A STUDY ON EFFECT OF VARIOUS MACHINE CONTROL VARIABLES AND ANGLE SIZE ON CORNER ERROR IN WIRE ELECTRIC DISCHARGE MACHINING (WEDM)

BY

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DEDICATION

To my family for supporting me during my studies and shouldering the extra burden

To my teachers for guiding me throughout the course work and thesis phase

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DECLARATION

None of the material contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institution of learning.

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THESIS ABSTRACT (SUMMARY)

In non-conventional machining processes, various techniques involving mechanical, thermal, electrical, chemical energy and in some cases combination of these energies is utilized. Wire Electric Discharge Machining (WEDM) is a non-conventional machining process which utilizes electricity to produce thermal heat in order to remove the material. Requirement of accuracy in manufacturing of intricate parts is increasing with every day. One of the areas in WEDM, which is focal area of research is corner error because it is of significant importance in all manufactured parts specially tool and die making. Therefore, this area has been focused for research in the study.

Tungsten carbide has been machined (rough cut) on WEDM with different sets of machine controllable variables to assess their effect on corner error. Tungsten carbide material has been chosen because it is primarily used for tool manufacturing due to its hardness. Six factors i.e. pulse-on time, pulse-off time, servo voltage, wire tension, wire feed and open voltage were controlled for three levels. Taguchi method was utilized for formulation of DOE and ANOVA was conducted for statistical analysis. Calculation for optimum response was also calculated by taking all level averages as a reference value.

Based on scope of this thesis, it is concluded that corner error decreases with increase in angle. Significant factors for corner error are pulse on time, pulse off time and wire tension.

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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.

1.1 CLASSIFICATION OF NONTRADITIONAL MACHINING PROCESSES

Nontraditional machining process can broadly be subdivided into four sections:

1.1.1 Mechanical energy process

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

1.1.2 Electrochemical machining process

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

1.1.3 Chemical machining process

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

1.1.4 Thermal energy process

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

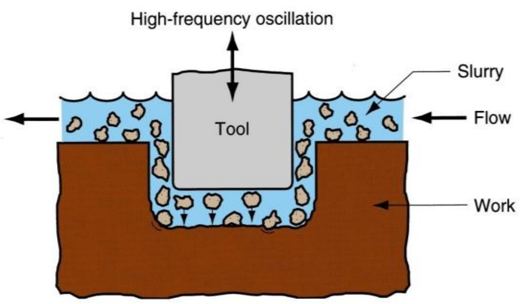
1.2 MECHANICAL ENERGY PROCESS

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).

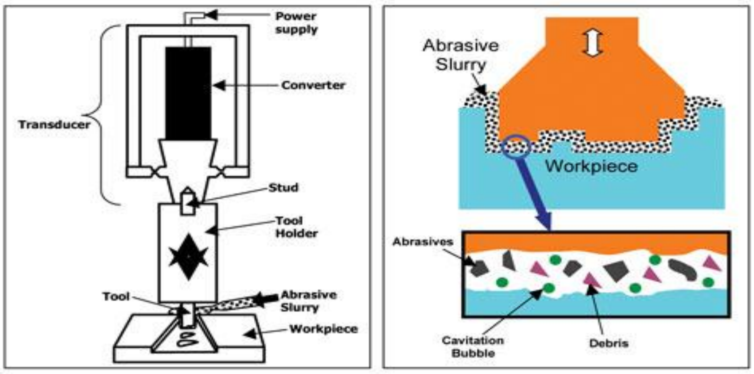
1.2.1 Ultrasonic machining

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

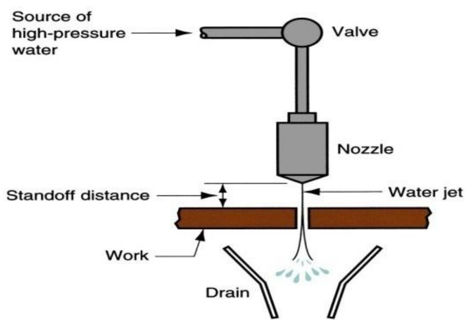
1.2.1.1 Applications of ultrasonic machining

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. "Coining operations".

1.2.2 Water jet cutting (WJC)

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



Schematic of Water Jet Cutting

Figure 1.3

1.2.2.1 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.

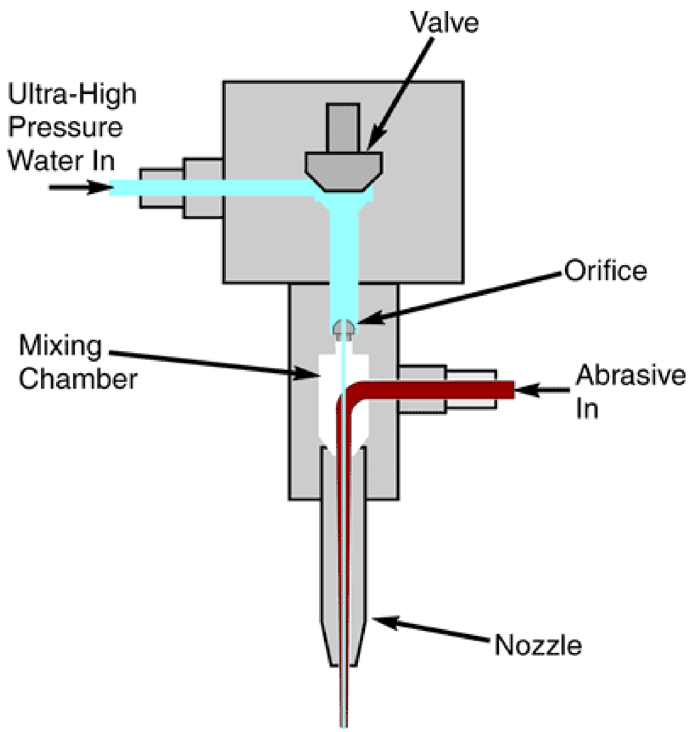
1.2.2.2 Advantages of water jet cutting (WJC)

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.

1.2.3 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 (a silicate 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

1.2.3.1 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).

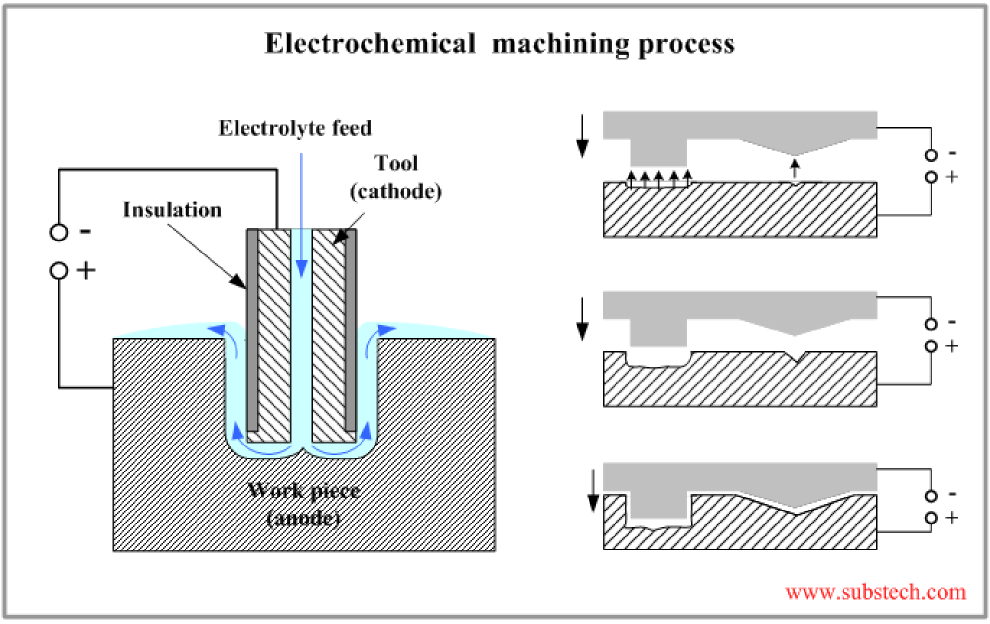
1.3 ELECTROCHEMICAL MACHINING PROCESS

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

1.3.1 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.

1.3.2 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.

1.3.3 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.

1.3.4 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:

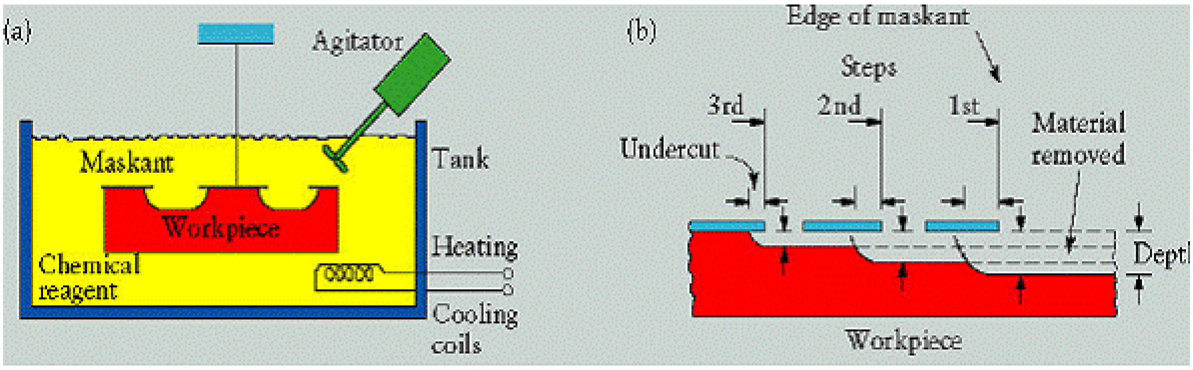
a. De-plating responsible for 95% of metal removal.
b. As machining is mostly by electrochemical action, grinding wheel lasts much longer.

1.4 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 applied to 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

1.4.1 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.

1.4.2 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.

1.4.3 Chemical engraving

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

1.4.4 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.

1.5 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.

1.5.1 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).

1.5.2 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.

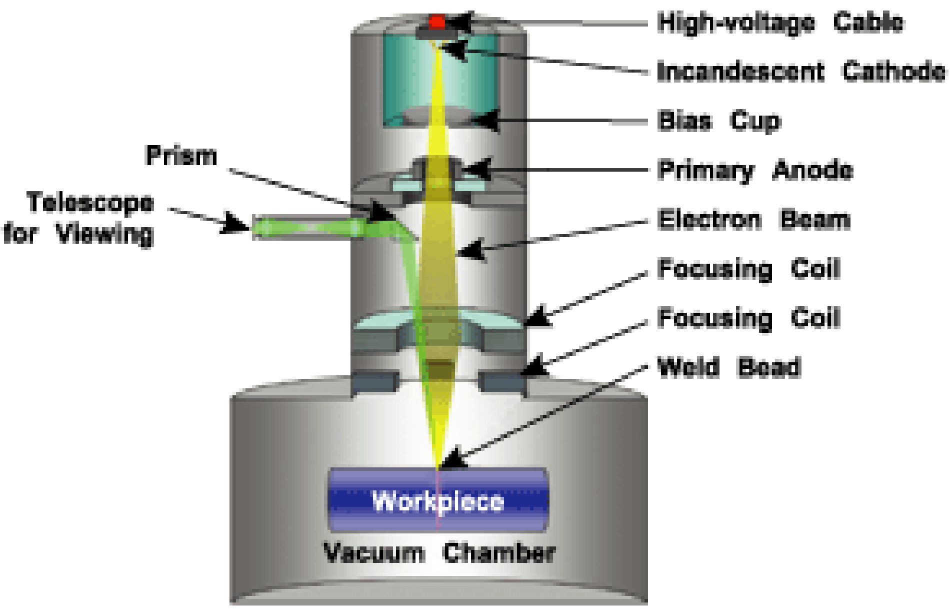
b. Ideal for micromachining.

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.

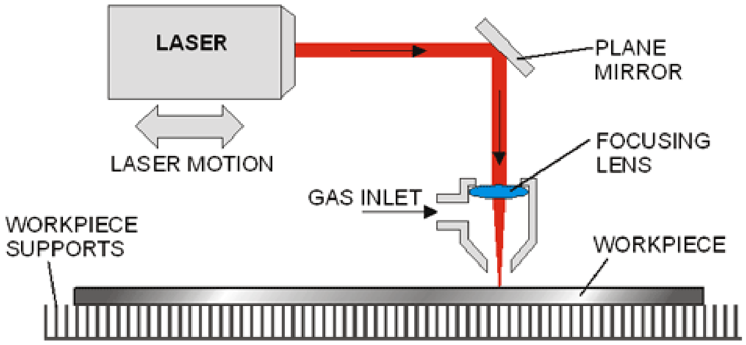


Schematic of Electron Beam Machining Operation

Figure 1.8

1.5.3 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.

