DEVELOPMENT OF HYBRID EDM ELECTRODE FOR IMPROVING SURFACE MORPHOLOGY

A THESIS

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for the award of degree of

MASTER OF TECHNOLOGY

in

Production Engineering

SUBMITTED BY

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DECLARATION

I, **RAMAKANT RANA** (Roll No. 2K11/PIE/23), hereby declare that the project work, which is being presented in this dissertation entitled "**Development of Hybrid EDM Electrode for improving Surface Morphology"** is an authentic work carried out by me at Delhi Technological University under the guidance of **Dr. Reeta Wattal** (Professor), Mechanical, Production & Industrial and Automobile Engineering Department and **Dr. R.S. WALIA** (Associate Professor), Mechanical, Production & Industrial and Automobile Engineering Department.

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CERTIFICATE

This is to certify that the report entitled *"Development of Hybrid EDM Electrode for improving Surface Morphology*" submitted by **Ramakant Rana (Roll No. - 2K11/PIE/23)** in partial fulfillment for the award of Masters of Technology in Production engineering from Delhi Technological University , is a record of bonafide project research work carried out by him. He has worked under our guidance and supervision.

To the best of our knowledge the results contained in this thesis, have not been submitted in part or full to any other university for the award of any degree or diploma.

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(Ramakant Rana)

ABSTRACT

Electric Discharge Machining (EDM) is an important method for the machining or drilling holes, especially for difficult to machine materials. In EDM, materials removal starts when a potential difference is applied between the workpiece and tool electrode. This voltage is high enough to produce a spark between two electrodes. The spark melts and vaporizes a small material volume on each of the electrodes. The dielectric fluid that fills the gap between the electrodes flushes part of this material for working zone. The circulation on dielectric and the removal on machine-debris are very difficult, specially when the hole or the cavity becomes deep, which reduce the machining efficiency due to poor flow of dielectric fluid from the working gap. This poor flushing ends up with stagnation of dielectric and build-up of machining residues which apart from low material removal rate (MRR) also lead to short circuits, arcs and low surface finish.

To improve the machining performance of EDM, a combined method of Electric Discharge Grinding EDG and Electric Discharge Machining has been developed. Most of the researchers have applied rotational motion to traditional electrode only. By this method due to rotation of electrode, dielectric circulation and debris removal improves. However, rotational head attachment of EDM is a very costly arrangement.

In order to solve the problem stated above, in this research a new hybrid electrode was developed. The most noteworthy feature of the method using this hybrid electrode is that it removes the metal by abrasive action of ceramic material also, as in traditional EDM machining there is no as such action performed. The major advantage of ceramic material attached to the EDM electrode is that it removes metal by abrasive action.

The objective of the present work is to investigate the effects of the various Developed Hybrid Electric Discharge Machine Electrode (HEDME) process parameters on the machining performance and to obtain the optimal sets of process parameters so that the performance of the developed hybrid machine can be enhanced. The Taguchi technique has been used to investigate the effects of the HEDME process parameters to predict optimal parameters.

In the experimentation Taguchi L_9 orthogonal array was used with Hybrid Electric Discharge Machine Electrode and it is explored with EN31 High Carbon Alloy Steel as workpiece.

The literature survey has revealed that a very little research has been conducted to obtain the optimal levels of machining parameters that yield the best machining quality in machining of difficult-to-machine materials like High Carbon Alloy Steel. This steel is widely used in die and punch in manufacturing with expected application growth in the rapidly developing micro world. With its exceptional hardness, wear resistance and high mechanical strength it is becoming very desirable for a number of applications.

The research work has been focused in the following aspects:

1. Design and development of experimental set-up capable of providing varying range of parameters of HEDME process.
2. Experimental study of the effect of various process parameters on performance characteristics of developed Hybrid Electric Discharge Machining Electrode.
3. Fabrication of set-up capable of providing rotating motion to Tool (electrode).

ORGANIZATION OF THE THESIS IS GIVEN BELOW:

Chapter 1 deals with the general introduction, advantages, applications, advancements, in EDM and hybridization of EDM process.

Chapter 2 presents the review of published literature on machining under different conditions, optimization of process parameters used in EDM process. It further presents the identified gaps in literature, statement of problem and objectives of the present investigation.

Chapter 3 deals with fundamental aspects of “design of experiment” used in the present research work.

Chapter 4 deals with design and fabrication of experimental set-up. The various components of HEDME process and measurement equipment used for this study are also discussed in this chapter

Chapter 5 deals with the selection of process parameters and their range. The levels of process parameters are finalized. The experimentation and measurement of response parameters are discussed. The scheme of experiment has also been presented.

Chapter 6 deals with experimental results and analysis on taghuchi method. The results are discussed for the response parameters viz. MRR, TWR and SR.

Chapter 7 highlights the important conclusion drawn from this research work. At the end of this chapter, scopes of future work on the related topics have been enumerated.

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NOMENCLATURE

Symbol	**Notation**
EDM	Electric Discharge Machining
DC	Direct Current
MRR	Metal Removal Rate
SR	Surface Roughness
HEDME	Hybrid EDM Electrode
OA	Orthogonal Array
ANOVA	Analysis of Variance
S/N	Signal- to- Noise ratio
R	Number of repetitions
MSD	Mean Squared Deviation
DOF	Degrees of Freedom
N	Number of trials
CI_{POP}	Confidence Interval For The Population
CI_{CE}	Confidence Interval For A Sample Group
EDG	Electric Discharge Grinding
PWM	Pulse width modulator
TWR	Tool Wear Rate
A	Ampere
V_e	Error variance
f_e	Error DOF

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF ELECTRIC DISCHARGE MACHINING (EDM)

The history of Electric Discharge Machining (EDM) dates back to the discovery of electric discharges. Besides the discharges produced by natural phenomena, namely lightning, the production of artificial discharges has been closely related to the development of electrical energy sources. First investigations of electrostatic phenomena were performed with frictional machines, during the first half of the 18^{th} century. After that, the first sparks and pulsed arcs were produced with "Leyden jars", an early form of capacitor invented in Germany and in the Netherlands around 1745 [Ander (2003)].

The history of EDM itself begins in 1943, with the invention of its principle by Russian scientists Boris and Natalya Lazarenko in Moscow. The Soviet government assigned them to investigate the wear caused by sparking between tungsten electrical contacts, a problem which was particularly critical for maintenance of automotive engines during the Second World War. Putting the electrodes in oil, they found that the sparks were more uniform and predictable than in air. They had then the idea to reverse the phenomenon, and to use controlled sparking as an erosion method [Lazarenko B.R. (1943)]. Though they could not solve the original wear problem, the Lazarenkos developed during the war the first EDM machines, which were very useful to erode hard metals such as tungsten or tungsten carbide.

The "Lazarenko circuit" remained the standard EDM generator for years. In the 1950's, progress was made on understanding the erosion phenomenon [Germer and Haworth (1949), Cobine et al. (1955), Zingerman (1956)]. It is also during this period that industries produced the first EDM machines. Swiss industries were involved very early in this market, and still remain leaders nowadays. Les Ateliers des Charmilles produced their first machine in 1955. Due to the poor quality of electronic components, the performances of the machines were limited at this time.

In the 1960’s, the development of the semi-conductor industry permitted considerable improvements in EDM machines. Die-sinking machines became reliable and produced surfaces with controlled quality, whereas wire-cutting machines were still at their very beginning.

With the introduction of numerical position control in the late 1960’s and early 1970’s, the movements of electrodes became much more precise. This major improvement pushed forward the performance of wire-cutting machines. Computer numerical controlled systems (CNC) improved further the performance of EDM in the mid 1970’s. During the following decades, efforts were principally made in generator design, process automatization, servo-control and robotics. Applications in micro-machining became also of interest during the 1980’s [Sato et al. (1985)]. It is also from this period that the world market of EDM began to increase strongly, and that specific applied EDM research took over basic EDM research. Finally, new methods for EDM process control arose in the 1990’s: fuzzy control and neural networks.

1.2 BASIC PRINCIPLE OF ELECTRIC DISCHARGE MACHINING

Electric Discharge Machining (EDM), also referred to as Spark Erosion Machining, is a process consisting in the removal of metal particles from a workpiece surface by a rapid succession of short time electric discharges. The tool used for spark eroding is an electrode whose shape is a negative replica of the contour to be produced on the work as shown in the Figure 1.1.

The schematic of an EDM machine tool is shown in Figure 1.2. The tool and the workpiece form the two conductive electrodes in the electric circuit. Pulsed power is supplied to the electrodes from a separate power supply unit. The appropriate feed motion of the tool towards the workpiece is provided for maintaining a constant gap distance between the tool and the workpiece during machining. This is performed by either a servo motor control or stepper motor control of the tool holder.

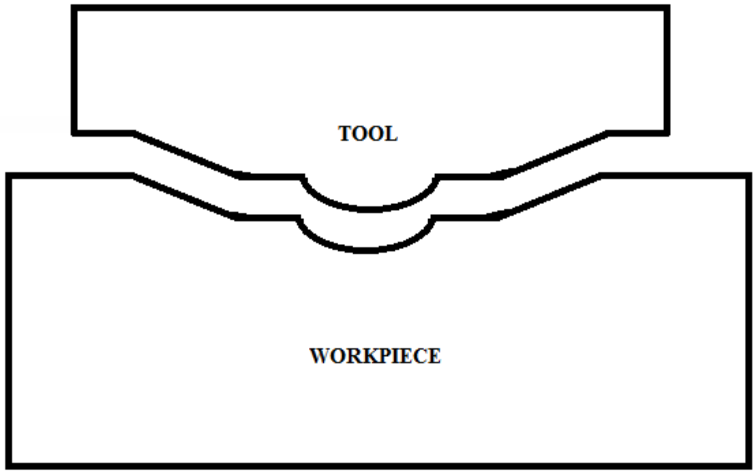

Figure 1.1: Tool shape and corresponding cavity formed on workpiece after EDM operation

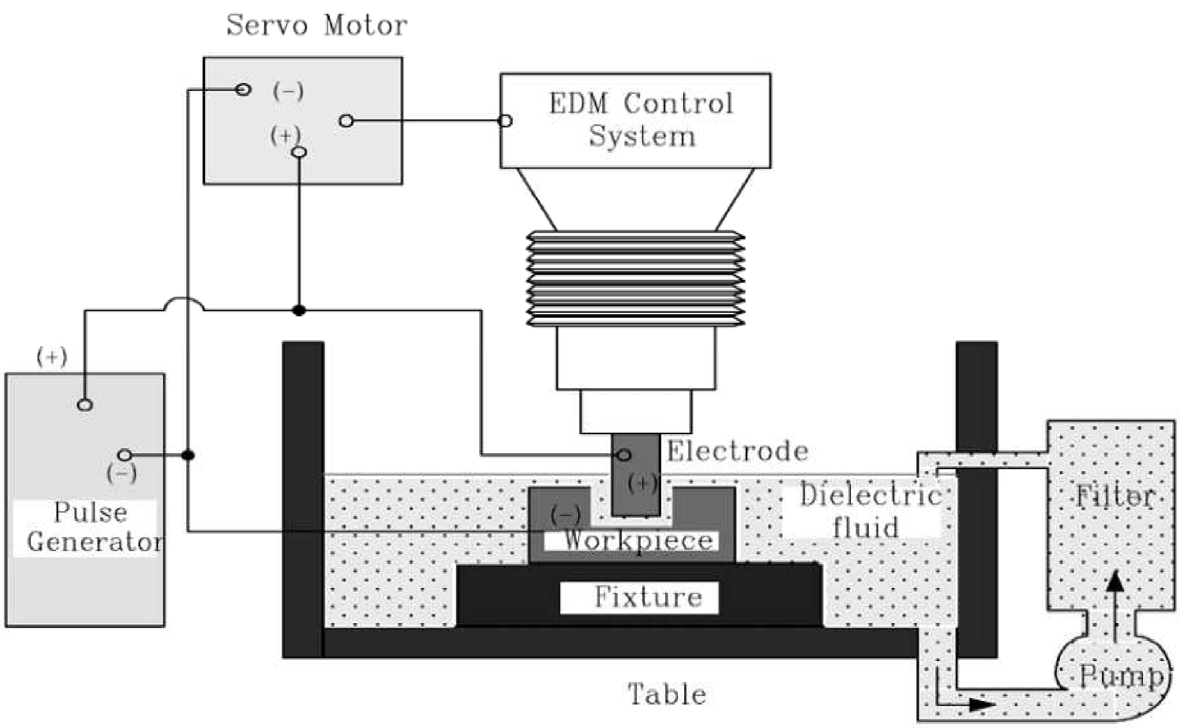

Figure 1.2: Schematic of an Electric Discharge machining (EDM) machine tool
[Walia et al. (2003)]

As material gets removed from the workpiece, the tool is moved downward towards the workpiece to maintain a constant inter-electrode gap. The tool and the workpiece are plunged in a dielectric tank and flushing arrangements are made for the proper flow of dielectric in the inter-electrode gap. Typically in oil die-sinking EDM, pulsed DC power supply is used where the tool is connected to the negative terminal and the workpiece is connected to the positive terminal. The pulse frequency may vary from a few kHz to several MHz.

The inter-electrode gap is in the range of a few tens of micro meters to a few hundred micro meters. Material removal rates upto 300 mm^3/min can be achieved during EDM. The surface finish (Ra value) can be as high as 50 µm during rough machining and even less than 1 µm during finish machining. Figure 1.3 illustrates the spark erosion in the EDM process.

