover.

**[2]** Dagamo's Materials and Processes in Manufacturing. Tenth Edition . J T Black and Ronald A Kohser.

**[3]** Presentation on Manufacturing Process - IME Department PNEC

**[4]** http://www.jacksmachine.com/pdf/what-is-wire-edm.pdf

**[5]** K.H. Ho, State of the art in wire electrical discharge machining (WEDM). International Journal of Machine Tools & Manufacture 44 (2004) 1247-1259 Apr 04, pp 1247

**[6]** E.C. Jameson, Description and development of electrical discharge machining (EDM), Electrical Discharge Machining, Society of Manufacturing Engineers, Dearbern, Michigan, 2001, pp. 16.

**[7]** G.F. Benedict, Electrical discharge machining (EDM), Non- Traditional Manufacturing Processes, Marcel Dekker, Inc, New York & Basel, 1987, pp. 231-232.

**[8]** A.B. Puri, B. Bhattacharyya, An analysis and optimization of the geometrical inaccuracy due to wire lag phenomenon in WEDM, Int. J. Mach. Tools Manuf. 43 (2) (2003) 151-159.

**[9]** E.I. Shobert, What happens in EDM, in: E.C. Jameson (Ed.), Electrical Discharge Machining: Tooling, Methods and Applications, Society of Manufacturing Engineers, Dearbern, Michigan, 1983, pp. 3–4.

**[10]** H.C. Tsai, B.H. Yan, F.Y. Huang, EDM performance of Cr / Cu-based composite electrodes, Int. J. Mach. Tools Manuf. 43 (3) (2003) 245–252.

**[11]** G. Boothroyd, A.K. Winston, Non-conventional machining processes, Fundamentals of Machining, Marcel Dekker, Inc, 1989, pp. 491.

**[12]** J.A. McGeough, Electrodischarge machining, Advanced Methods of Machining, Chapman & Hall, London, 1988, pp. 130.

**[13]** S.F. Krar, A.F. Check, Electrical discharge machining, Technology of Machine Tools, Glencoe/McGraw-Hill, New York, 1997, pp. 800.

**[14]** Y.F. Luo, C.G. Chen, Z.F. Tong, Investigation of silicon wafering by wire EDM, J. Mater. Sci. 27 (21) (1992) 5805–5810.

**[15]** G.N. Levy, R. Wertheim, EDM-machining of sintered carbide compacting dies, Ann. CIRP 37 (1) (1988) 175–178.

**[16]** A. Kruusing, S. Leppavuori, A. Uusimaki, B. Petretis, O. Makarova, Micromachining of magnetic materials, Sensors Actuators 74 (1-3) (1999) 45-51.

**[17]** J.A. Sanchez, I. Cabanes, L.N. Lopez de Lacalle, A. Lamikiz, Development of optimum electrodischarge machining technology for advanced ceramics, Inter. J. Adv. Manuf. Technol. 18 (12) (2001) 897-905.

**[18]** N. Mohri, Y. Fukuzawa, T. Tani, T. Sata, Some considerations to machining characteristics of insulating ceramics—towards practical use in industry, Ann. CIRP 51 (1) (2002) 161-164.

**[19]** W.S. Lau, W.B. Lee, A comparison between EDM wire-cut and laser cutting of carbon fibre composite materials, Mater. Manuf. Processes 6 (2) (1991) 331-342.

**[20]** W.S. Lau, T.M. Yue, T.C. Lee, W.B. Lee, Un-conventional machining of composite materials, J. Mater. Process. Technol. 48 (1-4) (1995) 199-205.

**[21]** G.A. Alekseyev, M.V. Korenblum, Analysis of the Conditions for the High Efficiency Wire Cut EDM, Proceedings of the Ninth International Symposium for Electro-Machining (ISEM- 9), Nagoya, Japan, 1989.

**[22]** Y. Suziki, M. Kishi, Improvement of Surface Roughness in wire EDM, Proceedings of the Ninth International Symposium for Electro-Machining (ISEM-9), Nagoya, Japan, 1989.

**[23]** Y.F. Luo, An energy-distribution strategy in fast-cutting wire EDM, J. Mater. Process. Technol. 55 (3-4) (1995) 380-390.

**[24]** D.F. Dauw, L. Albert, About the evolution of wire tool performance in wire EDM, Ann. CIRP 41 (1) (1992) 221-225.

**[25]** G.N. Levy, F. Maggi, WED machinability comparison of different steel grades, Ann. CIRP 39 (1) (1990) 183-185.

**[26]** R. Konda, K.P. Rajurkar, R.R. Bishu, A. Guha, M. Parson, Design of experiments to study and optimize process performance, Inter. J. Qual. Reliab. Manage. 16 (1) (1999) 56-71.