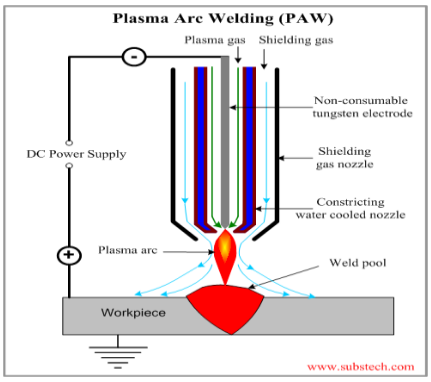
b. Drilling small diameter holes - down to 0.025 mm (0.001 in).

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.

1.5.4 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

1.5.5 Electric discharge processes

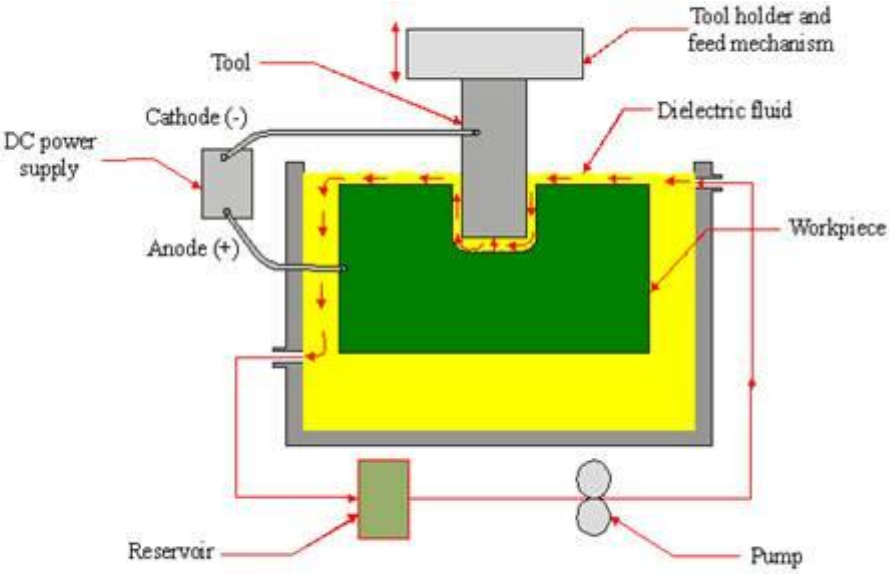
In electric discharge process, metal is removed by a series of discrete electrical discharges (sparks) causing localized temperatures high enough to melt or vaporize the metal. It is primarily used only on electrically conducting work materials. The two main processes are:

a. Electric Discharge Machining (Die Sinking).

b. Wire Electric Discharge machining (WEDM).

1.5.5.1 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 new research, 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.

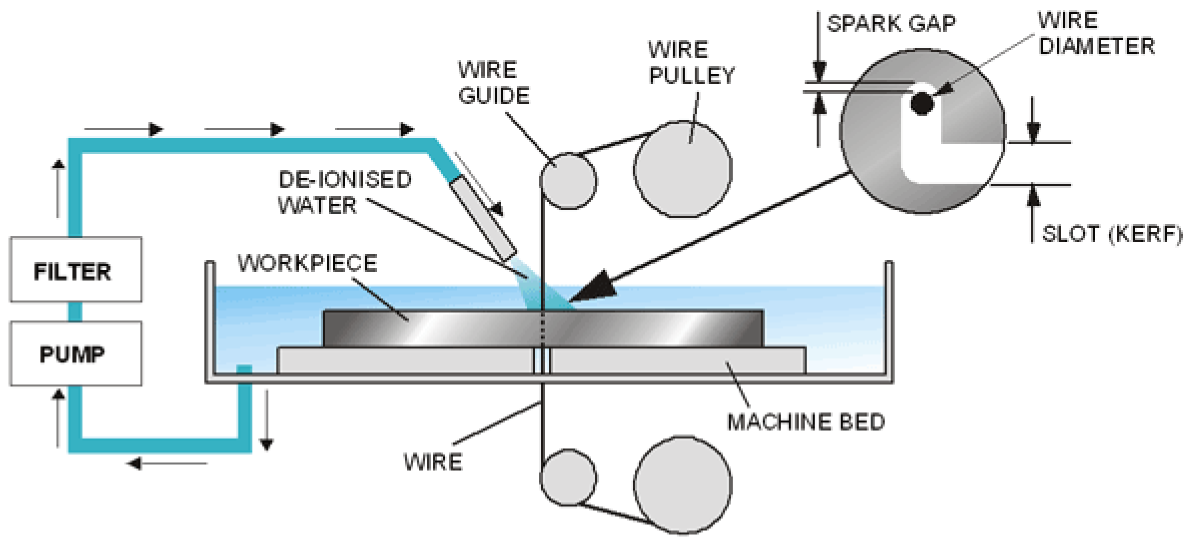
Areas of application of EDM are:

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.

1.5.5.2 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

1.6 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

1.6.1 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.

1.6.2 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.

1.6.3 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.

1.6.4 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.

1.6.5 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 above or below the centerline, it means the top and bottom nozzles are not balanced.

1.6.6 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 jump from the wire.

b. The spark hits the workpiece.

c. The spark is very hot and it melts a small section of the workpiece and a 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 times a 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.

1.6.7 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 of material 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 can use highest wire tensions for better tolerance.

1.6.8 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

1.6.9 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 discharges in 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.

2.1 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 switched off, 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 mm^2/min can also be achieved. Surface quality which can be achieved by WEDM is 0.04-0.25 μRa.

2.2 WEDM APPLICATIONS

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

2.2.1 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.

2.2.2 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].

2.2.3 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.

2.3 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.

2.3.1 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.

2.3.1.1 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 paragraphs same are briefly explained.

2.3.1.1.1 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].

2.3.1.1.2 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.

2.3.1.1.3 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.

2.3.1.1.4 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 surface roughness.

2.3.2 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.

2.4 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.

2.4.1 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.

2.4.2 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.

2.4.2.1 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.

2.4.2.2 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.

2.4.3 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].

2.5 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.

2.5.1 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. The front wheel and rear wheel does not travel in same path. This effect is also termed as 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.

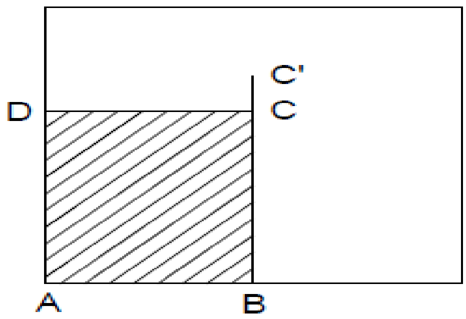
Study has been conducted both experimental and mathematical on the subject and only variable having direct relationship with the corner error identified is wire speed. If the wire speed is more, a profound corner error is obvious; however, at slow speeds cover error is not appreciable. However, so far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

2.5.2 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.

2.5.3 Method to remove corner error

One of the methods to remove corner error in case of orthogonal corner without reducing speed is by over travelling the defined path. Thereafter, wire can travel back to corner edge and then cut in appropriate direction. This concept is explained by Figure 2.1 appended below:



Method to remove corner error

Figure 2.1

This methodology is not only limited on corner error but it can only be used for cutting the curves provided the equation for curve is known. However, this simple solution cannot be adopted for curves whose equation is not known.

2.6 USING WEDM FOR IMPROVED CORNER CUTTING ACCURACY OF THIN PARTS

2.6.1 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 resistive to 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:

2.6.1.1 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.

2.6.1.2 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.

2.6.1.3 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.

2.6.1.4 Material removal rate increase

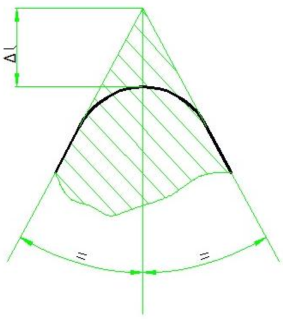
During the machining process near the corner, it is difficult to dissipate all the heat generated due to electric sparking. This difficultly results in increase of material removal rate near the corner. These phenomena should be seen in direct relationship with the above mentioned phenomena of intensification 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.

2.6.2 Segmentation of corner error

In order to focus on the subject, studies on corner error have been subdivided into three segments; first segment is of error for more than 135^o, the second is between 30^o-135^o and the third is for less than 30^o. This segmentation is primarily conducted on the basis of major causes of geometrical error. In the first group i.e. angle with more than 135^o, the error in comparison to other group is relatively smaller and the major cause is wire deflection. In the last segment i.e. angle less than 30^o the major cause is intense sparking at the corner. As far as the middle group (angle between 30^o to 135^o) is concerned, the geometrical error is significantly due to both phenomena (wire deflection and instance sparking) as already highlighted for above two segments.

2.6.3 Definition of corner error

Definition of corner error is fundamental to understand as it defines all of the further studies. Corner error is the difference in length between the top of ideal corner and the middle of the corner actually formed after machining. It is usually enumerated as ΔL.



Measurement of corner error

Figure 2.2

2.6.4 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.

2.7 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.

2.8 CORNER ERROR SIMULATION OF ROUGH CUTTING IN WEDM

Fuzhan Han [60] has indicated that one of the important areas of research in WEDM is the accuracy of corner error. However, if only research is conducted in this area using traditional methods then research in this area will lag behind; therefore, it is important that modern methods of research are actually pursued to remain abreast with modern development and research in this sphere. In the modern techniques, computer simulation is the way forward. Research has also been conducted in past about the corner machining to bring improvement in the corner accuracy during a rough cut [61-64].

Fuzhan Han [60] developed a simulation model. Simulation results are compared with experimental results. The experimental results and simulation results are found to be approximately same for obtuse angle and right angle. However, the simulation and experimental results were appreciably different for sharp angles.

2.9 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.

2.10 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. One of the areas in WEDM which is focal area of research is corner error since it is of significant importance in all manufactured parts especially tool and die making. Research work is available on various aspects of corner error such as wire lag, segmentation of corner error, corner error simulation etc. However, little research has been reported on corner error while machining tungsten carbide as workpiece, where as it is one of the most widely used materials for construction of form tools. The main aim of this thesis will be to identify the effects of various machine control variables and angle size on corner error in wire electric discharge machining while machining tungsten carbide.

CHAPTER 3

DESIGN OF EXPERIMENT, EXPERIMENTATION AND ANALYSIS

3.1 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.

3.1.1 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.

3.1.2 Design of experiment

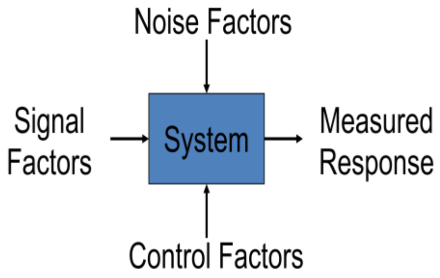
D.O.E is a well planned set of experiments. All parameters of interest are varied over a specified range. It is a comprehensive approach to obtain systematic data. Mathematically speaking, such a complete set of experiments gives the desired results. However, number of experiments and resources (materials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

3.1.3 Taguchi method

Taguchi method is based on orthogonal arrays which give much reduced variance for the experiments with optimum settings of control parameters. The main advantage of Taguchi's method is that it reduces the prohibitively large requirement of 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.

3.2 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.

3.3 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 to understand and conduct mathematical modeling for ANOVA. However, softwares are available which facilitate in determining the significant factors.

3.4 SIGNAL TO NOISE RATIO

One of the most important parameters in design is its effectiveness. However, in order to develop the same, a methodology needs to be developed that can evaluate the effectiveness of design parameters on quality characteristics. Output (Quality) characteristics should include both the acceptable and unacceptable portions. The desirable characteristics are analogous to signal while undesirable characteristics are analogous to the noise. Taguchi pooled the two factors into a singular component and termed it “Signal to noise ratio”. In mathematical term, S/N ratio can be dependent on three circumstances; target is the requirement, smaller results are desirable or larger is the requirement.

3.5 EXPERIMENTATION

Tungsten carbide K20 (Density 14.6 gm/cm^3, bending strength 3200 N/mm^2, WC grain size 0.7 µm) was procured from local market. Six machine controllable variables were selected and controlled for three levels. The machine variables were pulse on time, pulse off time, servo voltage, wire tension, wire feed and open voltage. Table 3.1 outlines the six 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
SIX MACHINE VARIABLES

Factors	UNITS	LEVEL 1	LEVEL 2	LEVEL 3
Open voltage	Volts	110	115	120
Pulse on time	Micro Sec	04	05	06
Pulse off time	Micro Sec	25	28	31
Servo voltage	Volts	40	50	60
Wire feed	mm/s	110	140	170
Wire tension	Gms	1180	1395	1610

3.5.1 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 L18 was utilized for current research. Orthogonal Array is tabulated as Table 3.2.