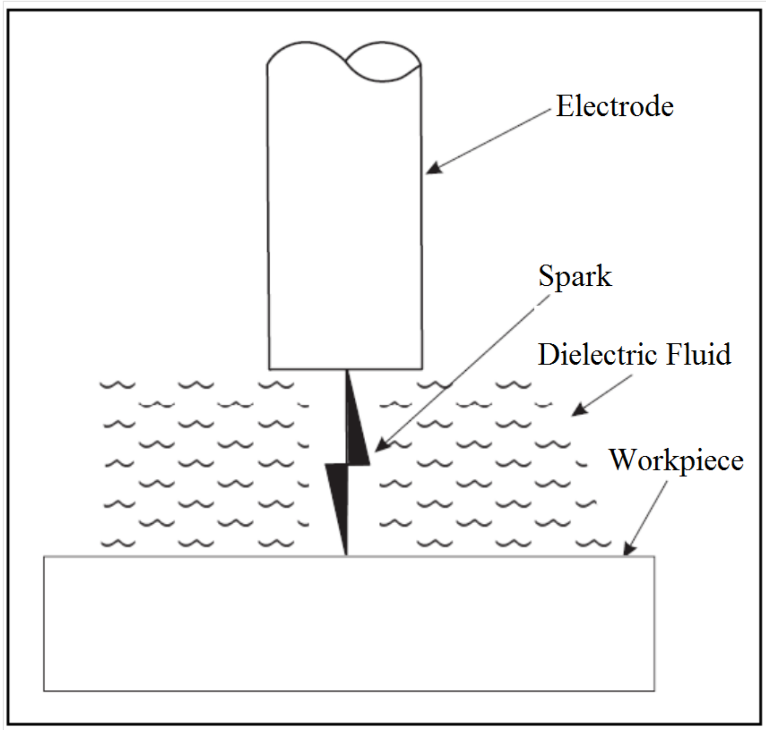

Figure 1.3: Spark Erosion in the EDM process [Jameson (2001)]

EDM is a thermal process; material is removed by heat and evaporation. Heat is introduced by the flow of electric current between the electrode and workpiece in the form of a spark.

Materials at the closest points between the electrode and workpiece as shown in Figure 1.4, where the spark originates and terminates, are heated to the point where the material vaporizes. While the electrode and workpiece never feel more than warm to the touch during

EDM, the area where each spark occurs is very hot. The area heated by each spark is very small so the dielectric fluid quickly cools the vaporized material and the electrodes. However, it is possible for metallurgical changes to occur from the spark heating the workpiece surface.

A dielectric is required to maintain the sparking gap between the electrode and workpiece. This dielectric material is normally a fluid. Die-sinker type EDM machines usually use hydrocarbon oil and kerosene oil.

The main characteristics of dielectric fluid are that it is an electrical insulator until enough electrical voltage is applied to cause it to change into an electrical conductor. The dielectric fluids used for EDM are able to remain electrical insulators except at the closest points between the electrode and workpiece. At these points, sparking voltage causes the dielectric fluid to change from an insulator to a conductor and the spark occurs.

The time at which the fluid changes into an electrical conductor is known as the ionization point. When the spark is turned off, the dielectric fluid deionizes and the fluid returns to being an electrical insulator.

This change of the dielectric fluid from an insulator to a conductor, and then back to an insulator, happens for each spark. As each spark occurs, a small amount of the electrode and workpiece material is melted /vaporized. The vaporized material is positioned in the sparking gap between the electrode and workpiece and which produce the cloud as shown in Figure 1.4.

When the spark is turned off, the vaporized cloud solidifies as shown in Figure 1.5. Each spark then produces an EDM chip or a very tiny hollow sphere of material made up of the electrode and workpiece material. For efficient machining, the EDM chip must be removed from the sparking area. Removal of this chip is accomplished by flowing dielectric fluid through the sparking gap [Elman Jameson (2001)].

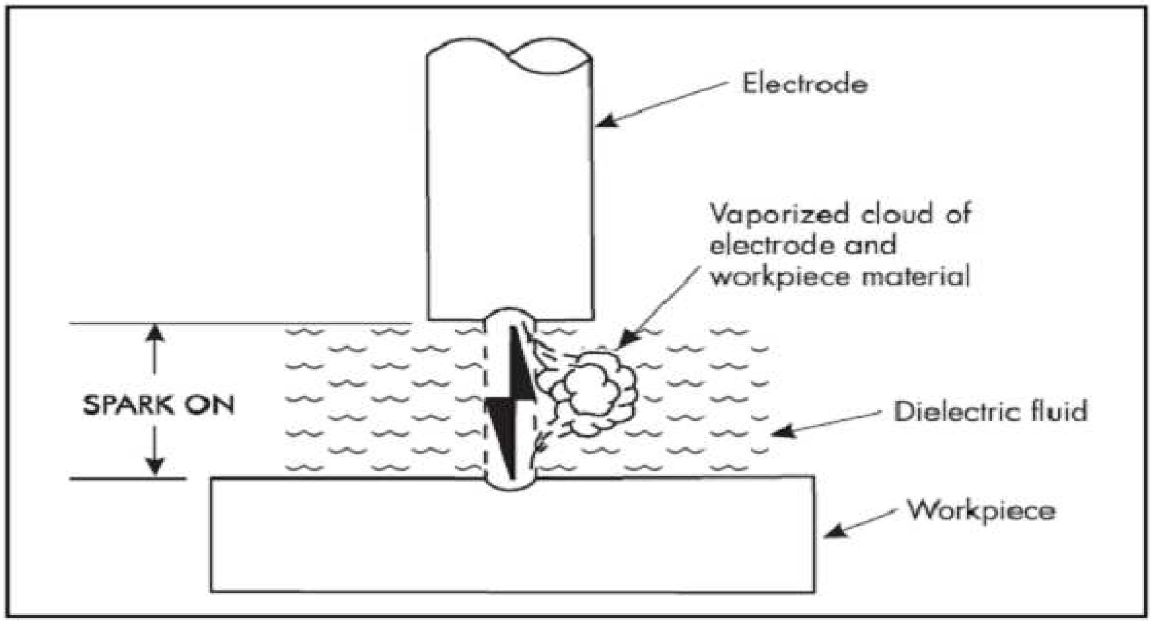

Figure 1.4: Spark ON: electrode and workpiece material vaporized [Jameson(2001)]

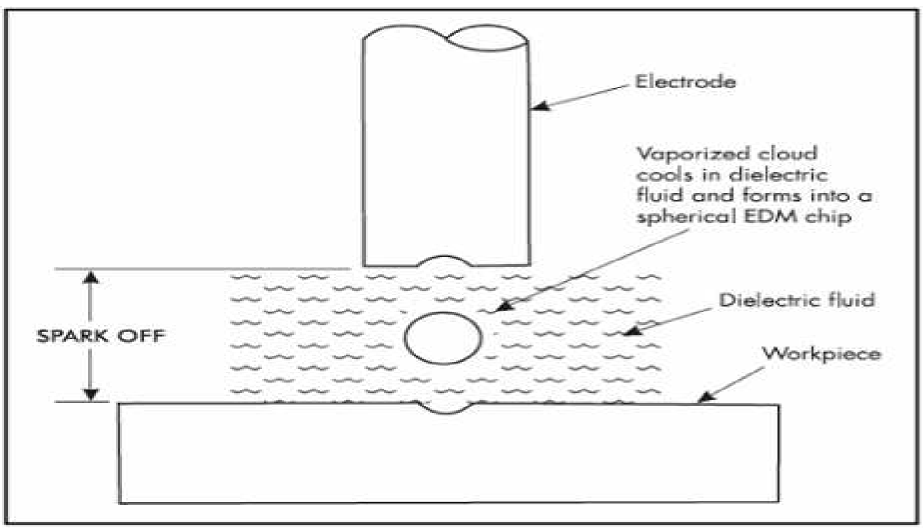

Figure 1.5: Spark-OFF: vaporized cloud solidifies to form EDM chip [Jameson(2001)]

1.3 MATERIAL REMOVAL MECHANISM

Material removal mechanism of EDM involves an electric erosion effect i.e. the breakdown of electrode material accompanying any form of electric discharge (The discharge is usually through a gas, liquid or in some cases solids). A necessary condition for producing a discharge is the ionization of the dielectric that is, splitting up of its molecules into ions and electrons [Garg et al. (2010)].

As soon as suitable voltage is applied across the electrodes, the potential intensity of the electric field between them builds up, until at some predetermined value, the individual electrons break loose from the surface of the cathode and are impelled towards the anode under the influence of field forces (Figure 1.6).

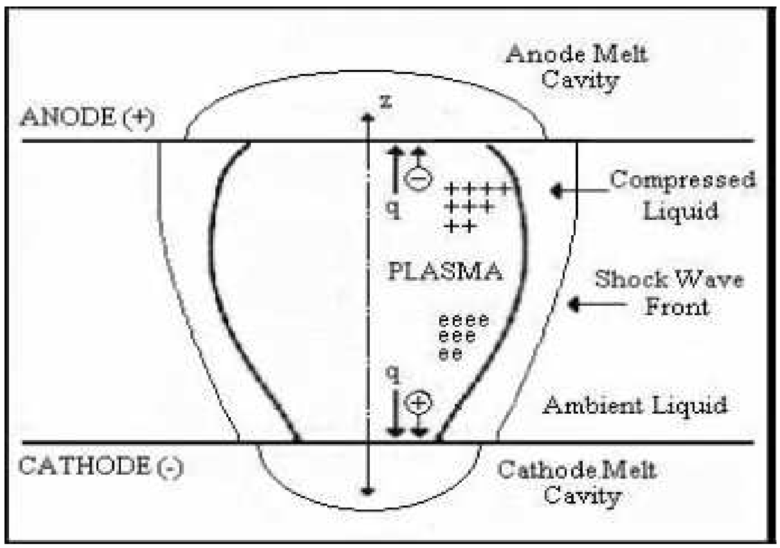

Figure 1.6: Schematic Diagram of the EDM Process Showing the Circle Heat Sources, Plasma Configuration, and Melt Cavities after a Certain Time

[Eubank et al., 1993]

In the movement of inter-electrode space, the electrons collide with the neutral molecules of the dielectric, detaching electrons from them and causing ionization. At some time or the other, the ionization becomes such that a narrow channel of continuous conductivity is formed. When this happens, there is a considerable flow of electrons along the channel to the anode, resulting in a momentary current impulse or discharge.

The liberation of energy accompanying the discharge leads to the generation of extremely high temperature, between 8,000° and 12,000°C, causing fusion or partial vaporization of the metal and the dielectric fluid at the point of discharge. The metal in the form of liquid drops is dispersed into the space surrounding the electrodes by the explosive pressure of the gaseous products in the discharge. This results in the formation of a tiny crater at the point of discharge in the workpiece [Panday and Shan (2003)].

1.4 COMPONENT OF EDM

Every EDM machine has the following basic elements (Figure 1.7).

- Spark Generator
- Servo System
- Dielectric System
- Mechanical Structure

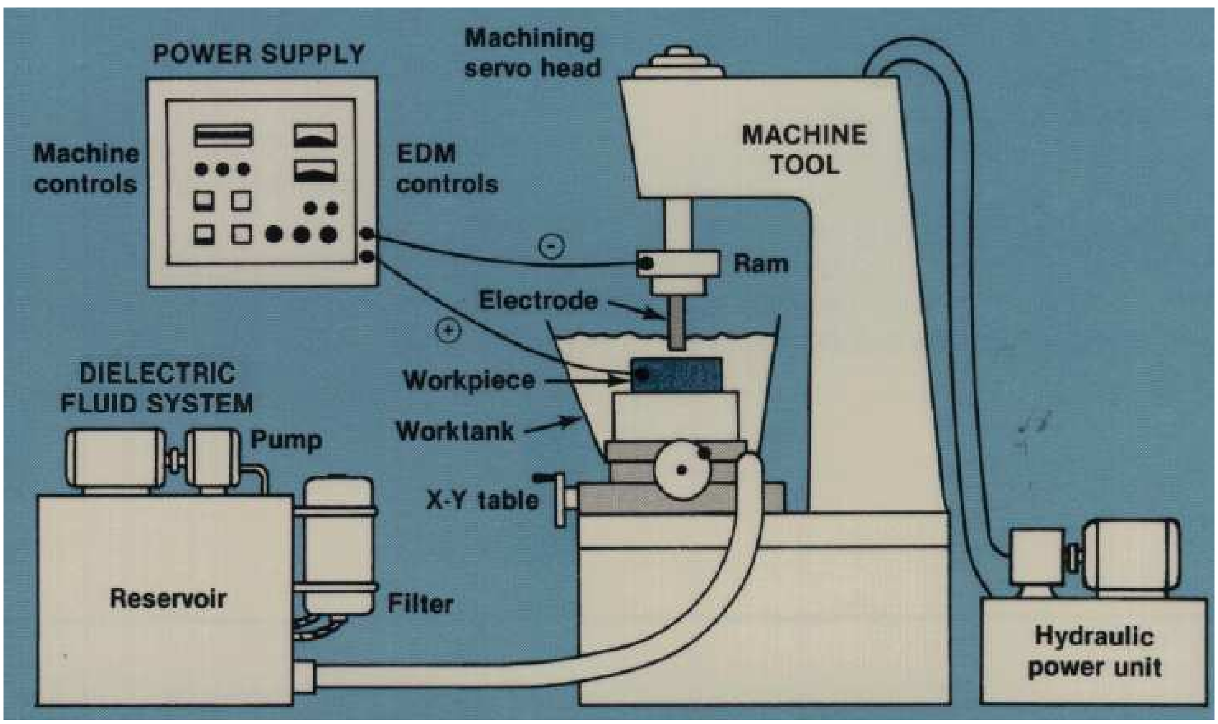

Figure 1.7: Basic Elements of an EDM system [ERPI (1986)]

1.4.1 SPARK GENERATOR

Electrical energy in the form of short duration impulses with a desired shape should be supplied to the inter-electrode gap. Spark generators are used as the source of electrical pulses in EDM. The generators can be distinguished according to the way in which the voltage is transformed and the pulse is controlled. The discharge may be produced in controlled manner by natural ignition and relaxation, or by means of a controllable semiconductor switching elements.