**[27]** D. Scott, S. Boyina, K.P. Rajurkar, Analysis and optimization of parameter combination in wire electrical discharge machining, Inter. J. Prod. Res. 29 (11) (1991) 2189-2207.

**[28]** M.I. Go¨ kler, A.M. Ozano¨zgu¨ , Experimental investigation of effects of cutting parameters on surface roughness in the WEDM process, Inter. J. Mach. Tools Manuf. 40 (13) (2000)
1831-1848.

**[29]** N. Tosun, C. Cogun, A. Inan, The effect of cutting parameters on workpiece surface roughness in wire EDM, Machining Sci. Technol. 7 (2) (2003) 209-219.

**[30]** T.A. Spedding, Z.Q. Wang, Study on modeling of wire EDM process, J. Mater. Process. Technol. 69 (1-3) (1997) 18-28.

**[31]** F. Han, M. Kunieda, T. Sendai, Y. Imai, High precision simulation of WEDM using parametric programming, Ann. CIRP 51 (1) (2002) 165-168.

**[32]** N. Kinoshita, M. Fukui, H. Shichida, G. Gamo, T. Sata, Study on E.D.M. with wire electrode; gap phenomena, Ann. CIRP 25 (1) (1976) 141-145.

**[33]** N. Kinoshita, M. Fukui, G. Gamo, Control of wire-EDM preventing electrode frombreaking , Ann. CIRP 31 (1) (1982) 111-114.

**[34]** K. Shoda, Y. Kaneko, H. Nishimura, M. Kunieda, M.X. Fan, Adaptive Control of WEDM with On-line Detection of Spark Locations, Proceeding of the Tenth International Symposium for Electro-Machining (ISEM-10), Magdeburg, Germany, 1992.

**[35]** M. Kunieda, H. Kojima, N. Kinoshita, On-line detection of EDM spark location by multiple connection of branched electric wires, Ann. CIRP 39 (1) (1990) 171-174.

**[36]** D.F. Dauw, I. Beltrami, High-precision wire-EDM by online wire positioning control, Ann. CIRP 43 (1) (1994) 193-197.

**[37]** N. Kinsohita, M. Fukui, Y. Kimura, Study on Wire-EDM: in process measurement of mechanical behaviour of electrode wire, Ann. CIRP 33 (1) (1984) 89-92.

**[38]** S. K. SINHA, ―Effect of wire lag in WEDM‖. International Journal of engineering science and technology vol 2(11) 2010 pp 6622

**[39]** Ho, K. H., et.al. (2004), ―State of art in wire-electro discharge machining,‖ International Journal of Machine Tool and Manufacture, 44, pp. 1247-1259.

**[40]** Puri, A. B., and Bhattacharya, B. (2003), ―An analysis and optimization of the geometrical in accuracy due to wire lag Phenomenon in Wireelectro discharge machining,‖ International Journal of Machine Tool and Manufacture, 43, pp. 151-159.

**[41]** Puri, A. B., and Bhattacharya, B. (2003), ―Modeling and analysis of wire tool vibration in wire cut electro discharge machining,‖ Journal of Material Processing Technology, 141, pp. 295-301.

**[42]** Arunachalam, C., Aulia, M., and Eubank, P. T. (2001), ―Wire vibration, bowing, and breakage in wire electrical discharge machining,‖ Journal of Applied Physics, 89, pp. 4255-4262.

**[43]** Tomura, S., and Kunieda, M. (2009), ―Analysis of Electromagnetic Force in wire EDM,‖ Precision Engineering, 33, 255-262

**[44]** Sanchez, J. A., et.al. (2007), ―On the influence of cutting speed limitation on the accuracy of wire-electro discharge machining corner cutting,‖ Journal of Material Processing Technology, 182, pp. 574-579

**[45]** O. Dodun, ―Using wire electrical discharge machining for improved corner cutting accuracy of thin parts‖ Int J Adv Manuf Technol (2009) 41:858-864 pp858

**[46]** Ho KH, Newman ST, Rahimifard S, Allen RD (2004) State of the art in wire electrical discharge machining (WEDM). Int J Mach Tools Manuf 44:1247-1259. doi:10.1016/j.ijmachtools.2004. 04.017

**[47]** Sarkar S, Mitra S, Bhattacharyya B (2005) Parametric optimization of wire electrical discharge machining of + titanium aluminide alloy through an artificial neural network model. Int J Adv Manuf Technol 27:501-508. doi:10.1007/s00170-004-2203-7

**[48]** Mahapatra SS, Patnaik A (2007) Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method. Int J Adv Manuf Technol 34(9-10):911-925. doi:10.1007/s00170-006-0672-6