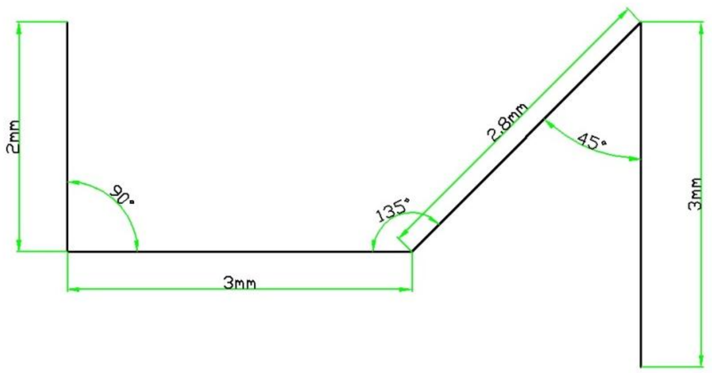
TABLE 3.2

TAGUCHI ORTHOGONAL ARRAY

Run	OPEN VOLTAGE (Volts)	PULSE ON (Micro sec)	PULSE OFF (Micro sec)	SERVO VOLT (Volt)	WIRE FEED (mm/s)	WIRE TENSION (Grams)
1	115	4	25	50	140	1610
2	115	6	31	40	110	1395
3	120	6	25	60	140	1180
4	120	4	28	40	170	1395
5	115	5	28	60	170	1180
6	110	4	25	40	110	1180
7	110	6	31	60	170	1610
8	110	5	28	50	140	1395
9	120	5	31	50	110	1610
10	120	5	25	60	110	1395
11	120	6	28	40	140	1610
12	115	6	25	50	170	1395
13	110	4	31	60	140	1395
14	110	5	25	40	170	1610
15	115	5	31	40	140	1180
16	120	4	31	50	170	1180
17	110	6	28	50	110	1180
18	115	4	28	60	110	1610

3.5.2 Machining of specimen

Eighteen cuts on the workpiece as per DOE were made at KTDMC by selecting different parameters. Shape of the cut along with the dimensions is shown in Figure 3.2



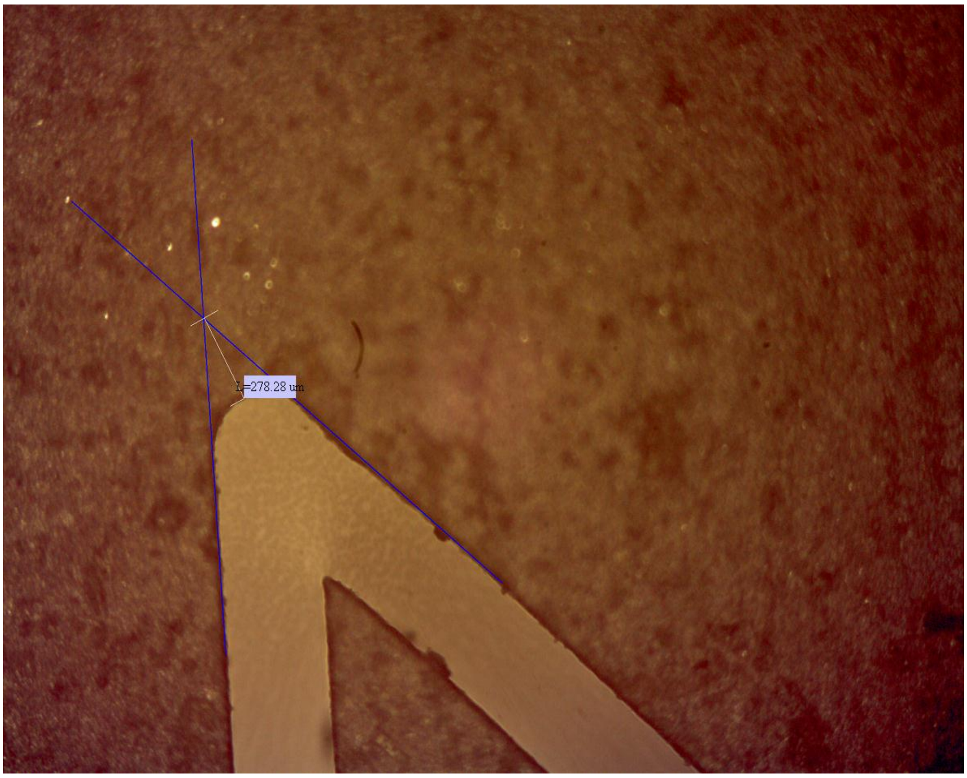
Shape of machined cut

Figure 3.2

3.5.3 Measurement of corner error

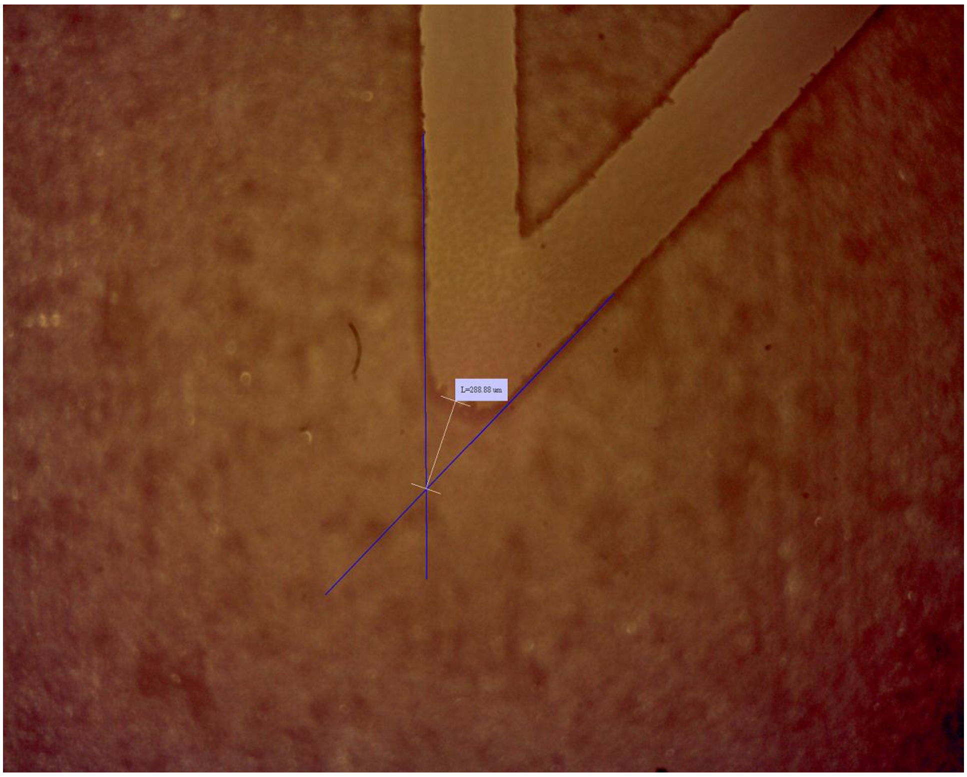
Photography of the machined segments was conducted using microscope at IME lab. Measurement of the corner error was undertaken utilizing “Infinity” software held at IME Department. Two snapshots each for 45^0, 90^0 and 135^0 depicting corner error reading are attached as Figure 3.3.1 to 3.5.2.

Each reading was undertaken thrice to obtain better results. Average reading in Table 3.3 - 3.5 was taken as a reference and used for further analysis. Table 3.6 – 3.8 indicate the corner error in case of each run undertaken for 45^0, 90^0 and 135^0 respectively.