Nowadays, sophisticated computer aided spark generators are in use as a result of fast development in electronics industry. These types of generators provide a better means of controlling the physical parameters. The required energy is in the form of pulses usually in rectangular form.

1.4.2 SERVO SYSTEM

Both tool electrode and workpiece are eroded during the process. Dimensions of the electrodes change considerably with respect to time and the gap between electrodes increases. This changes the required voltage for sparking. Increasing the pulse voltage or decreasing the gap could be the responses to retain machining process. The former is not feasible since most of the electrical energy used for breaking dielectric liquid and producing a discharge channel in it rather than machining, the resulting surface characteristic will be changed continuously, and furthermore, the required voltage for sparking will be increased to the levels that spark generator cannot supply. Therefore, the inter electrode gap should be maintained uniformly. This can be achieved by a servo system that keeps up a movement of the electrode towards the workpiece at such a speed that the working gap, and hence, the sparking voltage is unaltered significantly during machining.

1.4.3 DIELECTRIC SYSTEM

Erosion properties of tool and workpiece are determined partly by the discharging medium. The medium is composed mainly of dielectric liquid and debris formed due to solidification of vaporized material in cold dielectric liquid after each discharge either as irregularly shaped particles or hollow spherical particles.

In the case of the normal erosion process with sequential discharges, there are large changes of the process parameters (i.e. debris concentration, depth of cut etc.) as a consequence of the existing flushing. Such changes cause large differences in metal removal, accuracy, and surface integrity. Therefore, type of the flushing highly depends on the geometrical properties of the machined part. Hence, EDM machines are equipped with necessary pumps, filters and other devices necessary for fluid circulation.

Filtration of the liquid is required to keep debris concentration within acceptable limits. There are basically four functions of a dielectric liquid in the process of EDM [Panday and Shan (2003)].

I. Physically, the dielectric liquid holds the charge accumulated on the electrodes for a certain time period, determined by spark gap conditions. When the gap conditions are favorable, the liquid allows the electric current to flow with lowest electrical resistivity.

II. The dielectric liquid keeps the discharge in a narrow channel. Power density over the electrode surface is thus increased and machining rate is improved.

III. Heat released during discharge should be immediately removed, since it does not contribute to the erosion. Further, it may cause damage on the electrode surfaces. The dielectric liquid during Electric Discharge machining should remove the heat from the electrode surfaces as soon as the electric discharge ends.

IV. The dielectric liquid is expected to carry the machining products (debris) away from the spark gap to prevent short circuits and therefore prevent damage to the electrodes.

1.4.4. MECHANICAL STRUCTURE

EDM machines have similar construction with conventional drilling and milling machine frames with vertical tool feeding and horizontal worktable movements. Since there is not a real contact between electrodes, that’s why, it is considered that, the frame elements not taking much force as in conventional machining so simpler design is possible. This consideration needs a little bit attention, because gas bubbles collapses at the end of discharge and cause high frontal shock waves, therefore; the frame should be strong enough to keep its dimensional stability.

1.5 ADVANTAGES OF EDM

Conventional EDM machines can be programmed for vertical machining, orbital, vectorial, directional, helical, conical, rotational, spin and indexing machining cycles. This versatility gives Electrical Discharge Machines many advantages over conventional machine tools.

- **Suitability to Metals**:

  The process can be applied to all electrically conducting metals and alloys irrespective of their melting points, hardness, toughness or brittleness.

- **Shapes**

  Any complicated shape that can be made on the tool can be reproduces on the workpiece. Highly complicated shapes can be made by fabricating the tool with split sectioned shapes, by welding, brazing or by applying quick setting conductive epoxy adhesives.

- **Machining of hard metals:**

  EDM can be employed for extremely hardened workpiece. Hence, the distortion of the workpiece arising out of the heat treatment process can be eliminated. Time of machining for hard metals is less than conventional machining processes.

- **Mechanical stress:**

  No mechanical stress is present in the process. It is due to the fact that the physical contact between the tool and the workpiece is eliminated. Thus, fragile and slender workplaces can be machined without distortion.

- **Surface quality:**

  Cratering type of surface finish automatically creates accommodation for lubricants causing the die life to improve. Hard and corrosion resistant surfaces, essentially needed for die making, can be developed.

1.6 DRAWBACKS OF EDM

EDM is capable to do all operations that can be done by conventional machining but it has certain drawbacks also as mentioned below.

- **The need for electrical conductivity**

  To be able to create discharges, the workpiece has to be electrically conductive. Isolators like plastics, glass and most ceramics cannot be machined by EDM.

- **Predictability of the inter electrode gap**

  The dimensions of the gap are not always easily predictable, especially with intricate workpiece geometry. In these cases the flushing conditions and the contamination state is differ from the specified one. In the case of die-sinking EDM, the tool wear also contributes to a deviation of the desired workpiece geometry and it could reduce the achievable accuracy. Intermediate measuring of the workpiece or some preliminary tests can often solve the problems.

- **Low material removal rate**

  The material removal of the EDM process is rather low, especially in the case of die-sinking EDM where the total volume of a cavity has to be removed by melting and evaporating the metal. Due to the low material removal rate, EDM is principally limited to the production of small series. Also, it required additional time and cost for creating the cavity type electrodes.

- **Optimization of the electrical parameters**

  The choice of the electrical parameters of the EDM-process depends largely on the material combination of electrode and workpiece. EDM manufactures only supply these parameters for a limited amount of material combinations. Whenever the machining of special alloys is required, the user has to develop its own technology.

- **Environmental Effect**

  There are some potentially severe effects of EDM on the environment, most prominently the effects of the hazardous materials from the filters. Currently, since there is no regulation on the disposal of filters, debris, or any byproduct of EDM, it is the responsibility of the EDM user to properly handle and dispose of the wastes in a responsible manner. The fumes of EDM can have hazard of skin irritation to worker.

1.7 ADVANCEMENTS IN EDM

A significant number of ways have been focused for yielding optimal EDM performance measures of high Material Removal Rate, low tool wear rate and better Surface Quality. This section provides various advancements in EDM to achieve these measures.

1.7.1 DRY ELECTRIC DISCHARGE MACHINING

Dry Electric Discharge machining (dry EDM) is a modification of the oil EDM process in which the liquid dielectric is replaced by a gaseous dielectric. High velocity gas flowing through the tool electrode into the inter-electrode gap substitutes the liquid dielectric. The flow of high velocity gas into the gap facilitates removal of debris and prevents excessive heating of the tool and workpiece at the discharge spots. Providing rotation or planetary motion to the tool has been found to be essential for maintaining the stability of the dry EDM process.

The dry EDM process schematic is shown in Figure 1.8. Tubular tools are used and as the tool rotates, high velocity gas is supplied through it into the discharge gap. Gas in the gap plays the role of the dielectric medium required for electric discharge. Also, continuous flow of fresh gas into the gap forces debris particles away from the gap.

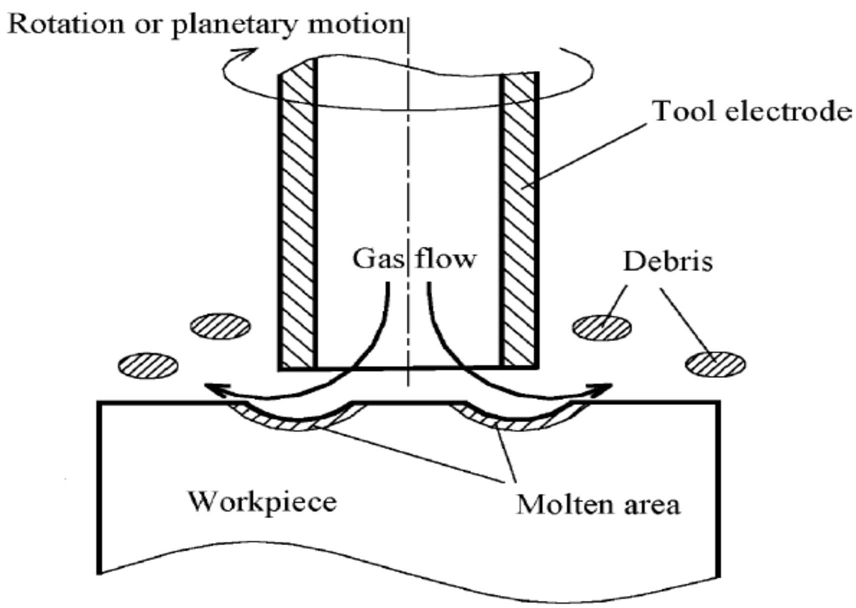

Figure 1.8: Schematic of dry EDM process [Zhang (2006)]

Tool rotation during machining not only facilitates flushing but also improves the process stability by reducing arcing between the electrodes. Dry EDM is an environment-friendly technique because of the absence of mineral oil-based liquid dielectric. Environmentally harmful oil-based dielectric wastes are not produced in dry EDM. Also, the process does not pose a health hazard since toxic fumes are not generated during machining. Additionally, absence of mineral oil-based dielectrics drastically reduces fire hazards during the process [Zhang (2006)].

1.7.2 EDM IN WATER

Water as dielectric is an alternative to hydrocarbon oil. The approach is taken to promote a better health and safe environment while working with EDM. This is because hydrocarbon oil such as kerosene will decompose and release harmful vapour (CO and CH_4). Research over the last 25 years has involved the use of pure water and water with additives. Machining in distilled water resulted in a higher MRR and a lower wear ratio than in kerosene when a high pulse energy range was used.

In 1981 Jaswani investigated the performances of kerosene and distilled water over the pulse energy range. It was also noticed that with distilled water, the machining accuracy was poor but the surface finish was better.

Jilani and Pandey in the year 1984 measures the performance of water as dielectric fluid in EDM using distilled water, tap water and a mixture of 25% tap and 75% distilled water. The best machining rates have been achieved with the tap water and machining in water has the possibility of achieving zero tool wear rate when using copper tools with negative polarities.

1.7.3 EDM IN WATER WITH ADDITIVES

EDM in water with additives is advancement of EDM in water; this technique is used to improve the performance of water. Some researchers have studied the feasibility of adding organic compound such as ethylene glycol, polyethylene glycol 200, polyethylene glycol 400, polyethylene glycol 600, dextrose and sucrose to improve the performance of de-ionized water.

The surface of titanium has been modified after EDM using dielectric of urea solution in water [Yan et al. (2005)]. Koenig and Joerres (1987) found that a highly concentrated aqueous glycerine solution has an advantage as compared to hydrocarbon dielectrics when working with long pulse durations and high pulse duty factors and discharge currents, i.e. in the roughing range with high open-circuit voltages and positive polarity tool electrode.

1.7.4 ROTATING WORKPIECE EDM

Rotating the workpiece is a technique in which rotational motion is given to workpiece to enhance the flushing of dielectric which subsequently improves the EDM performance.

Workpiece rotary motion improves the circulation of the dielectric fluid in the spark gap and temperature distribution of the workpiece yielding improved MRR and Surface quality [Guu and Hocheng (2001)]. Horizontal EDM process in which the main machining axis is horizontal instead of the conventional vertical axis is proposed by Kunieda and Masuzawa (1988). The change in the basic construction in addition to the rotary motion of the workpiece offered an accessible evacuation of debris improving the erosion efficiency and accuracy of the sparking process. Horizontal EDM has also been experimented in the micro-machining of small parts.

1.7.5 ROTATING ELECTRODE EDM

Performance measures of the EDM process also improves by the introduction of the rotary motion to the electrode. It serves as an effective gap flushing technique, which significantly improves the material removal rate and enhancing the surface quality of workpiece.

Soni (1984) observed the morphology, chemical composition and size distribution of debris, when using rotating electrodes for the same alloying effect of migrating material elements from the workpiece and tool.

CHAPTER 2

LITERATURE SURVEY AND PROBLEM FORMULATION

Modern metal working industry has several challenges such as to control cost, decrease lead-time from design to production, improvement of product quality, and machining/finishing of difficult to machine materials. Researchers have explored a number of ways to improve the performance of response parameters in EDM process but the full potential utilization of this process is not completely established because of large number of various materials being developed. The literature is reviewed with an objective of achieving improved surface integrity by developing a thorough understanding of the techniques evolved by the researchers on EDM.

2.1 REVIEW OF LITERATURE

Kahng (1977) stated that operating working voltage and the pulse interval plays an important role in obtaining the required surface finish. The flow movement of the dielectric fluid controls the homogeneous surface characteristics in the entire EDM controlled region. The spark gap control was also explained to obtain the desired level of surface roughness for a given set of operating variables. Fluttering of the edges in the EDM region was investigated for the variation in the controlling parameters.

Pandit (1978) conceptualized the theoretical aspects of the Electro Discharge machining Process. The energy parameters and the Metal removal rate relationships were developed for the given set of operating voltages and the dielectric pressure. The relationships obtained were used to plot graphs for the variation in the operating controlling parameters and their effects on the consequents such as metal removal rate, surface roughness and the power consumption by the machine etc.

Pandit (1981) stated the critical factors affecting the performance of the Electro Discharge machining process when the work piece material is Cemented carbide. A suitable hard alloy material is selected as electrode tool material. And the dielectric fluid is given turbulent flow in and around the EDM region. The operating variables like Pulse duration, Discharge

Current, Operating voltage, Pulse Interval time and heat dissipation rate differ in operating ranges considerably as compared to electro discharge machining of Steel alloys. However, it has been claimed that consistency and repeatability of the machine towards maintaining the minimum deviation in the operating conditions helps a lot in the Machining accuracy in the process.