**[49]** Gather U, Homberg W, Kleiner M, Klimmek C, Kuhnt S (2002) Parameter design for sheet metal hydroforming processes. Available at: http://www.statistik.uni-dortmund.de/de/content/einrichtungen/lehrstuehle/msind/publikationen/ictp_yokohama_2002_parameter_design.pdf. Accessed: 20 March 2007

**[50]** Dauw DF, Albert L (1992) About the evolution of wire tool performance in wire EDM. Ann CIRP 41:221-225

**[51]** Yan MT, Li HP, Liang JF (1999) The application of fuzzy control strategy in servo feed control of wire electrical discharge machining. Int J Adv Manuf Technol 15:780-784. doi:10.1007/s001700050131

**[52]** Mingqi L, Minghui L, Guangyao X (2005) Study on the variations of form and position of the wire electrode in WEDM-HS. Int J Adv Manuf Technol 25:929-934. doi:10.1007/s00170-003-1915-4

**[53]** Dauw DF, Beltrami I (1994) High-precision wire-EDM by online wire positioning control. Ann CIRP 43:193-197

**[54]** Puri AB, Bhattaharyya B (2003) An analysis and optimisation of the geometrical inaccuracy due to wire lag phenomenon in WEDM. Int J Mach Tools Manuf 43:151-159. doi:10.1016/ S0890-6955(02)00158-X

**[55]** Dodun O (2000) Contributions to the optimization of WEDM. PhD thesis, Technical University ―Gh. Asachi‖ of Iasi, Romania

**[56]** Oprea MC (1994) Growth of the wire electrode technological capacity during wire electrical discharge machining. PhD thesis, Technical University ―Politehnica‖, Timişoara, Romania,

**[57]** Hsue WJ, Liao YS, Lu SS (1999) Fundamental geometry analysis of wire electrical discharge machining in corner cutting. Int J Mach Tools Manuf 39:651-667. doi:10.1016/S0890-6955(98)00046-7

**[58]** T.A. Spedding, Z.Q. Wang, Study on modeling of wire EDM process, Journal of Material Processing Technology 69 (1997) 18–28.

**[59]** A.B. Puri, ¯An analysis and optimisation of the geometrical inaccuracy due to Wire lag phenomenon in WEDM‖ International Journal of Machine Tools & Manufacture 43 (2003) 151-159

**[60]** Fuzhu Hana, ¯Corner error simulation of rough cutting in wire EDM‖ Precision Engineering 31 (2007) pp 331–336

**[61]** Magara T, Yatomi T, Yamada H, Kobayashi K. Study on machining accuracy in Wire EDM Part I—improvement of machining accuracy of corner parts in rough-cutting. J Jpn Soc Elect Machining Eng 1991;25(49):23–32.

**[62]** Hsue WJ, Liao YS, Lu SS. A study of control strategy of wire-EDM based on quantitative MRR analysis. Int J Elect Machining 1999;4: 33–9.

**[63]** Obara H, Kawai T, Ohsumi T, Hatano M. Combined power and path control method to improve corner accuracy of rough cuts by wireEDM(1st report). Int J Elect Machining 2003;8:27–32.

**[64]** Obara H, Kawai T, Ohsumi T, Hatano M. Combined power and path control method to improve corner accuracy of rough cuts by wireEDM(2nd report). Int J Elect Machining 2003;8:33–8.

**[65]** ‗J.A. Sanchez a,∗, J.L. Rodil a, A. Herrero b, L.N. Lopez de Lacalle a, A. Lamikiz a' ‗On the influence of cutting speed limitation on the accuracy of wire-EDM corner-cutting' ‗Journal of Materials Processing Technology 182 (2007) 574–579'

**[66]** 'Chin-Teng Lin, I-Fang Chung, Shih-Yu Huang' ‗Improvement of machining accuracy by fuzzy logic at corner parts for wire-EDM' ‗Fuzzy Sets and Systems 122 (2001) 499–511' Fuzzy Sets and Systems 122 (2001) 499–511

**[67]** M. N. Islam, N. H. Rafai, and S. S. Subramanian, ‗An Investigation into Dimensional Accuracy Achievable in Wire-cut Electrical Discharge Machining' ‗Proceedings of the World Congress on Engineering 2010 Vol III WCE 2010, June 30 - July 2, 2010, London, U.K.'

**[68]** Nihat Tosun , Can Cogunb, Gul Tosun , ‗ A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method ', Journal Of Material Processing Technology 152 (2004) 316-322

**[69]** http://taughi%20method/EXPERIMENTAL%20DESIGN%20IN%20TAGUCHI%20METHOD/INTRODUCTION%20TO%20TAGUCHI%20METHOD.htm

**[70]** Fundamentals of Quality Control and Improvement by Amitava Mitra Second Editions pages 552-556 and 595- 625