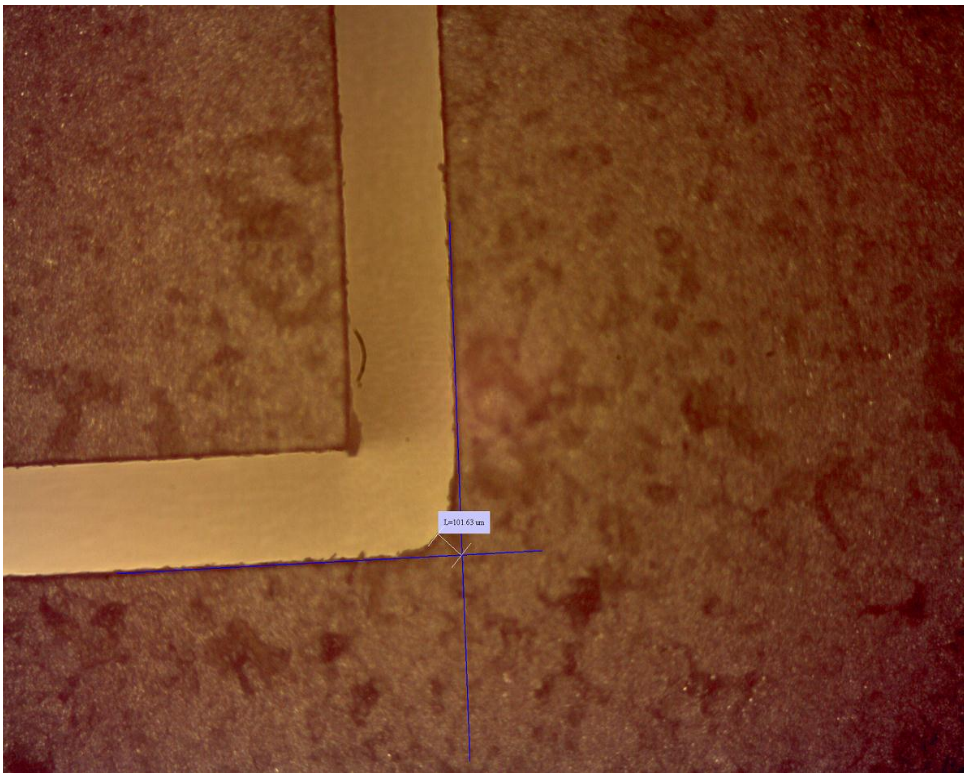
Measurement of corner error at 45^{O}

Figure 3.3.1



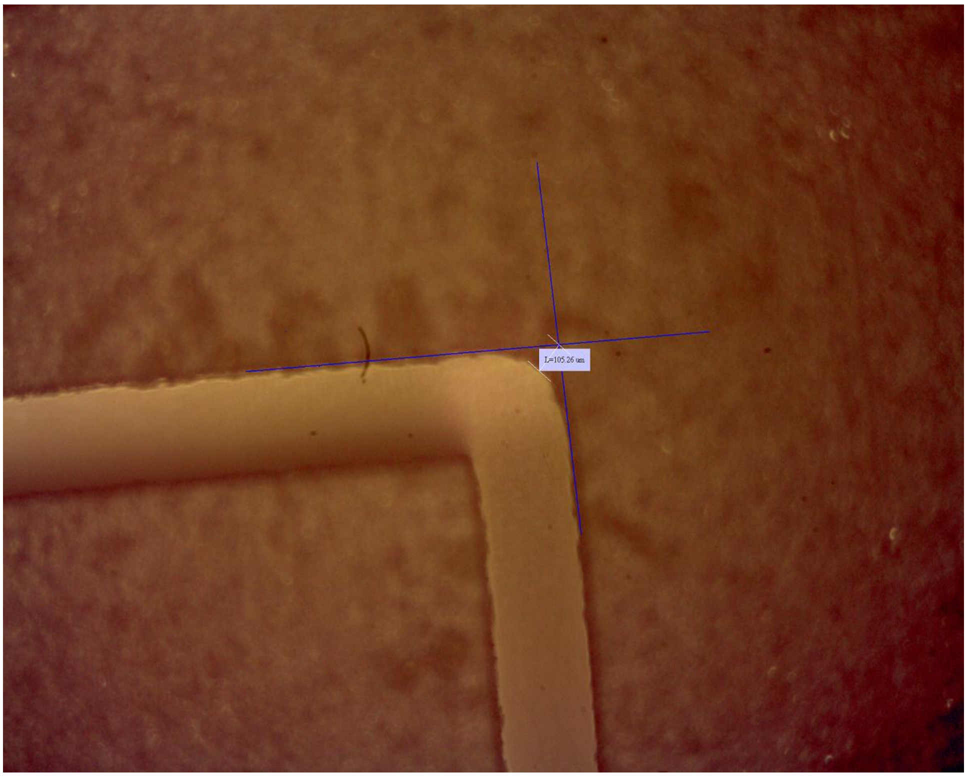
Measurement of corner error at 45^{O}

Figure 3.3.2



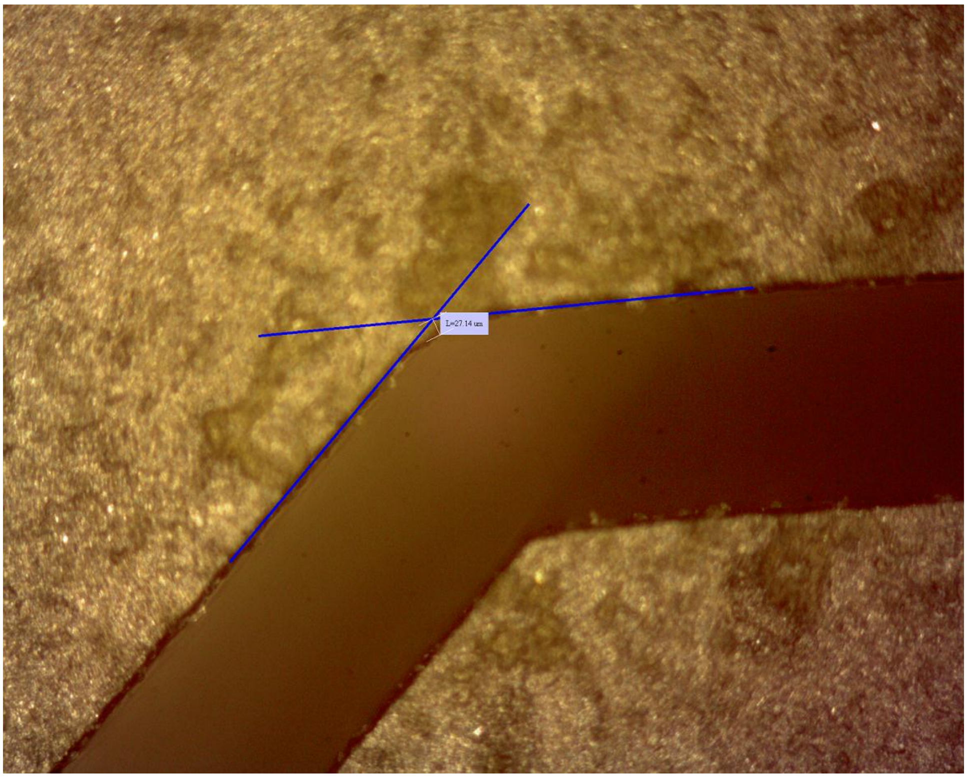
Measurement of corner error at 90^{O}

Figure 3.4.1



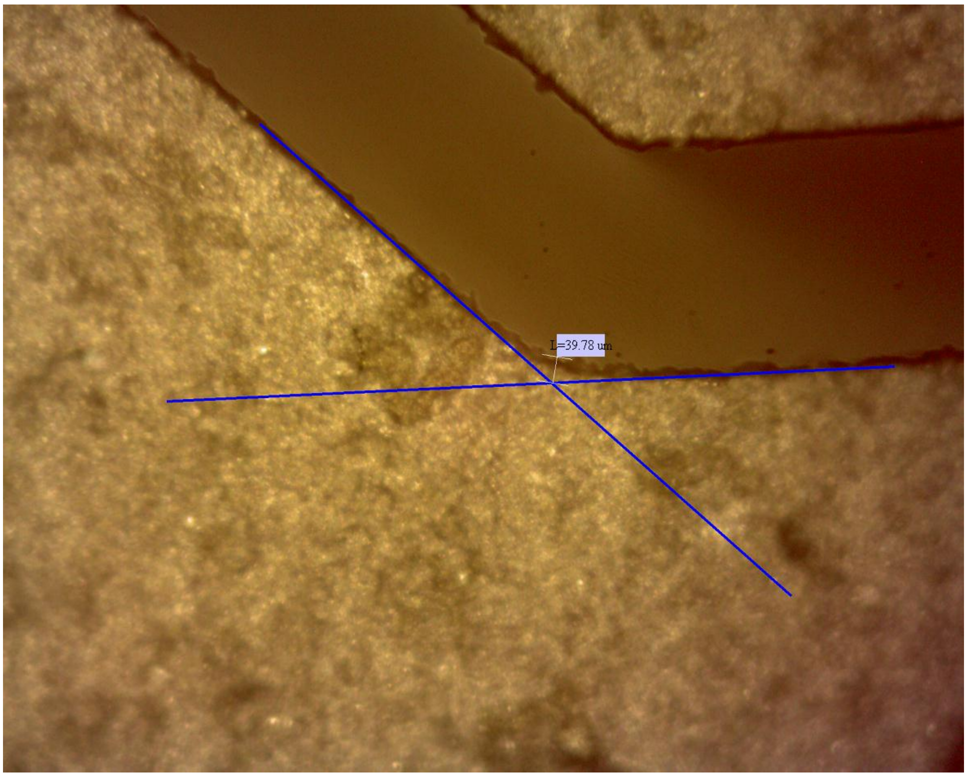
Measurement of corner error at 95^{O}

Figure 3.4.2



Measurement of corner error at 135^{O}

Figure 3.5.1



Measurement of corner error at 135^{O}

Figure 3.5.2

TABLE 3.3

CORNER ERROR READINGS AT 45^{O}

RUN	READING 1 (µm)	READING 2 (µm)	READING 3 (µm)	AVERAGE (µm)
1	312.02	312.56	306.7	310.43
2	282.24	280.65	277.14	280.01
3	322.45	316.75	320.98	320.06
4	307.54	308.88	309.41	308.61
5	280.47	283.73	276.49	280.23
6	360.54	356.22	357.81	358.19
7	245.65	247.26	243.95	245.62
8	293.45	296.62	297.54	295.87
9	285.46	289.21	278.95	284.54
10	310.45	311.38	311.95	311.26
11	261.54	259.18	260.15	260.29
12	291.84	289.89	289.11	290.28
13	265.45	262.18	262.57	263.40
14	271.49	264.87	268.45	268.27
15	251.12	248.97	249.82	249.97
16	326.49	325.5	324.54	325.51
17	294.25	295.8	299.45	296.50
18	280.12	280.94	282.54	281.20

TABLE 3.4 CORNER ERROR READINGS AT 90^{O}				
RUN	**READING 1 (µm)**	**READING 2 (µm)**	**READING 3 (µm)**	**AVERAGE (µm)**
1	124.25	117.09	118.54	119.96
2	104.51	96.85	99.24	100.20
3	118.24	111.62	117.54	115.80
4	119.28	112.28	115.93	115.83
5	96.34	102.76	102.4	100.50
6	141.26	128.55	134.29	134.70
7	97.25	101.3	103.25	100.60
8	117.56	113.0	114.32	114.96
9	110.26	100.87	109.24	106.79
10	116.25	114.96	119.25	116.82
11	102.23	97.64	95.27	98.38
12	115.24	107.48	113.25	111.99
13	95.26	103.06	98.26	98.86
14	102.46	102.33	97.25	100.68
15	90.25	95.98	95.23	93.82
16	130.26	119.55	125.64	125.15
17	114.51	111.97	107.45	111.31
18	104.25	109.13	103.24	105.54

TABLE 3.5 CORNER ERROR READINGS AT 135^{O}				
RUN	**READING 1 (µm)**	**READING 2 (µm)**	**READING 3 (µm)**	**AVERAGE (µm)**
1	33.24	34.31	36.52	34.69
2	32.25	32.81	28.54	31.20
3	36.52	36.59	31.29	34.80
4	33.24	35.58	36.21	35.01
5	31.25	31.5	36.91	33.22
6	40.27	43.05	37.25	40.19
7	27.45	29.03	31.24	29.24
8	34.21	35.34	29.51	33.02
9	31.15	35.55	34.46	33.72
10	32.54	35.41	36.42	34.79
11	27.45	31.73	33.61	30.93
12	39.25	30.68	33.21	34.38
13	32.45	27.19	33.21	30.95
14	28.65	28.45	32.45	29.85
15	27.43	31.58	30.21	29.74
16	36.58	34.17	38.54	36.43
17	36.25	30.96	35.24	34.15
18	34.52	33.32	32.15	33.33

TABLE 3.6 CORNER ERROR AT 45^{O}							
Run	OPEN VOLTAGE (Volt)	PULSE ON (Micro sec)	PULSE OFF (Micro sec)	SERVO VOLT (Volt)	WIRE FEED (mm/s)	WIRE TENSION (Grams)	RESPONSE AT 45^{O} (μm)
1	115	4	25	50	140	1610	310.43
2	115	6	31	40	110	1395	280.01
3	120	6	25	60	140	1180	320.06
4	120	4	28	40	170	1395	308.61
5	115	5	28	60	170	1180	280.23
6	110	4	25	40	110	1180	358.19
7	110	6	31	60	170	1610	245.62
8	110	5	28	50	140	1395	295.87
9	120	5	31	50	110	1610	284.54
10	120	5	25	60	110	1395	311.26
11	120	6	28	40	140	1610	260.29
12	115	6	25	50	170	1395	290.28
13	110	4	31	60	140	1395	263.40
14	110	5	25	40	170	1610	268.27
15	115	5	31	40	140	1180	249.97
16	120	4	31	50	170	1180	325.51
17	110	6	28	50	110	1180	296.50
18	115	4	28	60	110	1610	281.20

TABLE 3.7

CORNER ERROR AT 90^O

Run	OPEN VOLTAGE (Volt)	PULSE ON (Micro sec)	PULSE OFF (Micro sec)	SERVO VOLT (Volt)	WIRE FEED (mm/s)	WIRE TENSION (Grams)	RESPONSE AT 90^O (μm)
1	115	4	25	50	140	1610	119.96
2	115	6	31	40	110	1395	100.2
3	120	6	25	60	140	1180	115.8
4	120	4	28	40	170	1395	115.83
5	115	5	28	60	170	1180	100.5
6	110	4	25	40	110	1180	134.70
7	110	6	31	60	170	1610	100.6
8	110	5	28	50	140	1395	114.96
9	120	5	31	50	110	1610	106.79
10	120	5	25	60	110	1395	116.82
11	120	6	28	40	140	1610	98.38
12	115	6	25	50	170	1395	111.99
13	110	4	31	60	140	1395	98.86
14	110	5	25	40	170	1610	100.68
15	115	5	31	40	140	1180	93.82
16	120	4	31	50	170	1180	125.15
17	110	6	28	50	110	1180	111.31
18	115	4	28	60	110	1610	105.54

TABLE 3.8

CORNER ERROR AT 135^{O}

Run	OPEN VOLTAGE (Volt)	PULSE ON (Micro sec)	PULSE OFF (Micro sec)	SERVO VOLT (Volt)	WIRE FEED (mm/s)	WIRE TENSION (Grams)	RESPONSE AT 135^{O} (µm)
1	115	4	25	50	140	1610	34.69
2	115	6	31	40	110	1395	31.2
3	120	6	25	60	140	1180	34.8
4	120	4	28	40	170	1395	35.01
5	115	5	28	60	170	1180	33.22
6	110	4	25	40	110	1180	40.19
7	110	6	31	60	170	1610	29.24
8	110	5	28	50	140	1395	33.02
9	120	5	31	50	110	1610	33.72
10	120	5	25	60	110	1395	34.79
11	120	6	28	40	140	1610	30.93
12	115	6	25	50	170	1395	34.38
13	110	4	31	60	140	1395	30.95
14	110	5	25	40	170	1610	29.85
15	115	5	31	40	140	1180	29.74
16	120	4	31	50	170	1180	36.43
17	110	6	28	50	110	1180	34.15
18	115	4	28	60	110	1610	33.33

3.6 ANALYSIS

Corner errors for all three angles (45^0, 90^0 and 135^0) as mentioned in Table 3.6 - 3.8 were fed into software. Main effects were analyzed and ANOVA was conducted. Signal to noise ratios were also calculated. It is desired that there should be no corner error. Therefore, equation of signal to noise ratio "smaller the better" was used for further mathematical calculations.

$$L_{ij} = \frac{1}{n}\sum_{i=1}^{n} y_{ij}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

'n' symbolize number of runs

L_{ij}: Quality loss

y_{ij} : result of the experiment for desired response

Equation (2) represents signals to noise ratio whose units are decibel (db)

$$\eta_{ij} = -10\log_{10}L_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Aim of engineers is to maximize signal to noise ratio, if η_{ij} is analyzed and contrary to this Lij (the quality loss) would be minimized

$$SSN_{ij} = \frac{\eta^{ij} - \eta_j^{\min}}{\eta_j^{\max} - \eta_j^{\min}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

SSN is defined as scaled signal to noise ratio.