Lim and Lu (1990) specified the basic thumb rules for the analysis of surface features of Electro discharge machining process. His paper was mainly meant for skilled workmanship towards achieving the desired surface characteristics in minimum time and with safety. The saving of the production cost is justified for the EDM process carried out. Common measures and precautions which are helpful in carrying out the EDM process for efficient operation are also been suggested.

Jain (1990) formulated the generalized Electro Discharge Machining method with the limited constraints related to Pulse interval time and pulse duration. Many operating variables were considered as parameters with fixed working values over a given erosion depth and erosion rate on the work piece. The formulated problem was analyzed by using a simple optimization algorithm by keeping other objective functions unaffected and the results were concluded to give the suitable operating variable value selection on the basis of output obtained.

Madhu and Jain (1991) developed the governing equations for the analysis of Electro Discharge machining process under a controlled environment. A computer program was developed in the form of subroutines for the calculation of electrode wear rate. Metal removal rate and dielectric material effect on the EDM process. The results obtained by the formulation used with the help of quadratic elements showed a good convergence with those obtained by the commercial packages.

Joopelli (1994) modeled and formulated the Electric Discharge Machining process with the optimization of objective functions related to moving trajectories of machine tool electrode. Gradient based methods have been used to optimize the single objective function variable. A moving frame reference was also used to locate the tool electrode at any instant along its traversed trajectories.

Smyers and Guha (1995) stated a practical approach for Machining the Beryllium Copper alloys as work piece by Electro Discharge Machining process. They suggested methods for obtaining the desired level of surface characteristics by using this EDM method. Safety precautions and the indicative measures were suggested for the fruitful implementation of the process. A brief note was also given for specifying the operating characteristics and safety precautions for the EDM process to be carried out.

Kee (1996) specified an integrated approach for jointly solving process selection, machining parameter selection, and tolerance design problems to avoid inconsistent and infeasible decision. The integrated problem is formulated as bi-criterion model to handle both tangible and intangible costs. The model is solved using a modified chebyshev goal programming method to achieve a preferred compromise between the two conflicting and non-commensurable criteria.

Zhang (1997) calculated the effect of motion and turbulence level in the dielectric material during various stages of the electro-discharge machining process. The results are tabulated and graphs have been recommended for use for the machining of steel materials. The effect of the selection of dielectric fluid has also been analyzed for a given set of electrode tool and material combination.

Yan et al. (2000) optimized the cutting of Al_2O_3/6061Al composite using rotary Electro discharging machining with a disklike electrode by using Taguchi methodology. Four observed values, material removal rate (MRR), electrode wear rate (EWR), relative electrode rate (REWR) and surface roughness (SR), were used to verify this optimization of the machining technique. In addition, six independent parameters were chosen as variables in evaluating the Taguchi method and were categorized into two groups: (i) Electrical parameters, e.g. polarity, peak current, pulse duration, and powder supply voltage. (ii) Non-electrical parameters, e.g. circumferential speed of electrode, reciprocating speed. Rotary EDM with disklike electrode was shown from the observed results to reach a higher MRR although the EWR was higher. The polarity of EDM largely affected the MRR. The peak current of EDM mainly affects the EWR and REWR. The polarity, the peak current, the pulse duration and the circumferential speed of EDM mainly affect the SR.

Matoorian et al. (2008) presented the application of the Taguchi robust design methods to optimize the precision and accuracy of the electrical discharge machining process (EDM) for machining of precise cylindrical forms on hard and difficult-to-machine materials. Their study was carried out on the influence of six design factors: intensity supplied by the generator of the EDM machine (I), pulse-on time (t_i), voltage (V), pulse-off time (t_o), servo (V_G), and rotational speed (C) which are the most relevant parameters to be controlled by the EDM process machinists, over material removal rate (MRR) as an indicator of the efficiency and cost-effectiveness of the process. The study of behaviour of the mentioned response has done by means of the technique called design of experiments (DOE). In this case, an L_{18} ($2^1 \times 3^7$) Taguchi standard orthogonal array was chosen due to the number of factors and their levels in the study.

Patel et al. (2009) investigated in detail the machining characteristics, surface integrity and material removal mechanisms of advanced ceramic composite Al_2O_3–SiC_w–TiC with EDM. The surface and subsurface damages have also been assessed and characterized using scanning electron microscopy (SEM). The results provide valuable insight into the dependence of damage and the mechanisms of material removal on EDM conditions. Their study provided an important insight for selecting EDM parameters using the ceramic composite Al_2O_3– SiC_w–TiC and showed it could be efficiently machined without causing a significant loss to the surface integrity. They showed that the material removal rate could be considerably increased due to thermal spalling induced flake detachment at higher current range.

Shabgard et al. (2011) presented a finite element model (FEM) to model temperature distribution for AISI H13 tool steel workpiece in electric discharge machining at different machining parameters (pulse current, pulse on-time, temperature-sensitive material properties, size of heat source and material flushing efficiency). Scanning electron microscopy (SEM) with energy dispersive x-ray (EDX) and micro-hardness tests were used to validate accuracy of FEM predictions. Increasing pulse on-time leads to a higher depth of heat affected zone and increasing pulse current results in a slight decrease of depth of heat affected zone.

Weingärtner et al. (2012) evaluated wire electrical discharge dressing (WEDD). With a self-designed WEDD-device the dressing process was carried out inside a grinding machine, reducing non-productive time. Moreover, the in-process WED-dressing was assessed, showing potential for future applications. Their dressing experiments indicated that high erosion material removal rates can be achieved and, in comparison to conventionally conditioned wheels, better grinding wheel topography is generated. A model to calculate the axial dressing feed rate in WED-sharpening was also proposed.

Satyarthi and Pandey (2013) proposed a mathematical model based on the fundamental principles of material removal in electric discharge machining (EDM) and conventional grinding processes. The inter-dependence of the thermal and mechanical phenomena was realized by scanning electron microscopy (SEM) characterization of the samples machined at different processing conditions. The key input process parameters like pulse on time, pulse current, gap voltage, duty cycle, pulse off time, frequency, depth of cut, wheel speed and table speed are co-related with MRR for three distinct idealized processing conditions. The constant showing the extent of inter dependence of two phenomena were evaluated by experimental data. The obtained expressions of MRR have been validated for processing conditions other than those used for obtaining constants. It was found that the discharge energy plays prominent role in material removal. The percentage difference in experimental findings and theoretical predictions was found to be less than 3%.

2.2 IDENTIFIED GAPS IN THE LITERATURE

After a comprehensive study of the existing literature, a number of gaps have been observed in Hybrid Electric Discharge Machining Electrode (HEDME) Process research.

- Sufficient efforts have not been undertaken towards the further improvement in process productivity/efficiency in terms of greater machining rate and accuracy.
- Almost all studies investigated the influence of continuous rotation of single material tool only. There is almost no study on Hybrid EDM electrode.

- Literature review reveals that very few researchers have carried out the work on Hybrid EDM Electrode which includes development, monitoring and control of the process.
- There is no or very limited information available in the direction of Hybrid EDM Electrode from surface finish quality point of view.

2.3 STATEMENT OF THE PROBLEM

The present work "*Development of Hybrid EDM Electrode (HEDME) for improving Surface Morphology*" has been undertaken in the background of below mentioned observation. Major limitation of EDM process is the low productivity. The time to achieve the required machining is higher in EDM process as compared to conventional machining process. Despite a range of different approaches all the research works in this share the same objectives of achieving more efficient material removal. There appears to be a need for more research contribution to develop modification of EDM process which will give better MRR economically with better surface integrity. Present research work attends to focus on important aspect of economic productivity of EDM (i.e. reduction of cost and improving the Surface Integrity).

One such modification has been attempted in the present investigation. This involves addition of abrasive particles in tool (electrode) which may improve surface integrity. This has been achieved by attaching a Chain-Drive motor mechanism to tool (electrode) holder in EDM process that makes tool (electrode) to rotate.

2.4 OBJECTIVE OF PRESENT INVESTIGATION

In light of the mentioned gaps, the present investigation aims to study the potential of HEDME process with rotating tool (electrode) in response parameters (i.e. material removal, tool wear and surface roughness) with the following objectives:

1. Design and development of experimental set-up capable of providing varying range of parameters of HEDME process.
2. Experimental study of the effect of various process parameters on performance characteristics of developed Hybrid Electric Discharge Machining Electrode.
3. Fabrication of set-up capable of providing rotating motion to Tool (electrode).

CHAPTER-3

EXPERIMENTAL DESIGN METHODOLOGY

A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. By the statistical design of experiments the process of planning the experiment is carried out, so that appropriate data will be collected and analyzed by statistical methods resulting in valid and objective conclusions. When the problem involves data that are subjected to experimental error, statistical methodology is the only objective approach to analysis.

3.1 TAGUCHI'S PHILOSOPHY

Taguchi's comprehensive system of quality engineering is one of the greatest engineering achievements of the 20th century. His methods focus on the effective application of engineering strategies rather than advanced statistical techniques. The farther upstream a quality method is applied, the greater leverages it produces on the improvement, and the more it reduces the cost and time. Taguchi's philosophy is founded on the following three very simple and fundamental concepts [Ross, 1988; Roy, 1990]:

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

3.2 EXPERIMENTAL DESIGN STRATEGY

Taguchi recommends orthogonal array (OA) for laying out of experiments. These OA's are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns [Roy, 1990].

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

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

- To estimate the response under the optimum condition

The optimum condition is identified by studying the main effects of each of the parameters.

The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control [Ross, 1988].

3.3 SIGNAL TO NOISE RATIO

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

3.4 STEPS IN EXPERIMENTAL DESIGN AND ANALYSIS

The important steps are discussed in the subsequent article.

3.4.1 SELECTION OF ORTHOGONAL ARRAY (OA)

In selecting an appropriate OA, the pre-requisites are [Ross, 1988; Roy, 1990]:

- Selection of process parameters and/or interactions to be evaluated
- Selection of number of levels for the selected parameters

The total Degrees of Freedom (DOF) of an experiment is a direct function of total number of trials. If the number of levels of a parameter increases, the DOF of the parameter also increases because the DOF of a parameter is the number of levels minus one. Thus, increasing the number of levels for a parameter increases the total degrees of freedom in the experiment which in turn increases the total number of trials. Thus, two levels for each parameter are recommended to minimize the size of the experiment [Ross, 1988].

If curved or higher order polynomial relationship between the parameters under study and the response is expected, at least three levels for each parameter should be considered [Barker, 1990].

The number as subscript in the array designation indicates the number of trials in that array. The total degrees of freedom (DOF) available in an OA are equal to the number of trials minus one [Ross, 1988]:

- $f_{LN} = N-1$ ...3.1

  Where,

  f_{LN} = Total degrees of freedom of an OA

  L_N = OA designation

  N = Number of trials

When a particular OA is selected for an experiment, the following inequality must be satisfied [Ross, 1988]:

$f_{LN} \geq$ Total degree of freedom required for parameters and interactions …3.2

3.4.2 EXPERIMENTATION AND DATA COLLECTION

The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried to reduce bias in the experiment.

The data (raw data) are recorded against each trial condition and S/N ratios of the repeated data points are calculated and recorded against each trial condition.

3.4.3 DATA ANALYSIS

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average response curves, interaction graphs etc. [Ross, 1988].

However, in the present investigation the following methods have been used:

Plot of average response curves

- ANOVA for raw data
- ANOVA for S/N data
- S/N response graphs

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of parameter on the response. The change in the response characteristic with the change in levels of a parameter can easily be visualized from these curves. Typically, ANOVA for OA's are conducted in the same manner as other structured experiments [Ross, 1988].

3.4.4 PARAMETERS DESIGN STRATEGY

3.4.4.1PREDICTION OF THE MEAN

The mean is estimated only from the significant parameters. The ANOVA identifies the significant parameters. Suppose, parameters A and B are significant and A_2B_2 (second level of $A=A_2$, second level of $B=B_2$) is the optimal treatment condition.

Then, the mean at the optimal condition (optimal value of the response characteristic) is estimated as [Ross, 1988]:

$$\mu = \overline{T} + \left(\overline{A}_2 - \overline{T}\right) + \left(\overline{B}_2 - \overline{T}\right)$$

$$= \overline{A}_2 + \overline{B}_2 - \overline{T}$$

Where

$\overline{T}$ = Overall mean of the response

$\overline{A}_2$, $\overline{B}_2$ = Average values of response at the second levels of parameters A and B respectively

3.4.4.2 DETERMINATION OF CONFIDENCE INTERVAL

The estimate of the mean (μ) is only a point estimate based on the average of results obtained from the experiment. Statistically this provides a 50% chance of the true average being greater than μ. It is therefore customary to represent the values of a statistical parameter as a range within which it is likely to fall, for a given level of confidence [Ross, 1988]. This range is termed as the confidence interval (CI) [Ross, 1988].

The following two types of confidence interval are suggested by Taguchi in regards to the estimated mean of the optimal treatment condition [Ross, 1988].

1. Around the estimated average of a treatment condition predicted from the experiment. This type of confidence interval is designated as CI_{POP} (confidence interval for the population).
2. Around the estimated average of a treatment condition used in a confirmation experiment to verify predictions. This type of confidence interval is designated as CI_{CE} (confidence interval for a sample group).

The difference between CI_{POP} and CI_{CE} is that CI_{POP} is for the entire population i.e., all parts ever made under the specified conditions, and CI_{CE} is for only a sample group made under the specified conditions. Because of the smaller size (in confirmation experiments) relative to entire population, CI_{CE} must slightly be wider. The expressions for computing the confidence intervals are given below [Ross, 1988; Roy, 1990].

$$CI_{POP} = \sqrt{\frac{F_{\alpha}(1, f_e)V_e}{n_{eff}}} \qquad \text{...3.3}$$

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \qquad \text{...3.4}$$

Where, $F\alpha$ (1, f_e) = The F ratio at a confidence level of (1-α) against DOF 1, and error degree of freedom f_e.

$$n_{eff} = \frac{N}{1 = [\text{Total DOF associated in the estimate of the mean}]}$$

N = Total number of results

R = Sample size for confirmation experiment

In Eq. 3.7, as R approaches infinity, i.e., the entire population, the value 1/R approaches zero and $CI_{CE} = CI_{POP}$. As R approaches 1, the CI_{CE} becomes wider.