3.6.1 ANOVA for corner error

In order to determine significant factors affecting the corner error at different angles, statistical technique i.e. ANOVA was utilized. Calculated values clearly differentiate between significant factors and non significant factors.

3.6.2 Signal to Noise ratio for corner error

Signal to noise ratio is a combination of two factors, i.e. desirable and non desirable. Signal to noise ratio is calculated for three conditions. The three conditions are target is the requirement, smaller results are desirable or larger are the requirement. In the case of corner error, requirement is that there should be no corner error. Therefore, the condition smaller results are desirable is utilized.

3.6.2.1 Signal to noise ratio for corner error at 45^{o} and graphs

Signal to noise ratio for corner error at 45^{o} is calculated using equation 1 and 2. Detail of calculations is tabulated in Table 3.9.

TABLE 3.9 SIGNAL TO NOISE RATIO AT 45^{O}							
Run	**OPEN VOLTAGE (Volt)**	**PULSE ON (Micro sec)**	**PULSE OFF (Micro sec)**	**SERVO VOLT (Volt)**	**WIRE FEED (mm/s)**	**WIRE TENSION (Grams)**	**SIGNAL TO NOISE RATIO AT 45^{O}**
1	115	4	25	50	140	1610	- 49.83
2	115	6	31	40	110	1395	- 48.94
3	120	6	25	60	140	1180	- 50.10
4	120	4	28	40	170	1395	- 49.78
5	115	5	28	60	170	1180	- 48.95
6	110	4	25	40	110	1180	- 51.08
7	110	6	31	60	170	1610	- 47.80
8	110	5	28	50	140	1395	-49.42
9	120	5	31	50	110	1610	- 49.08
10	120	5	25	60	110	1395	- 49.86
11	120	6	28	40	140	1610	- 48.30
12	115	6	25	50	170	1395	- 49.25
13	110	4	31	60	140	1395	- 48.41
14	110	5	25	40	170	1610	- 48.57
15	115	5	31	40	140	1180	- 47.95
16	120	4	31	50	170	1180	- 50.25
17	110	6	28	50	110	1180	- 49.44
18	115	4	28	60	110	1610	- 48.98

Significant and non significant factors identified after conducting ANOVA for signal to noise ration at corner error of 45^{o} are Pulse ON time, Pulse OFF time and Wire Tension. Detail of calculations is tabulated in Table 3.10.

TABLE 3.10

ANOVA FOR CORNER ERROR AT 45^{O} (SIGNAL TO NOISE RATIO)

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	SIGNIFICANCE
A Open Voltage	1.10	2	0.55	2.18	0.2088	Not Significant
B Pulse On	2.25	2	1.13	4.46	0.0774	Significant
C Pulse OFF	3.32	2	1.66	6.58	0.0398	Significant
D Servo Voltage	0.96	2	0.48	1.91	0.2422	Not Significant
E Wire Feed	1.07	2	0.53	2.11	0.2163	Not Significant
F Wire Tension	2.28	2	1.14	4.51	0.0759	Significant
Residual	1.26	5	0.25			
Cor Total	12.25	17				

Graph indicating relationship between signal to noise ratio of corner errorr at 45^{o} and six machine control variables (Open Voltage, Pulse ON time, Pulse OFF time, Servo Voltage, Wire Feed and Wire Tension) are shown in Figure 3.3.1.1 to 3.3.1.6.

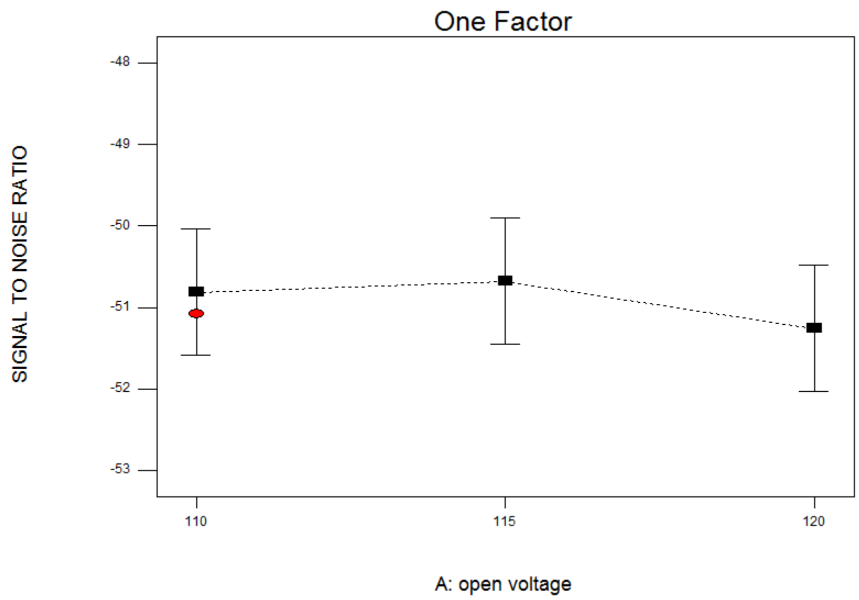


Figure 3.6.1.1 Relationship between Open Voltage and Corner Error (Signal to noise ratio) at 45^{O}

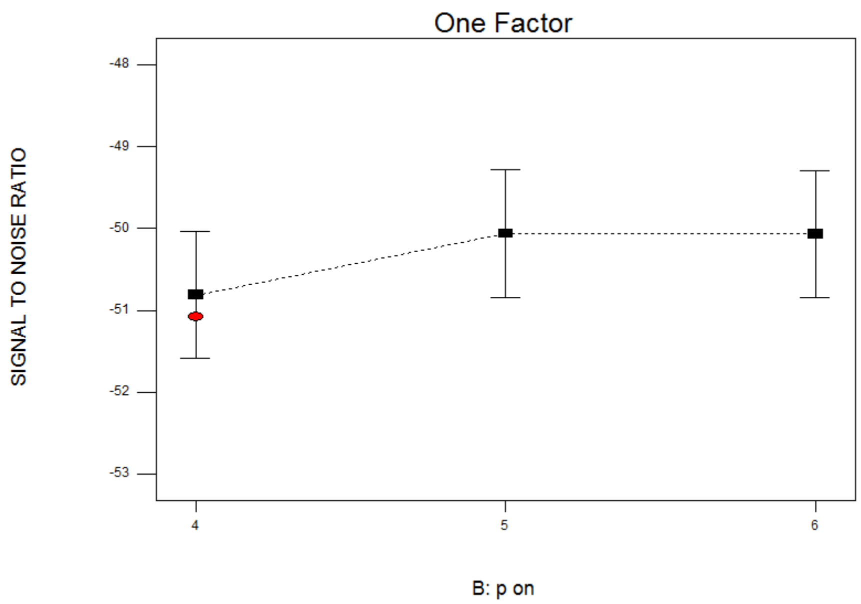


Figure 3.6.1.2 Relationship between Pulse ON time and Corner Error (Signal to noise ratio) at 45^{O}

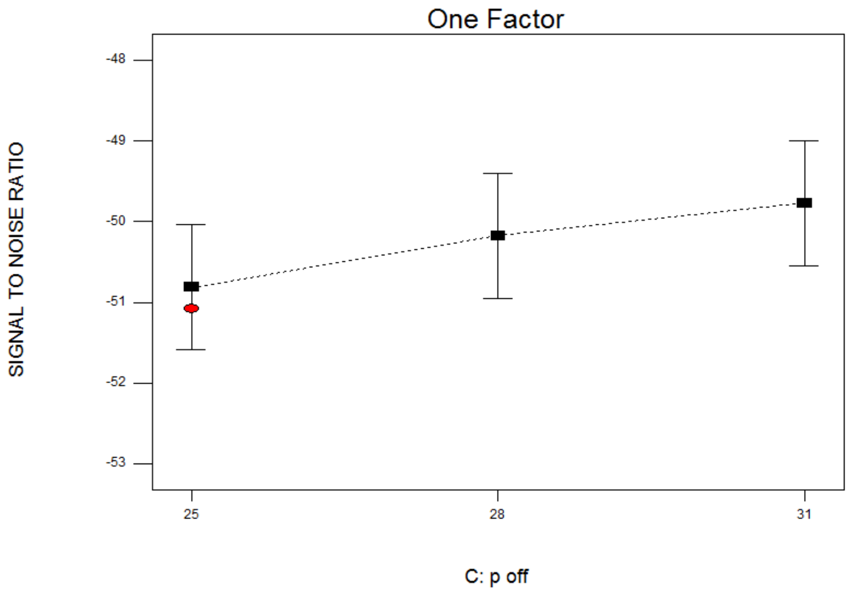


Figure 3.6.1.3 Relationship between Pulse OFF time and Corner Error (Signal to noise ratio) at 45^{O}

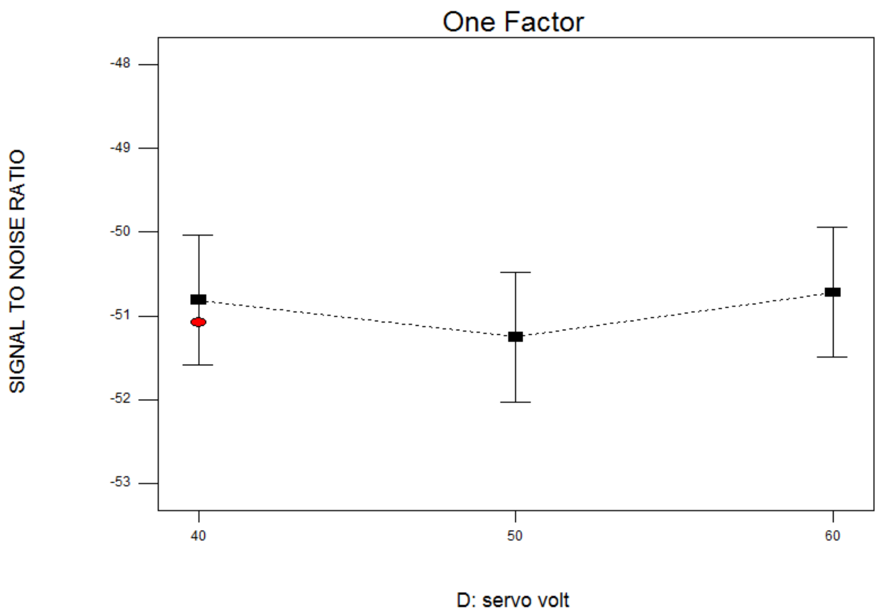


Figure 3.6.1.4 Relationship between Servo Volatge and Corner Error (Signal to noise ratio) at 45^{O}

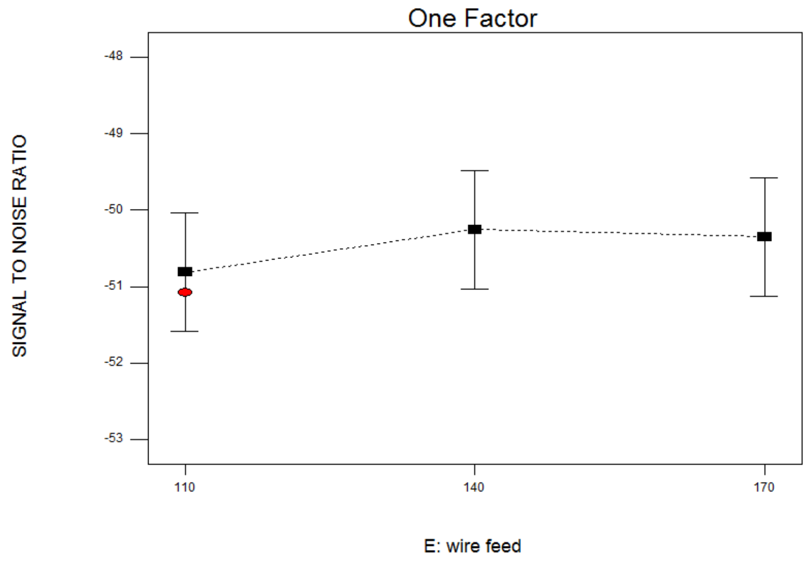


Figure 3.6.1.5 Relationship between Wire feed and Corner Error (Signal to noise ratio) at 45^{O}

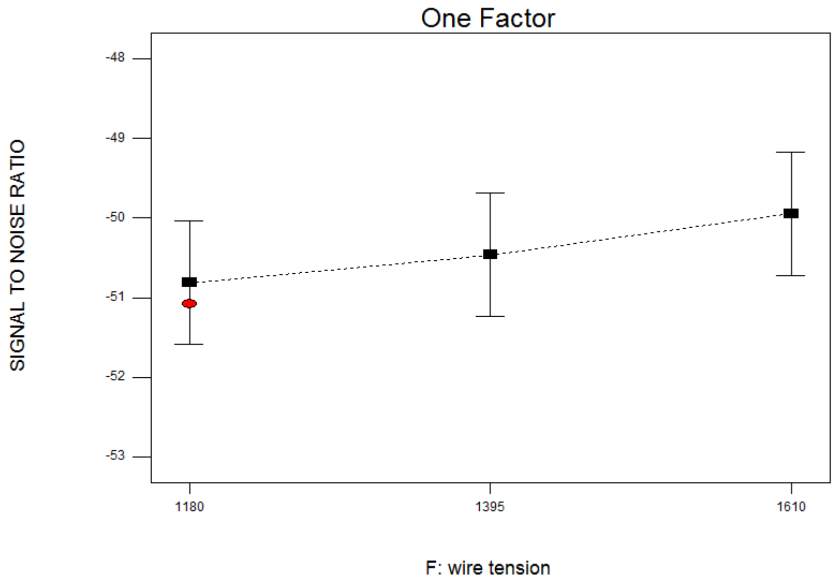


Figure 3.6.1.6 Relationship between Wire Tension and Corner Error (Signal to noise ratio) at 45^{O}

3.6.2.2 Signal to noise ratio for corner error at 90^{O} and graphs

Signal to noise ratio for corner error at 90^{O} is calculated using equation 1 and 2. Detail of calculations is tabulated in Table 3.11.

TABLE 3.11

SIGNAL TO NOISE RATIO AT 90^{O}

Run	OPEN VOLTAGE (Volt)	PULSE ON (Micro sec)	PULSE OFF (Micro sec)	SERVO VOLT (Volt)	WIRE FEED (mm/s)	WIRE TENSION (Grams)	SIGNAL TO NOISE RATIO AT 90^{O}
1	115	4	25	50	140	1610	- 41.58
2	115	6	31	40	110	1395	- 40.01
3	120	6	25	60	140	1180	- 41.27
4	120	4	28	40	170	1395	- 41.27
5	115	5	28	60	170	1180	- 40.04
6	110	4	25	40	110	1180	- 42.58
7	110	6	31	60	170	1610	- 40.05
8	110	5	28	50	140	1395	- 41.21
9	120	5	31	50	110	1610	- 40.57
10	120	5	25	60	110	1395	- 41.35
11	120	6	28	40	140	1610	- 39.85
12	115	6	25	50	170	1395	- 40.98
13	110	4	31	60	140	1395	- 39.90
14	110	5	25	40	170	1610	- 40.05
15	115	5	31	40	140	1180	- 39.44
16	120	4	31	50	170	1180	- 41.94
17	110	6	28	50	110	1180	- 40.93
18	115	4	28	60	110	1610	- 40.46

Significant and non significant factors identified after conducting ANOVA for signal to noise ration at corner error of 90^{o} are Pulse ON time and Pulse OFF time. Detail of calculations is tabulated in Table 3.12.

TABLE 3.12

ANOVA FOR CORNER ERROR AT 90^{O} (SIGNAL TO NOISE RATIO)

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	SIGNIFICANCE
A Open Voltage	1.18	2	0.59	1.79	0.2591	Not Significant
B Pulse On	2.64	2	1.32	4.02	0.0910	Significant
C Pulse OFF	3.03	2	1.52	4.61	0.0732	Significant
D Servo Voltage	1.83	2	0.92	2.79	0.1539	Not Significant
E Wire Feed	0.59	2	0.30	0.90	0.4629	Not Significant
F Wire Tension	1.12	2	0.56	1.70	0.2739	Not Significant
Residual	1.64	5	0.33			
Cor Total	12.04	17				

Graph indicating relationship between signal to noise ratio of corner errorr at 90^{o} and six machine control variables (Open Voltage, Pulse ON time, Pulse OFF time, Servo Voltage, Wire Feed and Wire Tension) are shown in Figure 3.3.2.1 to 3.3.2.6.

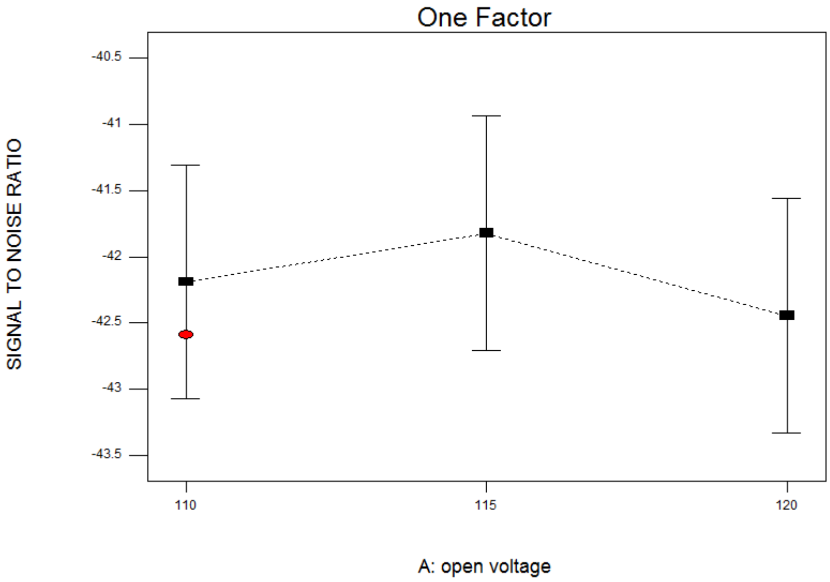


Figure 3.6.2.1 Relationship between Open Voltage and Corner Error (Signal to noise ratio) at 90^{O}

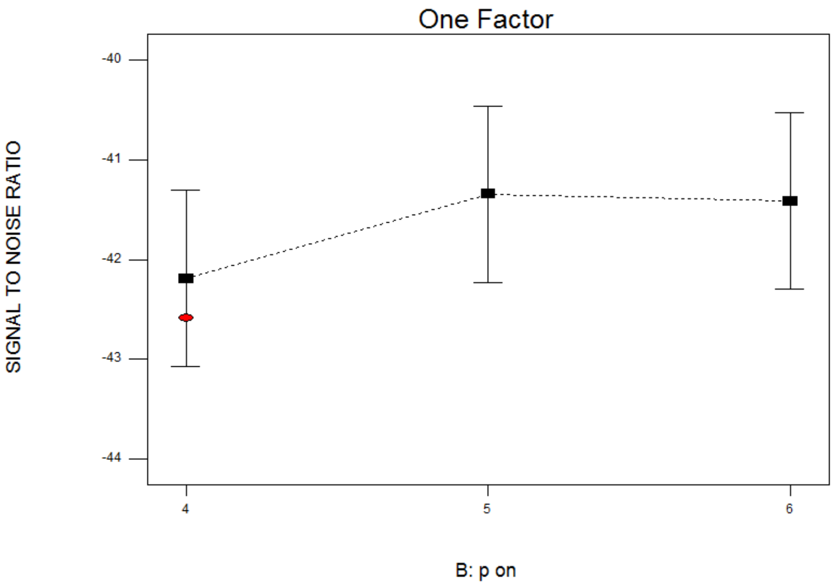


Figure 3.6.2.2 Relationship between Pulse ON time and Corner Error (Signal to noise ratio) at 90^{O}

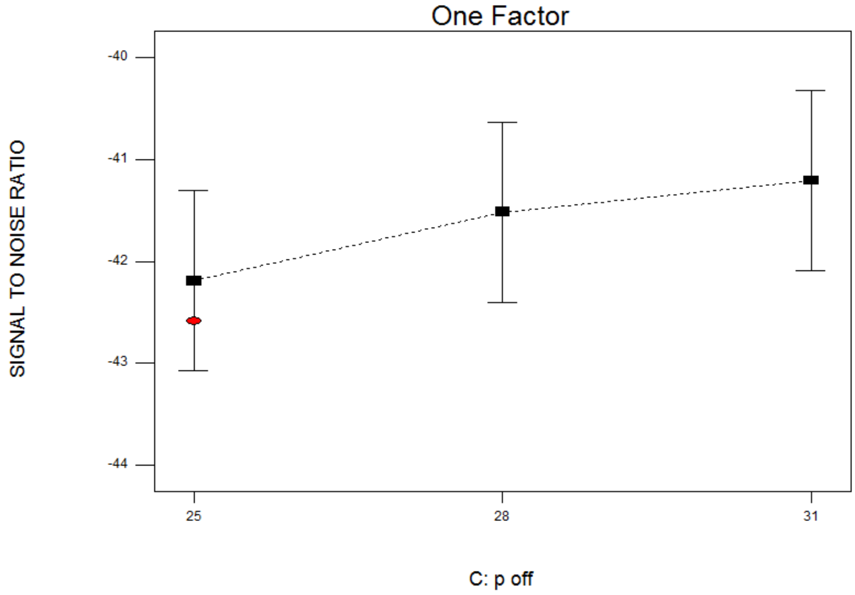


Figure 3.6.2.3 Relationship between Pulse OFF time and Corner Error (Signal to noise ratio) at 90^O

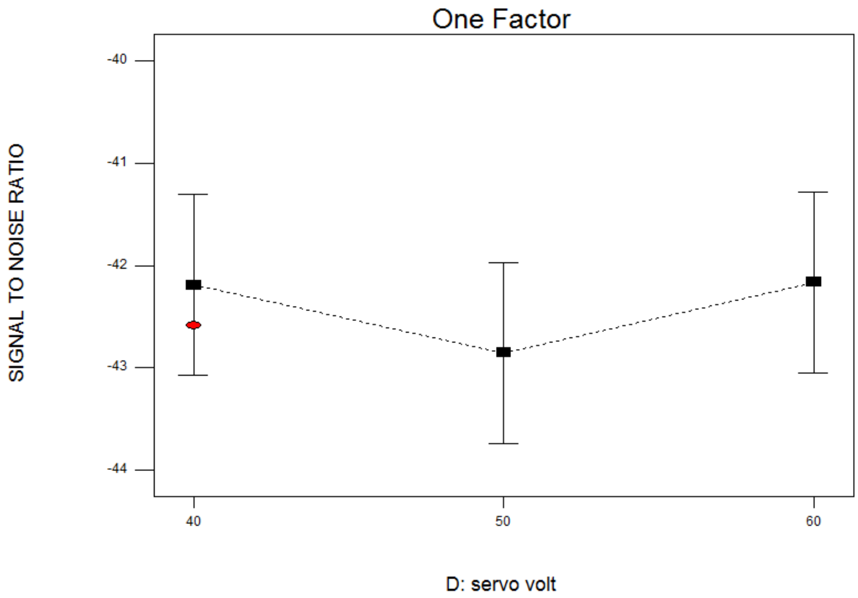


Figure 3.6.2.4 Relationship between Servo Volatge and Corner Error (Signal to noise ratio) at 90^O

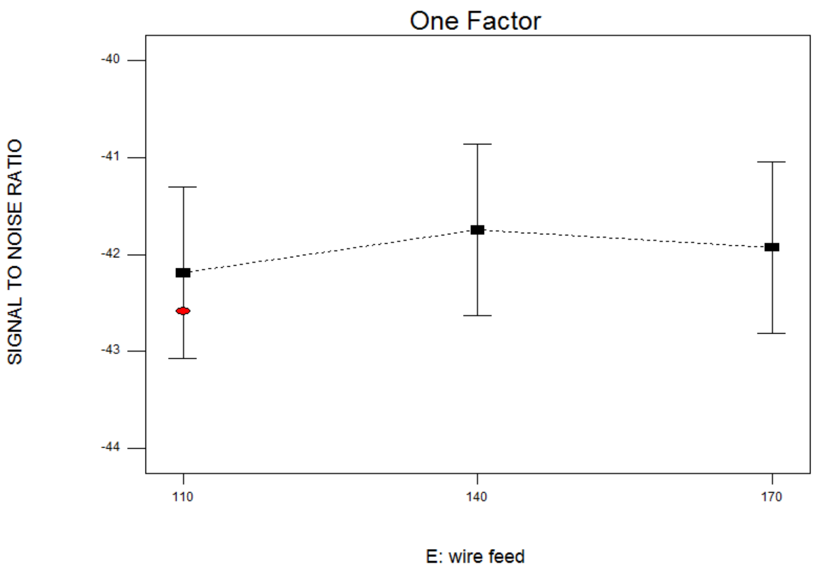


Figure 3.6.2.5 Relationship between Wire feed and Corner Error (Signal to noise ratio) at 90^{O}

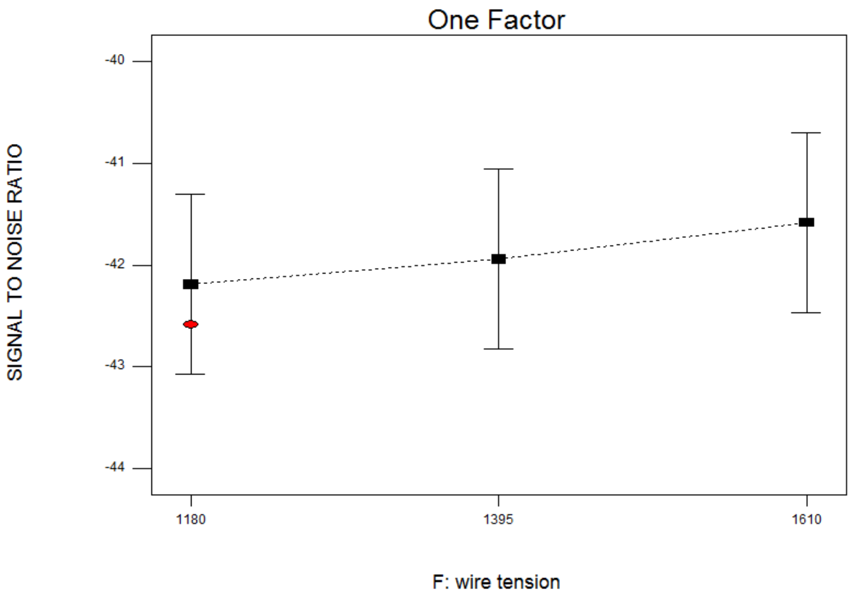


Figure 3.6.2.6 Relationship between Wire Tension and Corner Error (Signal to noise ratio) at 90^{O}

3.6.2.3 Signal to noise ratio for corner error at 135^{O} and graphs

Signal to noise ratio for corner error at 135^{o} is calculated using equation 1 and 2. Detail of calculations is tabulated in Table 3.13.