3.4.4.3 CONFIRMATION EXPERIMENT

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

CHAPTER-4

DESIGN AND FABRICATION OF EXPERIMENTAL SETUP

4.1 DESIGN OF EXPERIMENTAL SETUP

Hybrid Electric Discharge Machining Electrode (HEDME) system is used as machining process for better material removal rate and the removal of machine debris especially when high surface integrity is required. Therefore, an appropriate frame and housing is necessary to accommodate the system and proper functioning of the setup. The experimental set up an important element of the Hybrid Electric Discharge Machining developed for this research has been described in this chapter. The line diagram of Hybrid EDM is shown in Figure 4.1.

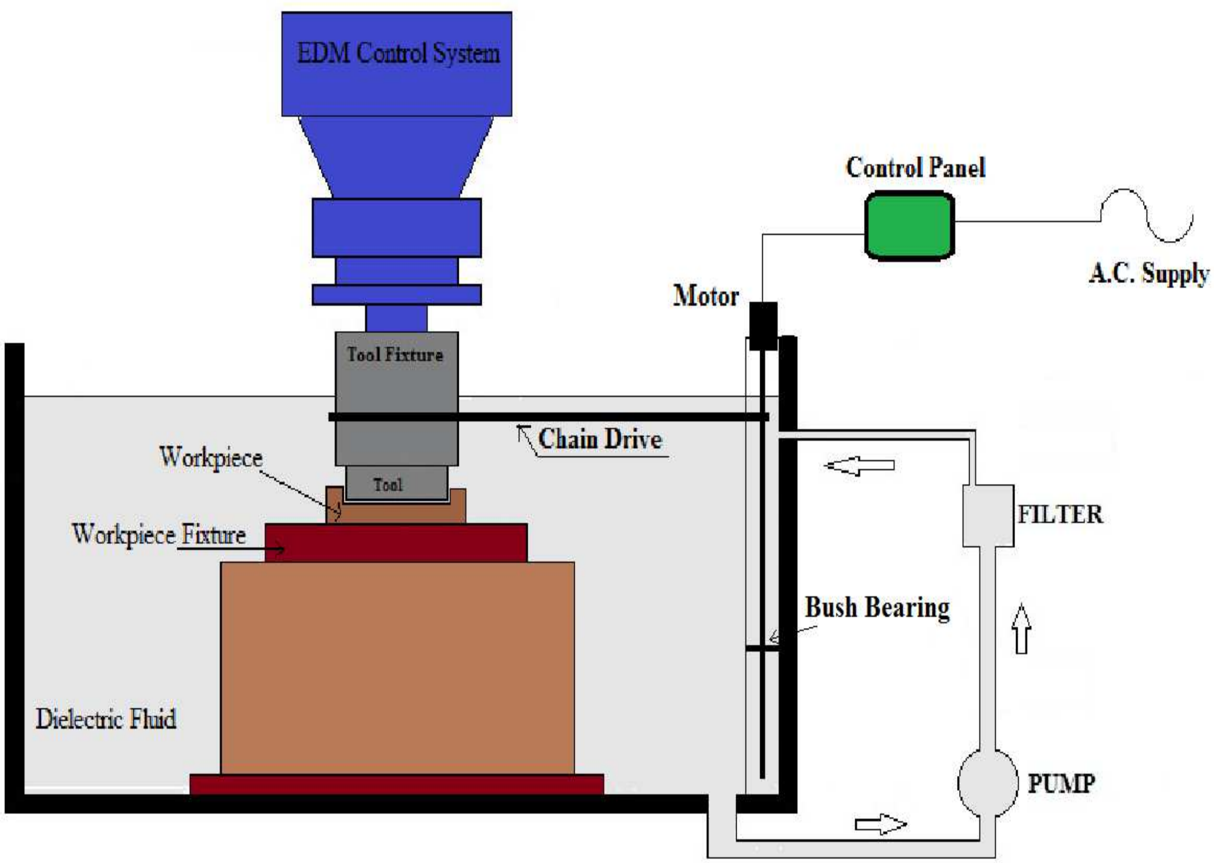

Figure 4.1: Line diagram of HEDME set-up

The Developed Hybrid Electric Discharge Machining Electrode (HEDME) setup can be divided into two elements:

- Electric Discharge Machine
- Rotating Electrode Unit

4.2 ELECTRIC DISCHARGE MACHINE

The Sparkonix S35 machine (Sparkonix India Pvt. Ltd.) shown in Figure 4.2 is used for Hybrid EDM setup.

The EDM machine tool has the following specifications:

Design	:	Fixed Column, Moving Table
Maximum working current	:	35 Ampere
Input Mains Voltage	:	415V±10%, 3 phase, 50 Hz.
Open Gap Voltage	:	1-200 V
Pulse-on Time	:	1 to 1000 µs
Tank Size	:	775 x 450 x 325 mm
Quill	:	200 mm
Maximum height of workpiece	:	300 mm
Maximum weight of workpiece	:	400 Kg
Maximum weight of Electrode	:	35 Kg
Capacity of Dielectric System	:	260 Ltrs
Height	:	1320 mm
Width	:	725mm
Depth	:	450 mm

Figure 4.2: HEDME Machine Tool (1: Display Motor. 2: Motor for Rotating Mechanism, 3: Die-Electric tank, 4: Servo-Control)

4.3 HYBRID ELECTRODE SYSTEM

The Hybrid Electric Discharge Machining Electrode (HEDME) system incorporates to operate EDM in rotation. Hybrid Electric Discharge Machining Electrode (HEDME) is developed by comprising the features of Electric Discharge Machining and Grinding which occurs alternatively in place of their simultaneous effect as EDG process.

In HEDME process, the metallic electrode used during EDG process has been replaced with slotted electrode. The slot on the surface of metallic electrode is completely filled with vitrified bond abrasive ceramic slab and finally gets a uniform circular shape, which is used for alternative application of the EDG processes due to the rotation of the hybrid electrode. The mechanism of material removal of the HEDME process is shown in the Figure 4.3.

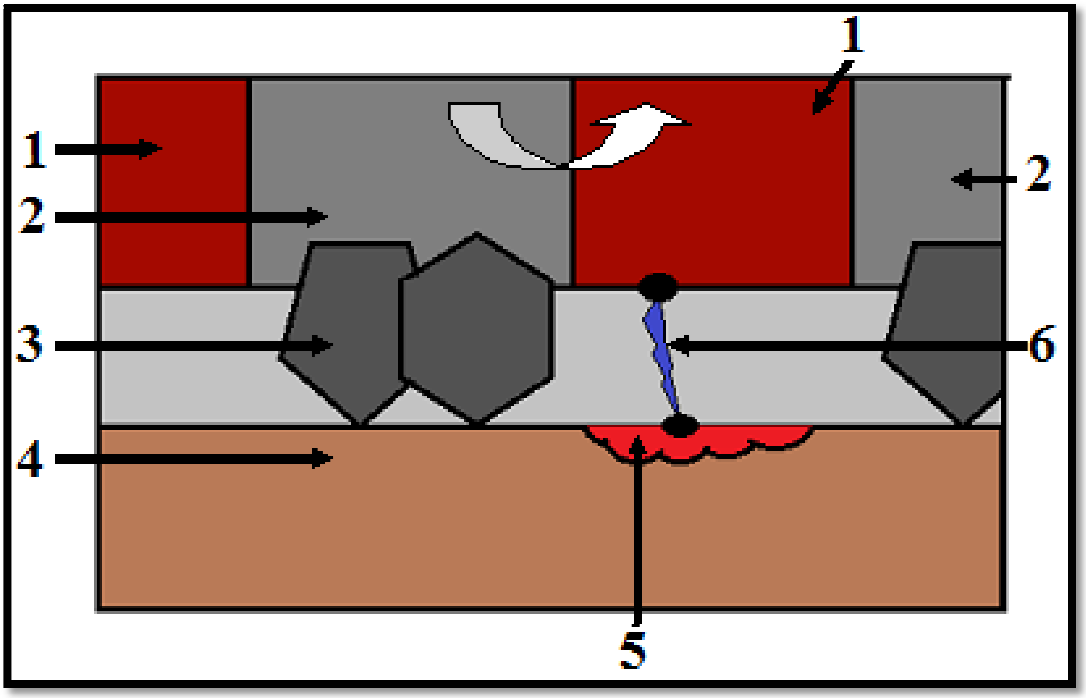

Figure 4.3: Interaction of Electrode - Workpiece in HEDME Process
(1: Metallic Slot of Electrode, 2: Abrasive Ceramic Slot of Electrode, 3: Abrasive Ceramic particles, 4: Workpiece, 5: Recast Layer, 6: Spark)

In this process, the material is removed in two phases. Firstly, the spark is generated between workpiece and metallic portion of the slotted Electrode during Pulse-on in the EDM machine. Due to the spark material is melted and softened below the melt zone.

The molten material is removed during pulse off-time of EDM process. This phenomenon is repeated during entire metallic portion of the hybrid electrode. Secondly the material is removed due to the abrasive action of the abrasive ceramic particles. These two actions are repeated due to rotation of the electrode and material is removed due to the individual effect of spark erosion and abrasion processes.

Many process parameters affect the performance of the HEDME process. These parameters are either EDM, grinding or related to the both. The Figure 4.4 shows the schematic diagram of the HEDME process.

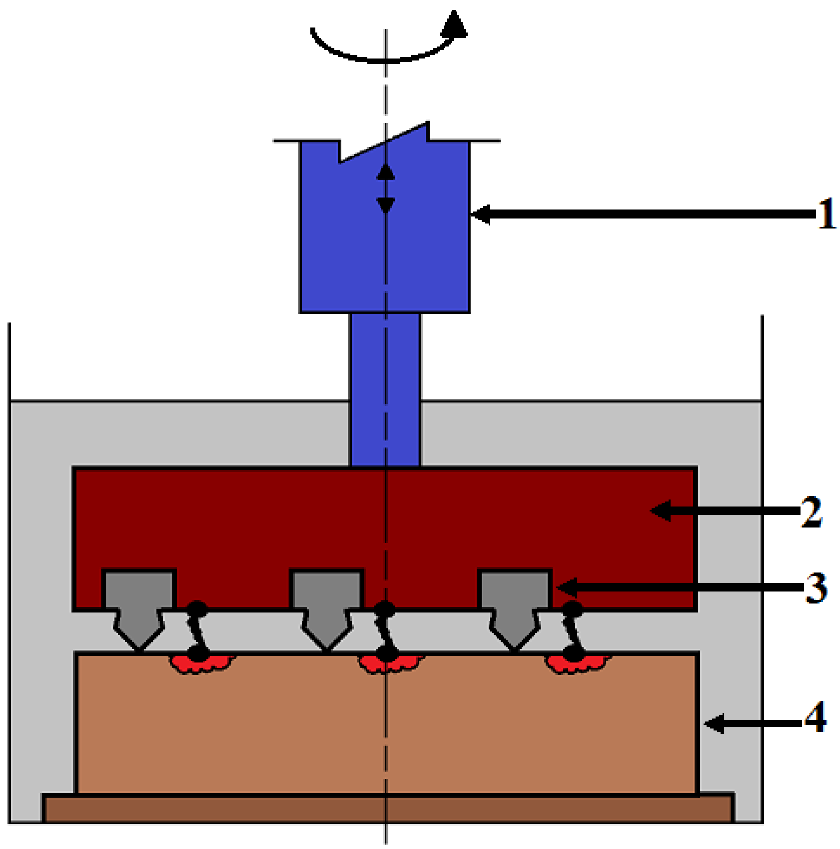

Figure 4.4: Schematic view of the HEDME process (1: EDM Machine RAM, 2: Metallic part of Electrode, 3: Abrasive Ceramic Particles, 4: Workpiece)

Figure 4.5, 4.7 and 4.9 shows Photographic views of 1st 2nd and 3rd developed Hybrid Electric Discharge Machining Electrode (HEDME) respectively.

Figure 4.6, 4.8 & 4.10 shows the line diagram of 1st, 2nd and 3rd design of developed Hybrid Electric Discharge Machining Electrode (HEDME) with their Dimensions respectively.

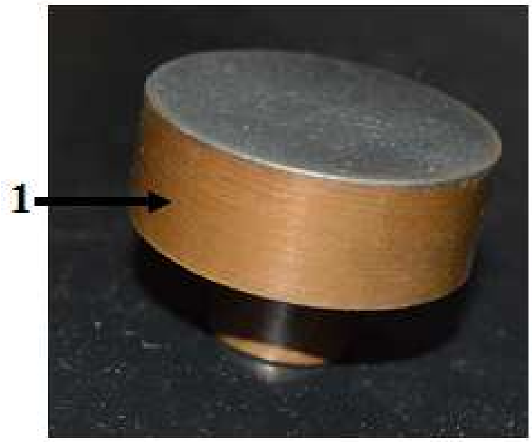

Figure 4.5: Photographic view of 1st developed Hybrid Electric Discharge Machining Electrode (1: Copper Part)

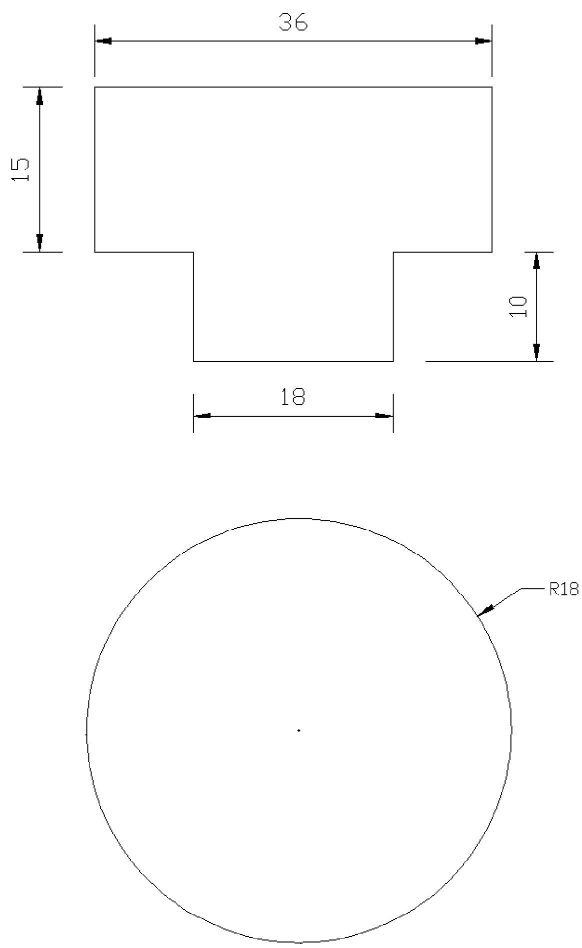

Figure 4.6: Line diagram of 1st developed Hybrid Electric Discharge Machining Electrode (all Dimensions in mm)

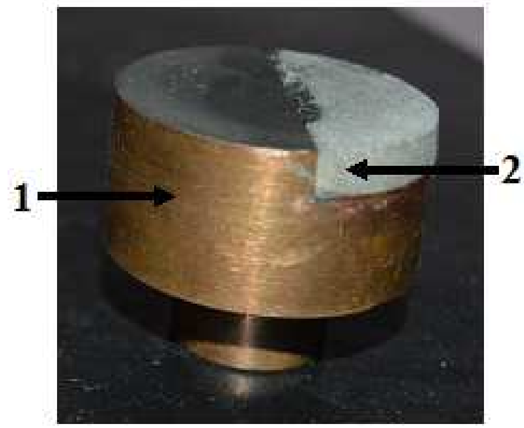

Figure 4.7: Photographic view of 2nd developed Hybrid Electric Discharge Machining Electrode (1: Copper Part, 2: Abrasive Ceramic particles Slab)

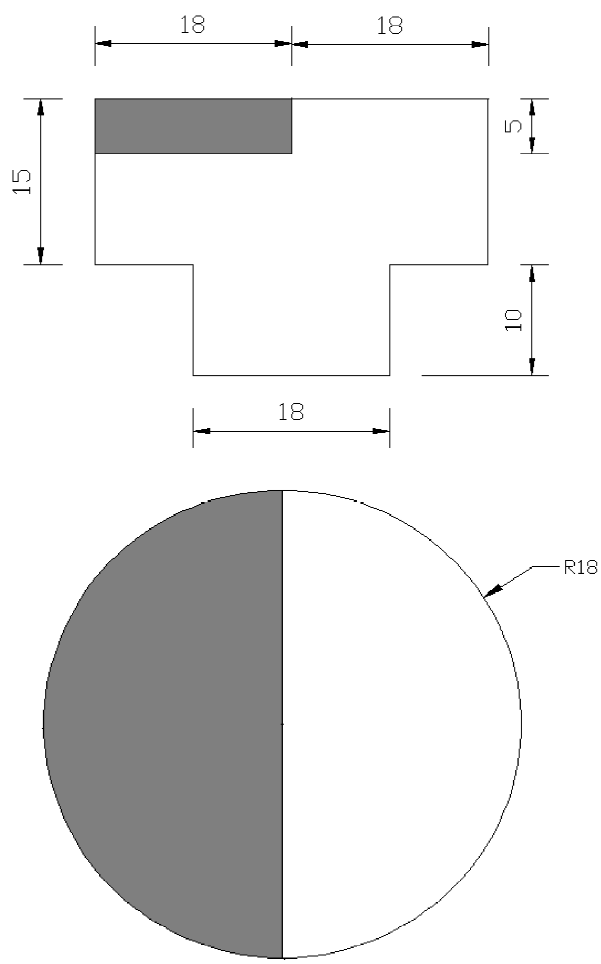

Figure 4.8: Line diagram of 2nd developed Hybrid Electric Discharge Machining Electrode (all Dimensions in mm)

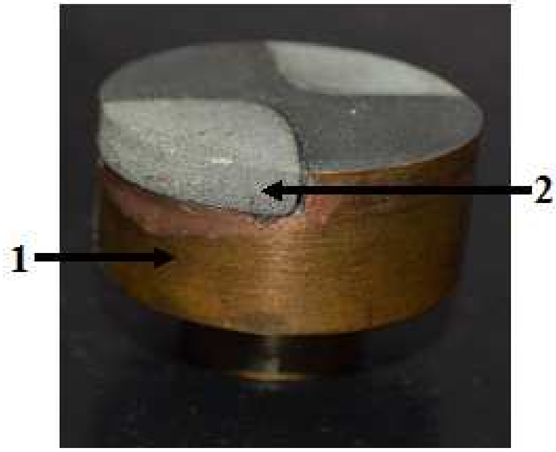

Figure 4.9: Photographic view of 3rd developed Hybrid Electric Discharge Machining Electrode (1: Copper Part, 2: Abrasive Ceramic particles Slab)

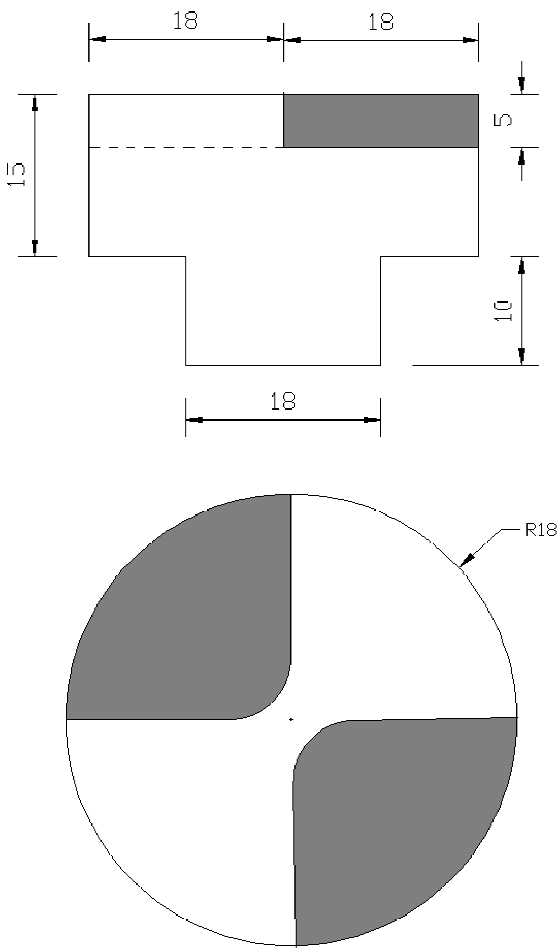

Figure 4.10: Line diagram of 3rd developed Hybrid Electric Discharge Machining Electrode (all Dimensions in mm)

The following are the major components of the HEDME system:

- ➢ Control panel
- ➢ A PWM generator circuit
- ➢ Adapter
- ➢ Electrode Holder

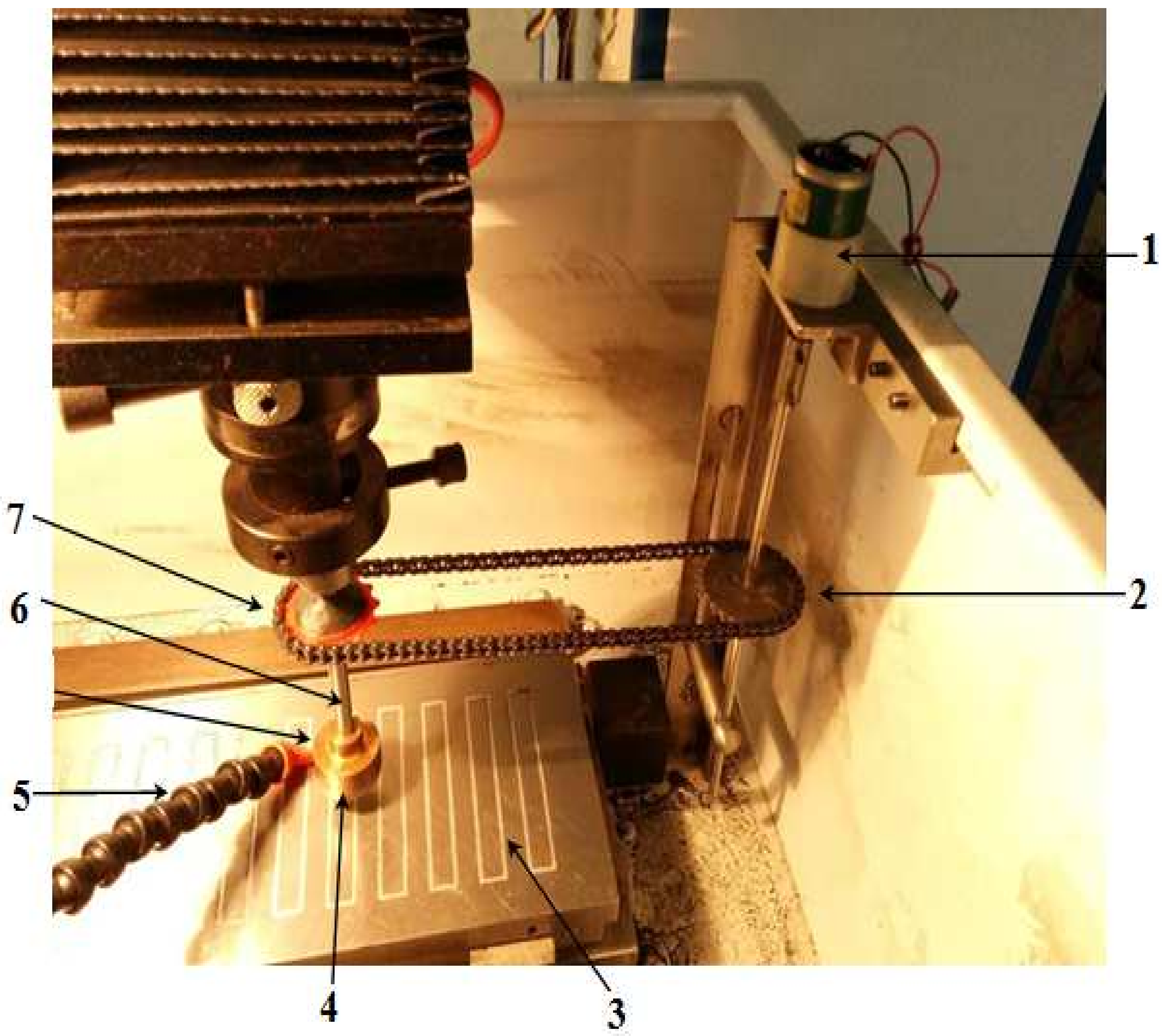

Figure 4.11: Photographic view of HEDME System setup (1: DC Motor, 2: Chain Drive for the rotation motion, 3: Magnetic Chuck for Holding workpiece, 4: Hybrid EDM Electrode, 5: Flushing Pipe, 6: Electrode Holder, 7: Plastic Gear)

4.3.1 CONTROL PANEL

A control panel consisting of a PWM generator circuit, Potentiometer, 555 Timer (PWM) & Capacitor for controlling speed of motor by adjusting duty cycle of square wave.

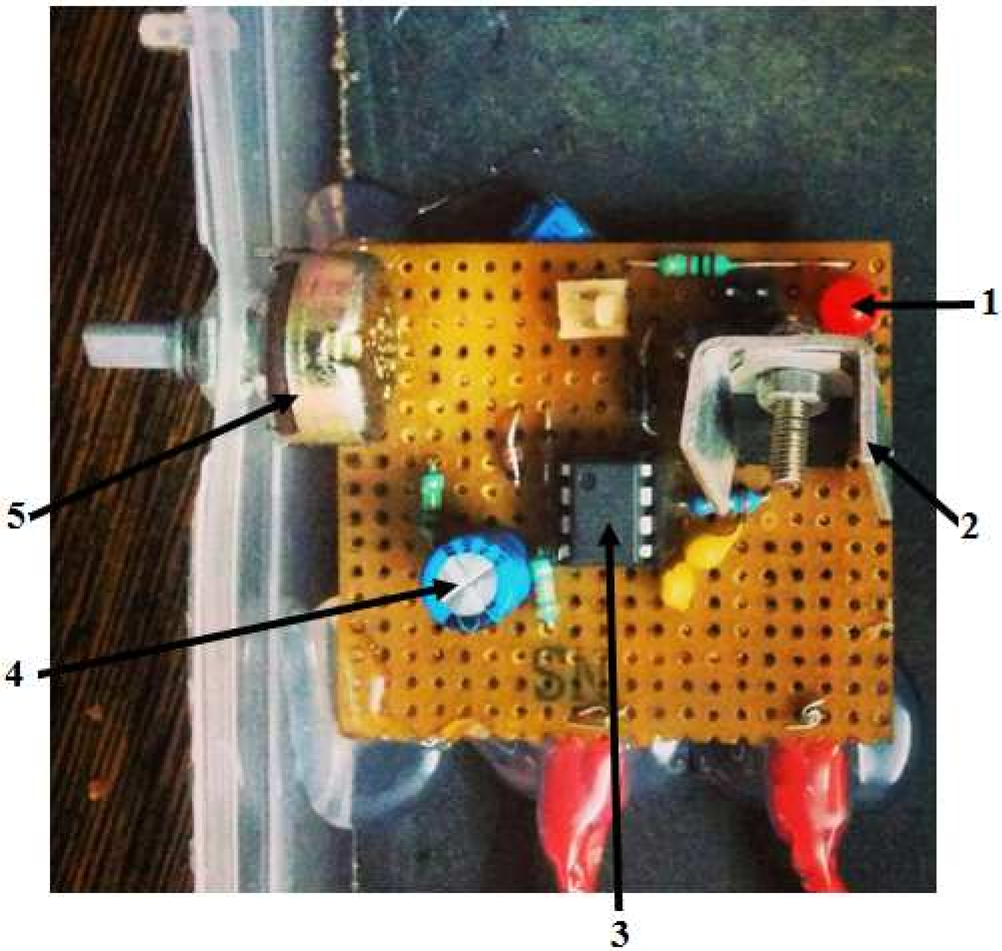

Figure 4.12: Control Panel Circuit (1: LED, 2: Voltage Regulator for Motor Driving, 3: 555 Timer for PWM, 4: Capacitor, 5: Potentiometer)

4.3.2 POTENTIOMETER

A Potentiometer is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used, one end and the wiper, it acts as a variable resistor or rheostat. A potentiometer measuring instrument is essentially a voltage divider used for measuring electric potential (voltage); the component is an implementation of the same principle, hence its name. Potentiometers are commonly used to control electrical devices such as volume controls on audio equipment. Potentiometers operated by a mechanism can be used as position transducers, for example, in a joystick.