TABLE 3.13

SIGNAL TO NOISE RATIO AT 135^{O}

Run	OPEN VOLTAGE (Volt)	PULSE ON (Micro sec)	PULSE OFF (Micro sec)	SERVO VOLT (Volt)	WIRE FEED (mm/s)	WIRE TENSION (Grams)	SIGNAL TO NOISE RATIO AT 135^{O}
1	115	4	25	50	140	1610	- 30.80
2	115	6	31	40	110	1395	- 29.88
3	120	6	25	60	140	1180	- 30.83
4	120	4	28	40	170	1395	- 30.88
5	115	5	28	60	170	1180	- 30.42
6	110	4	25	40	110	1180	- 32.08
7	110	6	31	60	170	1610	- 29.31
8	110	5	28	50	140	1395	- 30.37
9	120	5	31	50	110	1610	- 30.55
10	120	5	25	60	110	1395	-30.82
11	120	6	28	40	140	1610	- 29.80
12	115	6	25	50	170	1395	- 30.72
13	110	4	31	60	140	1395	- 29.81
14	110	5	25	40	170	1610	- 29.49
15	115	5	31	40	140	1180	- 29.46
16	120	4	31	50	170	1180	- 31.22
17	110	6	28	50	110	1180	- 30.66
18	115	4	28	60	110	1610	- 30.45

Significant and non significant factors identified after conducting ANOVA for signal to noise ration at corner error of 135^{o} are Pulse ON time, Pulse OFF time and Wire Tension. Detail of calculations is tabulated in Table 3.14.

TABLE 3.14

ANOVA FOR CORNER ERROR AT 135^{O} (SIGNAL TO NOISE RATIO)

Source	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	SIGNIFICANCE
A Open Voltage	0.63	2	0.31	1.97	0.2333	Not Significant
B Pulse On	1.84	2	0.92	5.80	0.0498	Significant
C Pulse OFF	1.69	2	0.85	5.31	0.0579	Significant
D Servo Voltage	0.82	2	0.41	2.57	0.1711	Not Significant
E Wire Feed	1.01	2	0.50	3.16	0.1296	Not Significant
F Wire Tension	1.51	2	0.76	4.76	0.0697	Significant
Residual	0.80	5	0.16			
Cor Total	8.29	17				

Graph indicating relationship between Signal to noise ratio of corner errorr at 135^o and six machine control variables (Open Voltage, Pulse ON time, Pulse OFF time, Servo Voltage, Wire Feed and Wire Tension) are shown in Figure 3.3.3.1 to 3.3.3.6.

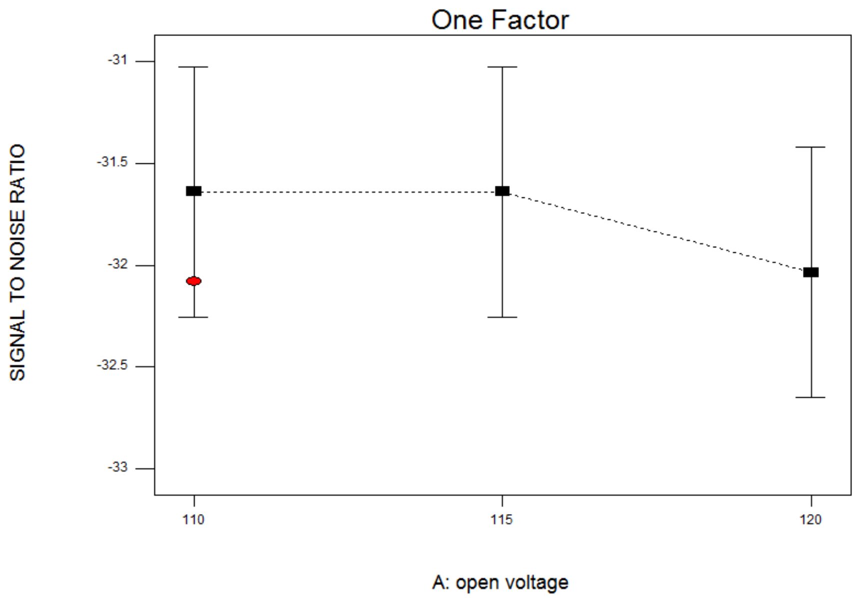


Figure 3.6.3.1 Relationship between Open Voltage and Corner Error (Signal to noise ratio) at 135^O

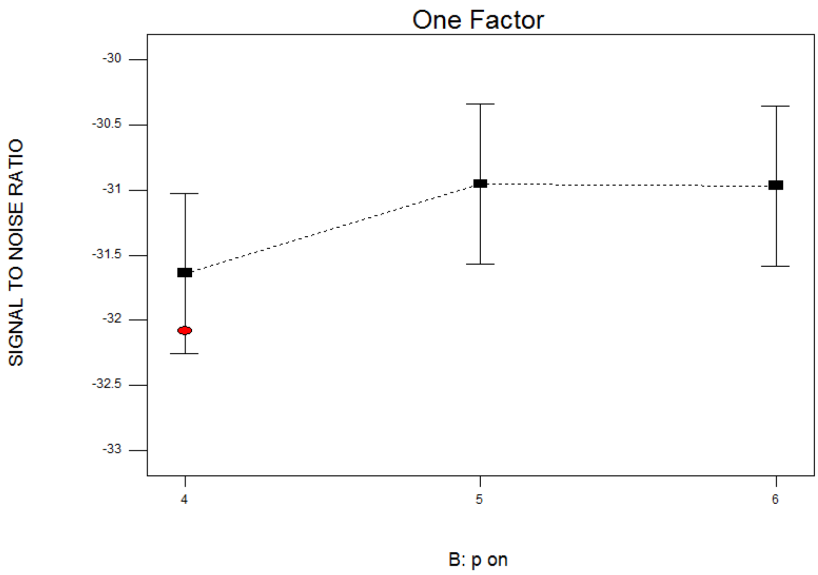


Figure 3.6.3.2 Relationship between Pulse ON time and Corner Error (Signal to noise ratio) at 135^O

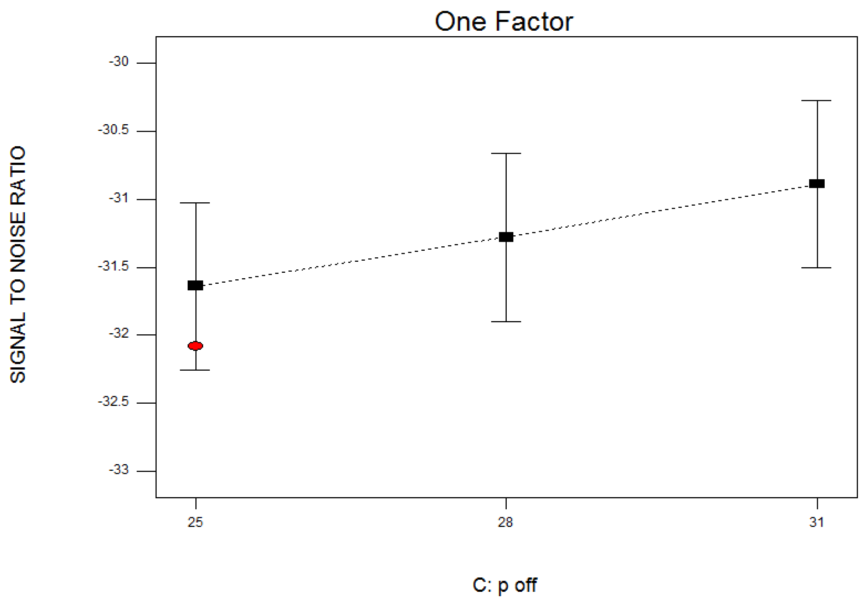


Figure 3.6.3.3 Relationship between Pulse OFF time and Corner Error (Signal to noise ratio) at 135^{O}

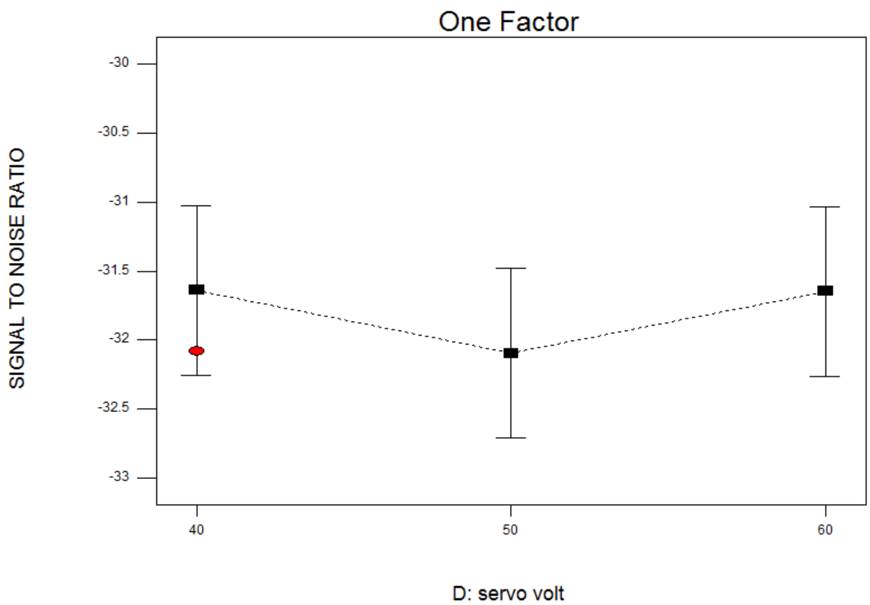


Figure 3.6.3.4 Relationship between Servo Volatge and Corner Error (Signal to noise ratio) at 135^{O}

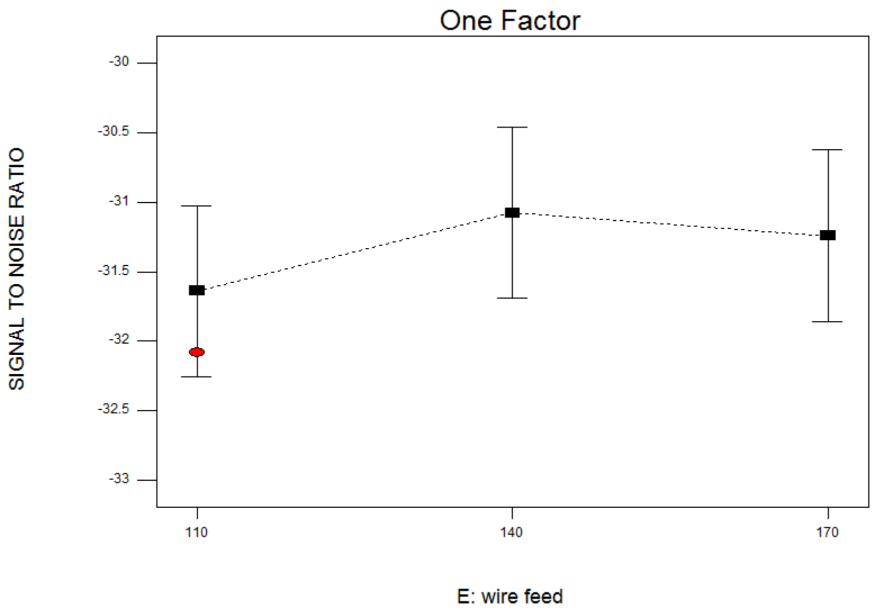


Figure 3.6.3.5 Relationship between Wire feed and Corner Error (Signal to noise ratio) at 135^O