Figure 4.13: Photographic view of a Potentiometer

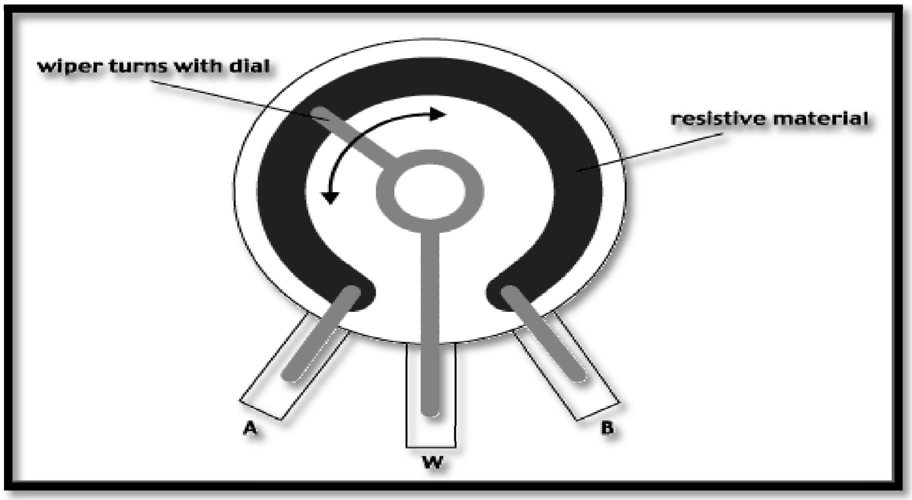

Figure 4.14: Inside view of a Potentiometer

4.3.3 A 555 TIMER PWM GENERATOR CIRCUIT

By varying the internal set points using the 555's "control" pin, we can make an adjustable pulse width generator. Every time the "trigger" pin pulses low briefly, the 555's output switches to be high, and the discharge transistor is disabled, so C1 charges through R1. It keeps charging until its voltage is above the "control" pin voltage, at which point the 555 changes states. The output goes low, and the discharge transistor is activated, nearly immediately discharging C1. The width (in time) of the output pulse is determined by the control voltage. By putting a constant stream of brief low-going pulses into the "trigger" pin, this cycle repeats again and again, and we get a digital sampled PWM representation of our analog waveform. It is useful for motor control.

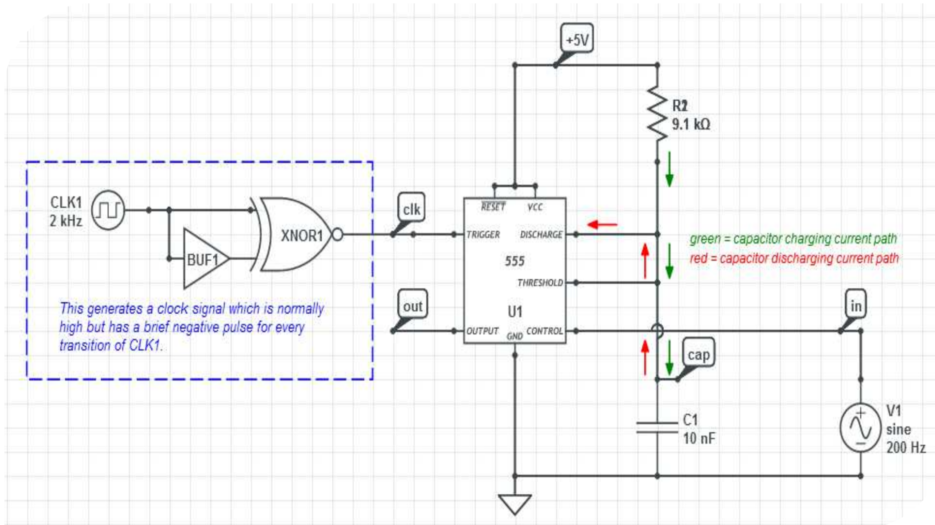

Figure 4.15: Circuit Diagram of 555 Timer for PWM

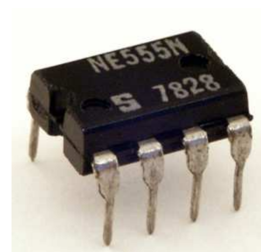

Figure 4.16: 555 Timer for PWM

4.3.4 AC ADAPTER

An AC adapter or AC/DC converter is a type of external power supply, often enclosed in a case similar to an AC plug. Adapters for battery-powered equipment may be described as chargers or rechargers. AC adapters are used with electrical devices that require power but do not contain internal components to derive the required voltage and power from mains power.

Input: 100V-210V

Frequency: 50-60Hz

Output: 12V DC

Figure 4.17: A 12V AC Adapter

4.3.5 ELECTRODE HOLDER

Tool (Electrode) holder is made up of mild steel, it consists of two parts one which will be fixed at quill of EDM machine and the other part (lower part) which has thread to hold tool (electrode). Both parts are combined by a bearing system in between them so that the relative motion can be achieved in between the upper part and lower part of Tool (electrode) holder.

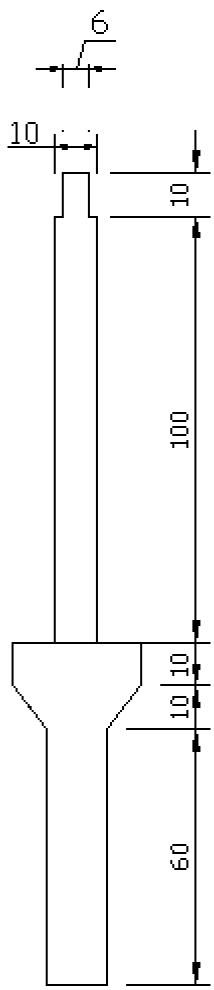

Figure 4.18: Dimension of Electrode holder (all dimensions in mm)

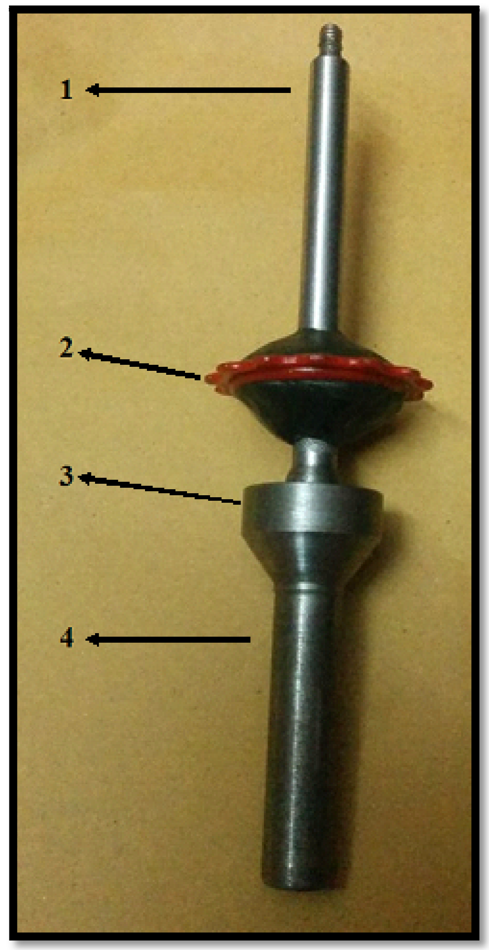

Figure 4.19: Photographic view of developed Electrode Holder

(1: Lower part, 2: Plastic Gear, 3: Bearing, 4: Upper Part)

CHAPTER-5

PROCESS PARAMETER SELECTION AND EXPERIMENTATION

In the present chapter, the process parameters which may affect the machining characteristics such as material removal rate, tool wear rate and surface integrity are selected.

The range of the process parameters for the experimentation was decided on the basis of literature and past experience. The scheme of experiments for process parameters selection is laid out. The experiments are conducted within the range of selected process parameters of EDM. The details of process parameters, their values and detail experimentation are given in the subsequent sections.

5.1 SELECTION OF PROCESS PARAMETERS AND THEIR RANGE

In order to obtain high material removal rate, low tool wear rate and better quality of surface produced by EDM process, the working range of the various parameters is to be determined.

5.1.1 PEAK CURRENT

The peak current is basically a most important machining parameter in EDM. The peak current is maximum value of the current passing through the electrodes for the given pulse and it is represented by I_P and measures in unit of amperage (A). During each pulse on-time, the current increases until it reaches a preset level, which is expressed as the peak current.

The maximum amount of amperage is governed by the surface area of the cut. Higher amperage is used in roughing operations and in cavities or details with large surface areas. Higher currents will improve MRR, but at the cost of surface roughness and tool wear rate. All these factors are also important in EDM because the machined cavity is a mirror image of tool electrode and excessive wear will obstruct the accuracy of machining.

5.1.2 NO-LOAD VOLTAGE

No-load voltage can be measured as two different values during one complete cycle. The voltage which can be read across the electrode/ workpiece gap before the spark current begins to flow, is called the No-load voltage. The voltage that can be read across the gap during the spark current discharge is the working gap voltage. Before current can flow, the No-load voltage increases until it has created an ionization path through the dielectric. Once the current starts to flow, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and workpiece. Higher voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the cut. Material removal rate, tool wear rate and surface roughness increases, by increasing No-load voltage, because electric field strength increases. Increase in the no-load voltage value will increase the pulse discharge energy which in turn can improve the MRR.

5.1.3 PULSE-ON TIME AND PULSE-OFF TIME

The pulse-on time is duration of time and pulse-off time is pulse interval of EDM spark. These are expressed in units of microseconds and generally expressed by T_{on} and T_{off} respectively. All the cutting was done during pulse on-time, so the duration of these pulses and the number of cycles per second (frequency) have vital role. Metal removal rate is directly proportional to the amount of energy applied during the pulse on-time [Kansal et al. (2005)]. This energy is controlled by the peak current and the length of the pulse on-time. With longer pulse duration, more workpiece material will be melted away. The resulting crater will be broader and deeper than a crater produced by shorter pulse duration. This will increase the surface roughness. Extended pulse duration also allow more heat to sink into the workpiece and spread, which means the recast layer will be larger and deeper heat affected zone. However, extreme pulse duration can be counter-productive. When the optimum pulse duration for each tool and workpiece material combination is exceeded, material removal rate starts to decrease.

Long pulse duration can also restrict electrode from machining. The cycle is completed when sufficient pulse interval is allowed before the start of the next cycle. Pulse interval will affect the speed and stability of the cut.

According to theory, the shorter the interval, the faster will be the machining operation. But if the interval is too short, the expelled workpiece material will not be flushes away with the flow of the dielectric fluid and the dielectric fluid will not be de-ionized. This will cause the next spark to be unstable and slows down cutting more than long stable off-times. At the same time, pulse interval must be greater than the deionization time to prevent continued sparking at one point [Fuller and John (1996)]. Modern power supplies allow independent setting of pulse on-times and pulse off-times.

5.1.4 DUTY FACTOR

The duty factor (τ) is referred as the percentage of the on-time relative to the sum of the on-time and off-time setting for a particular cut. The effect of duty factor depends upon the effect of pulse-on time and pulse-off time.

5.1.5 POLARITY

The polarity of the electrode can be either positive or negative. But the excess material is removed in positive polarity. When series discharge starts under the electrode area and passes through the gap, which creates high temperature causing material evaporation at the faces of both the electrode. The plasma channel is composed of ion and electron flows. As the electron processes (mass smaller than an ions) show quicker reaction, the anode material is worn out predominantly. This effect causes minimum wear to the tool electrodes and becomes of importance under finishing operations with shorter pulse on-times. However, while running longer discharges, the early electron process predominance changes to positron process (proportion of ion flow increases with pulse duration), resulting in high tool wear. In general, polarity is determined by experiments and is a matter of tool material, work material, current density and pulse length combinations. In the present study positive polarity was chosen for experimentation.

The selected process parameters and their range for the detailed experiments are shown in Table 5.1

Table 5.1: Different process parameters and their range

S. No.	Process Parameter	Range	Units
1	Type of Tool	3 Different Shapes	-
2	Current	2-10	A
3	Time	30-50	Minutes
4	No-load Voltage	1-200	V
5	Pulse-on Time	1-1000	μs
6	Pulse-off Time	1-1000	μs
7	Polarity	Positive/Negative	---
8	Flushing method	Submerged/Pressure	---

5.2 WORKPIECE AND TOOL MATERIAL

The workpiece used for study was EN-31 High Carbon Alloy Steel with a Circular Disk shape (Diameter 50mm). EN-31.