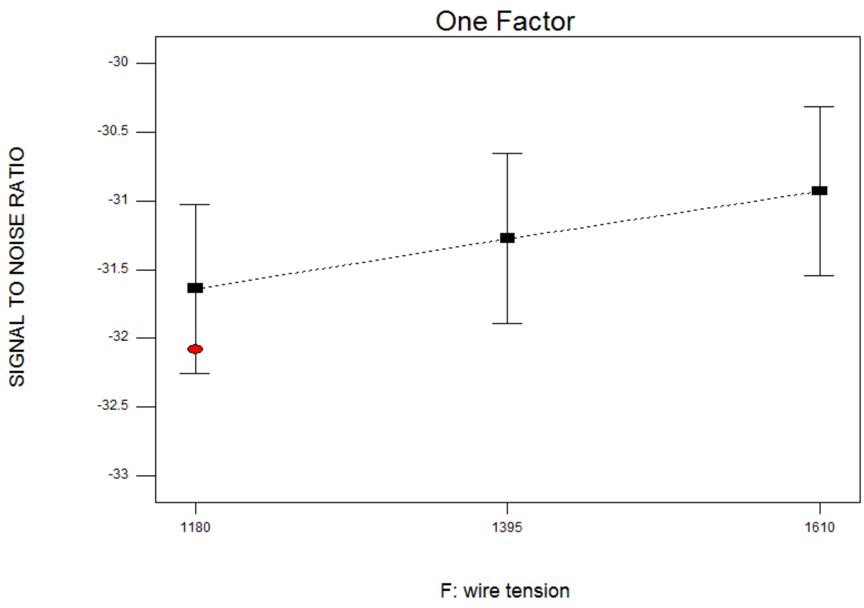


Figure 3.6.3.6 Relationship between Wire Tension and Corner Error (Signal to noise ratio) at 135^O

3.7 OPTIMIZATION

Although optimization was not 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. Level averages are taken as reference values. Addition of all response at each level of variable is calculated. Answer is obtained by dividing it with number of trials at each level. Detail of calculation is tabulated in Table 3.15. Optimum level combination is tabulated in Table 3.16.

TABLE 3.15

LEVEL AVERAGES

LEVEL AVERAGES	45^{O}	90^{O}	135^{O}
Open voltage A1	0.598099	0.572109	0.647697
Open voltage A2	0.639111	0.688922	0.647248
Open voltage A3	0.462569	0.490474	0.504022
ACCEPTABLE LEVEL	2	2	1
Pulse On B1	0.413995	0.411803	0.435834
Pulse On B2	0.643210	0.681387	0.683970
Pulse On B3	0.642573	0.658315	0.679163
ACCEPTABLE LEVEL	2	2	2
Pulse Off C1	0.395545	0.407911	0.465832
Pulse Off C2	0.590132	0.622651	0.595689
Pulse Off C3	0.714102	0.720943	0.737446
ACCEPTABLE LEVEL	3	3	3
Servo Voltage D1	0.602245	0.651461	0.655827
Servo Voltage D2	0.467976	0.440291	0.490663
Servo Voltage D3	0.629557	0.659753	0.652477
ACCEPTABLE LEVEL	3	3	1
Wire Feed E1	0.462911	0.509266	0.483647
Wire Feed E2	0.633124	0.650096	0.687422
Wire Feed E3	0.603743	0.592143	0.627898
ACCEPTABLE LEVEL	2	2	2
Wire Tension F1	0.442829	0.493100	0.469836
Wire Tension F2	0.549731	0.572203	0.602240
Wire Tension F3	0.727218	0.686202	0.726891
ACCEPTABLE LEVEL	3	3	3

TABLE 3.16 OPTIMUM LEVEL COMBINATION						
Angle	**FACTORS**					
	A	**B**	**C**	**D**	**E**	**F**
45^O	2	2	3	3	2	3
90^O	2	2	3	3	2	3
135^O	1	2	3	1	2	3

3.8 CALCULATION OF PREDICTED VALUE

Predicted values of individual response are calculated by utilizing under mentioned equation.

$$\eta_{pred} = \eta_{avg} + (\eta_{A\ opt} - \eta_{avg}) + (\eta_{B\ opt} - \eta_{avg}) + (\eta_{C\ opt} - \eta_{avg}) + (\eta_{D\ opt} - \eta_{avg}) + (\eta_{E\ opt} - \eta_{avg}) + (\eta_{F\ opt} - \eta_{avg}) \quad \ldots\ldots\ldots\ldots\ldots (4)$$

After calculation of η, response values are calculated using Equations 1-3. Calculations for predicted corner result are tabulated in Table 3.17.

TABLE 3.17 CALCULATION OF PREDICTED CORNER ERROR				
	η_{pred}	η_{ij}	**QUALITY LOSS (L_{ij})**	**CORNER ERROR**
45^O	1.133358	-47.3683	54553.96	233.56
90^O	1.168129	-38.9179	7794.517	88.28
135^O	1.140957	-28.9301	781.6385	27.95

3.9 CONFIRMATORY RUNS

Confirmatory runs were conducted to reconfirm the predicated results. Confirmatory results are tabulated in Table 3.18. Results of confirmatory run are in line with the perceived results as tabulated in Table 3.17. Therefore, it is concluded that design of experiment furnished logical results.

TABLE 3.18

PREDICTED AND CONFIRMATORY CORNER ERROR

Angle	Predicated corner error	Confirmatory corner error
45^{O}	233.56	235.12
90^{O}	88.28	89.98
135^{O}	27.95	28.46

3.10 IMPROVEMENT IN CORNER ERROR

Improvement in corner error was calculated by comparing the actual results obtained for corner error after optimization and calculated corner error readings at any single level of variables by utilizing equation 1 to 4. Calculations for predicted corner error at initial setting for 45^{o}, 90^{o} and 135^{o} are tabulated in Table 3.19.

TABLE 3.19

CALCULATION OF PREDICTED CORNER ERROR AT INITIAL SETTING

	η_{pred}	η_{ij}	QUALITY LOSS (L_{ij})	CORNER ERROR
45^{O}	0.08266	-50.8114	120542.2	347.19
90^{O}	0.126474	-42.1902	16558.49	128.6798
135^{O}	0.160394	-31.6392	1458.55	38.19

3.10.1 Improvement in corner error at 45^o

Improvement in corner error at 45^o is 32.27%. Calculation and level setting details are tabulated in Table 3.20.

TABLE 3.20

IMPROVEMENT IN CORNER ERROR AT 45^O

	FACTORS						
	A	B	C	D	E	F	CORNER ERROR
OPTIMUM LEVEL	2	2	3	3	2	3	235.12
SINGLE LEVEL	1	1	1	1	1	1	347.19
IMPROVEMENT	32.27%						

3.10.2 Improvement in corner error at 90^o

Improvement in corner error at 90^o is 30.07%. Calculation and level setting details are tabulated in Table 3.21.

TABLE 3.21

IMPROVEMENT IN CORNER ERROR AT 90^O

	FACTORS						
	A	B	C	D	E	F	CORNER ERROR
OPTIMUM LEVEL	2	2	3	3	2	3	89.98
SINGLE LEVEL	1	1	1	1	1	1	128.67
IMPROVEMENT	30.07 %						

3.10.3 Improvement in corner error at 135^o

Improvement in corner error at 135^o is 25.47%. Calculation and level setting details are tabulated in Table 3.22.

TABLE 3.22

IMPROVEMENT IN CORNER ERROR AT 135^O

	FACTORS						
	A	B	C	D	E	F	CORNER ERROR
OPTIMUM LEVEL	1	2	3	1	2	3	28.46
SINGLE LEVEL	1	1	1	1	1	1	38.19
IMPROVEMENT	25.47%						

Equation for corner error at 45^o is appended below:

503.34 + 1.37 (open voltage) -12.88 (Pulse on) - 5.81 (Pulse off) - 0.196 (servo voltage) – 0.25 (wire feed) – 0.069 (wire tension) ……………………… (5)

Comparison of actual results and results obtained by using Equation 5 are tabulated in Table 3.23.

TABLE 3.23 VALIDATION OF EQUATION AT 45^O			
Run	CORNER ERROR AT 45^O	CALCULATED CORNER ERROR AT 45^O BY USING FORMULA	PERCENTAGE ERROR
1	310.43	306.36	-1.30
2	280.01	270.36	-3.44
3	320.06	315.56	-1.40
4	308.61	304.91	-1.19
5	280.23	296.37	5.76
6	358.19	339.16	-5.31
7	245.62	229.18	-6.69
8	295.87	284.17	-3.95
9	284.54	273.20	-3.98
10	311.26	321.20	3.19
11	260.29	271.91	4.46
12	290.28	287.84	-0.83
13	263.40	277.70	5.43
14	268.27	280.76	4.65
15	249.97	265.21	6.09
16	325.51	300.56	-7.66
17	296.50	294.05	-0.82
18	281.20	294.77	4.82

Equation for corner error at 90^o is appended below:

196.37+ 0.29 (open voltage) - 5.14 (Pulse on) – 2.07 (Pulse off) - 0.0458 (servo voltage) – 0.05 (wire feed) – 0.019 (wire tension) ……………………… (6)

Comparison of actual results and results obtained by using Equation 6 are tabulated in Table 3.24.

TABLE 3.24

VALIDATION OF EQUATION AT 90^O

Run	CORNER ERROR AT 90^O	CALCULATED CORNER ERROR AT 90^O BY USING FORMULA	PERCENTAGE ERROR
1	119.96	116.37	2.98
2	100.20	99.95	0.24
3	115.80	115.31	0.41
4	115.83	114.46	1.18
5	100.50	111.08	-10.52
6	134.70	125.31	6.97
7	100.60	90.05	10.47
8	114.96	107.68	6.32
9	106.79	101.98	4.50
10	116.82	118.06	-1.05
11	98.38	101.78	-3.45
12	111.99	108.49	3.12
13	98.86	106.16	-7.38
14	100.68	108.51	-7.77
15	93.82	97.48	-3.90
16	125.15	111.91	10.58
17	111.31	108.37	2.63
18	105.54	111.43	-5.57

Equation for corner error at 135^o is appended below:

50.52 + 0.138 (open voltage) -1.325 (Pulse on) – 0.483 (Pulse off) - 0.004 (servo voltage) – 0.0256 (wire feed) – 0.0065 (wire tension) ……………………… (7)

Comparison of actual results and results obtained by using Equation 7 are tabulated in Table 3.25.

TABLE 3.25

VALIDATION OF EQUATION AT 135^O

Run	**CORNER ERROR AT 135^O**	**CALCULATED CORNER ERROR AT 135^O BY USING FORMULA**	**PERCENTAGE ERROR**
1	34.69	34.76	-0.21
2	31.2	31.42	-0.71
3	34.8	35.56	-2.18
4	35.01	34.67	0.95
5	33.22	33.97	-2.28
6	40.19	37.67	6.24
7	29.24	27.72	5.19
8	33.02	32.69	0.97
9	33.72	32.00	5.09
10	34.79	36.25	-4.21
11	30.93	31.39	-1.50
12	34.38	32.74	4.75
13	30.95	32.53	-5.12
14	29.85	32.02	-7.27
15	29.74	33.37	-12.23
16	36.43	34.58	5.06
17	34.15	33.54	1.78
18	33.33	34.04	-2.14

Depending upon the error, equations can be used for predication or approximation if required.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Based on the scope of thesis, following is concluded:

a. Corner error decreases with increase in angle.

b. Significant factors for corner error are pulse on time, pulse off time and wire tension.

4.2 RECOMMENDATIONS

During the thesis, analysis was undertaken for six machine variable to determine the significant factors affecting corner error for a rough cut (first cut). Following is recommended:

a. Significant factor(s) affecting corner error during trim cut for Tungsten carbide can be analyzed.

b. Form tool be manufactured and cutting be conducted on lathe to verify the results achieved in the study.

c. Distance between wire guides can be varied to analyze the effect on corner error.

d. Comparative study between WEDM and milling process can be undertaken for analysis of corner error.

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