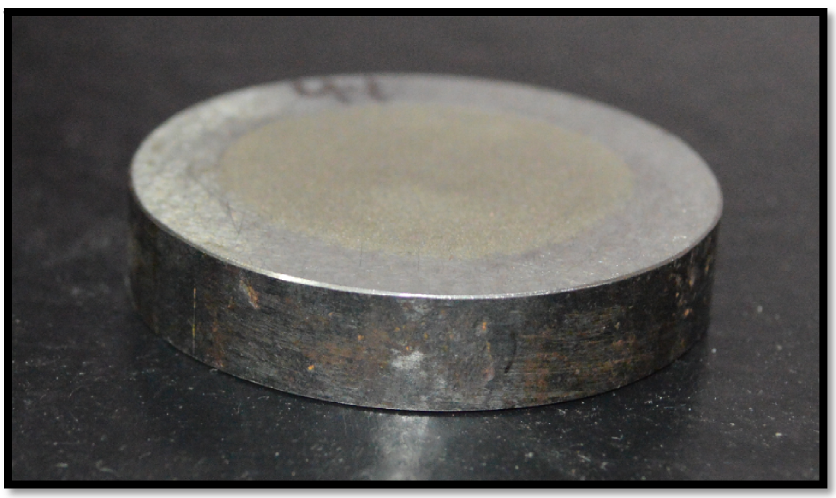

Figure 5.1: Photographic view of Workpiece

By its character this type of steel has high resisting nature against wear and can be used for components which are subjected to severe abrasion, wear or high surface loading.

The Chemical and Mechanical properties of High Carbon high Chromium Steel are shown in Table 5.2 and Table 5.3 respectively.

Table 5.2: Chemical compositions of EN-31 High Carbon Alloy Steel

Element	C	Cr	Mn	Si	Fe
Percentage	1.1	1.3	.33	.19	Balance

Table 5.3: Mechanical properties of EN-31 High Carbon Alloy Steel

S. No.	Essential Properties	Value
1	Specific Gravity	7.83
2	Density (Kg/ m^3)	7833.44
3	Machinability	70
4	Modulus of Elasticity Tension	29
5	Thermal Conductivity (W/(m·K))	240
6	Coefficient of Thermal Expansion	6.5
7	Melting Point (^{O}F)	2595

The EN-31 High Carbon Alloy Steel is widely used in roller bearing components such as brakes, cylindrical, conical & needle rollers. With its exceptional hardness, wear resistance and high mechanical strength it is becoming very desirable for a number of applications.

5.3 PREPARATION OF ELECTRODES

The electrodes are prepared by using several conventional machining methods such as turning, parting, facing and grinding. The front face of the electrode against the workpiece was ground using emery paper to gain better surface finish and the flatness of each electrode at the same level. The specimen of workpiece and tool used are shown in Figure 5.4, 5.5, 5.6 and 5.7.

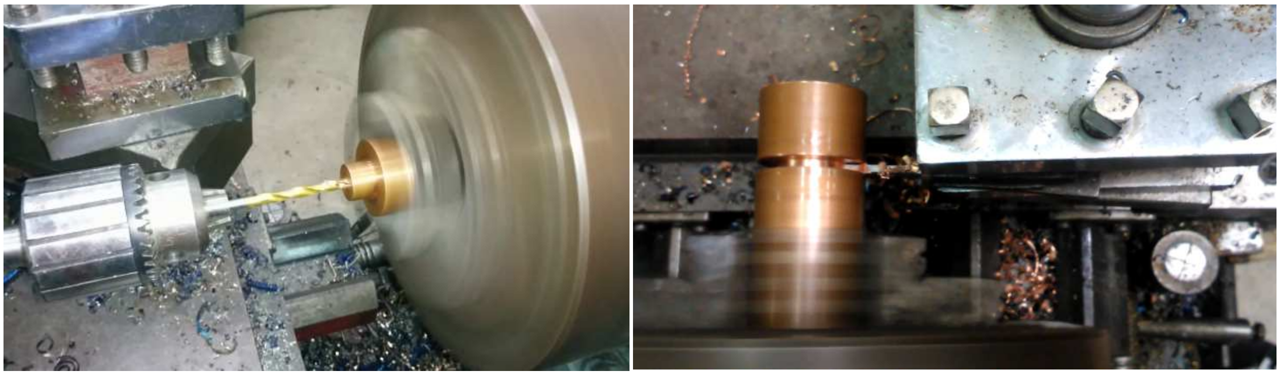

Figure 5.2: Turning Processes on Electrode

Figure 5.3: Milling Processes on Electrode

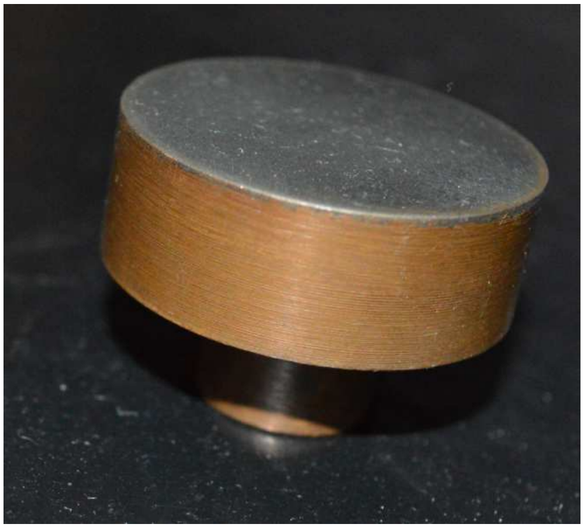

Figure 5.4: Specimen of 1st design of Developed Hybrid EDM Electrode of Copper

Figure 5.5: Specimen of 2nd design of Developed Hybrid EDM Electrode of Copper

Figure 5.6: Specimen of 3rd design of Developed Hybrid EDM Electrode of Copper

Figure 5.7: The Specimen Workpiece after machining

5.4 RESPONSE CHARACTERISTICS

The effect of selected process parameters was studied on the following response characteristics of EDM process:

1. Material Removal Rate (MRR)
2. Tool Wear Rate (TWR)
3. Surface Roughness (SR)

5.4.1 MATERIAL REMOVAL RATE (MRR)

Material removal rate was calculated by measuring the difference between initial and final weight of the specimen after processing at a specified set of condition by EDM process. The initial and final weights of the workpiece are measured on electronic balance having a least count of 0.01 gm. The weight material removal rate (MRR) was then converted into volumetric material removal rate.

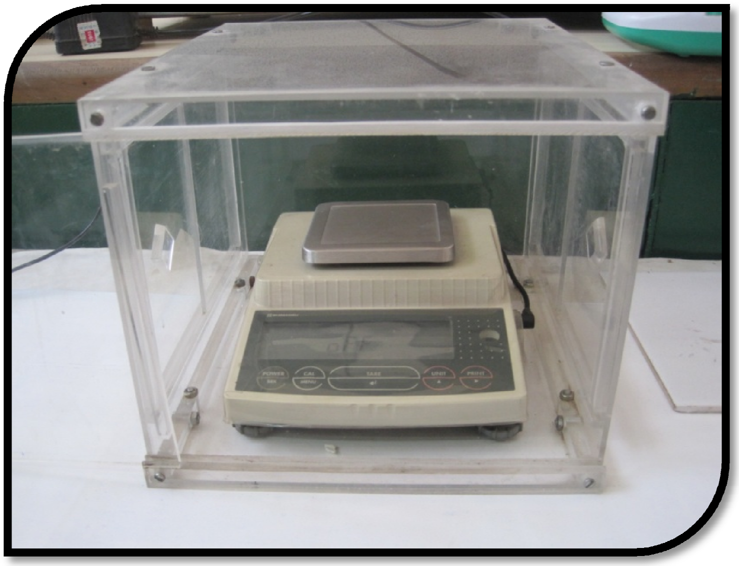

Figure 5.8 Shimadzu's Electronic Balance Machine

Volumetric material removal rate (mm^3/min) is calculated by using the relation:

$$MRR = \frac{(M_1 - M_2)}{\rho M_t} X 10^3 \quad \text{.....5.1}$$

Where 'M_1' and 'M_2' are the initial and final workpiece weight (gm) respectively, 'ρ' is the density of workpiece (gm/cm^3), and 'M_t' is the machining time (min.)

An alternate method of MRR calculation is by measuring the depth of cut and then multiplying it with the area of cross-section of the cut. However, such a method may lead to faulty values if a constant area of cross-section is assumed since it is expected that the machined section would be tapered. On the other hand, the weight loss method of MRR calculation gives the actual material removed during machining. Hence this method has been used for calculating the MRR. Figure 5.6 shows the electronic balance used for the calculation of MRR.

5.4.2 TOOL WEAR RATE (TWR)

The chips collected in the filter come not only from the workpiece, but can also originate from the metal of the electrode. As the spark melts the workpiece, tool also gets affected. The same procedure was used to calculate the TWR as in case of MRR.

Volumetric tool wear rate (mm^3/min) was calculated by using the relation:

$$TWR = \frac{(M_1 - M_2)}{\rho M_t} X\ 10^3 \qquad \text{.....5.2}$$

Where ‘M_1’ and ‘M_2’ are the tool weight (gm) before and after machining respectively, ‘ρ’ is the density of electrode (gm/cm^3), and ‘M_t’ is the machining time (min.).

5.4.3 SURFACE ROUGHNESS (SR)

Surface roughness is the measure of the fine surface irregularities in the surface texture. These are the results of the EDM process employed to create the surface. Surface roughness is related as the arithmetic average deviation of the surface valleys and peaks expressed in micro-meters.

The parameter mostly used for general surface roughness is Ra. It measures average roughness by comparing all the peaks and valleys to the mean line, and then averaging them all over the entire cut-off length. Cut-off length is the length that the stylus was dragged across the surface; a longer cut-off length will give a more average value, and a shorter cut-off length might give a less accurate result over a shorter stretch of surface.

Figure 5.9: Surface Roughness Tester [Mahr Federal (Model: Pocket Surf III)]

In this work the surface roughness is measured by Mahr Federal Pocket Surf III. The Pocket Surf is a shop–floor type surface-roughness measuring instrument, which traces the surface of various machine parts and calculates the surface roughness based on roughness standards, and displays the results in µm. The workpiece is attached to the detector which traces the minute irregularities of the workpiece surface. The vertical stylus displacement during the trace is processed and digitally displayed on the display of the instrument. The surf test has following measuring range:

R_a 0.03 µm to 6.35 µm / ***1 µinch to 250 µinch***

R_y 0.2 µm to 25.3 µm / ***8 µinch to 999 µinch***

R_{max} 0.2 µm to 25.3 µm / ***8 µinch to 999 µinch***

R_z 0.2 µm to 25.3 µm / ***8 µinch to 999 µinch***

The roughness values are taken by averaging at least three measurements per specimen at different locations of specimens. Figure 5.8 shows the surface roughness tester used for the measure of surface roughness and Figure 5.9 shows the surface roughness tester machine and its various ranges of measurements.

Figure 5.10: Surface Roughness Tester showing its various measuring range [Mahr Federal (Model: Pocket Surf III)]

5.5 SCHEME OF EXPERIMENTS

The experiments were designed to study the effect of some of the EDM parameters on response characteristics. Taguchi parametric design methodology was adopted in experimentation. Table 5.4 shows the process parameters and their values at different levels.

5.5.1 SELECTION OF ORTHOGONAL ARRAY (OA) AND PARAMETER ASSIGNMENT

Before selection a particular OA to be used as a matrix for conducting the experiments, the following two points were considered as suggested by Ross (1996) and Roy (1990):

1. The number of parameters and interactions of interest
2. The number of levels for the parameters of interest

The non-linear behavior, if exist, among the process parameters can only be studied if more than two levels of the parameters are used. Therefore, each parameter was analyzed at three levels.

Table 5.4: Selected Process Parameters and Their Levels

Symbol	**Process Parameters**	**Unit**	**Level 1**	**Level 2**	**Level 3**
A	Type of Tool	-	-	-	-
B	Current	A	2	6	10
C	Time	Min.	30	40	50
Work Material: EN-31 High Carbon Alloy Steel, Workpiece Diameter : 50 mm, Electrode (Tool): Copper and Abrasive particles (Diameter 36mm, Abrasive particle Height 5mm, Total Height 18mm), Polarity: Positive, Dielectric Fluid: EDM Oil (LL 21), Flushing Pressure: Normal Submerged (1kg/cm^2)					

Standard L_9 OA with the parameters assigned by using linear graphs is given in Table 5.5. The unassigned columns were treated as error. For each trial, experiments were replicated three times.

Table 5.5: The L_9 OA (Parameters assigned) with Response

Exp. No.	**Run order**	**Parameters Trial Conditions**				**Responses (Raw Data)**			**S/N ratio (db)**
		A	**B**	**C**	**e**	**R_1**	**R_2**	**R_3**	
		1	**2**	**3**	**4**				
1	1	1	1	1	-	Y_{11}	Y_{12}	Y_{13}	S/N (1)
2	4	1	2	2	-	Y_{21}	Y_{22}	Y_{23}	S/N (2)
3	7	1	3	3	-	-	-	-	-
4	9	2	1	3	-	-	-	-	-
5	2	2	2	1	-	-	-	-	-
6	5	2	3	2	-	-	-	-	-
7	8	3	1	2	-	-	-	-	-
8	6	3	2	1	-	-	-	-	-
9	3	3	3	3	-	Y_{91}	Y_{92}	Y_{93}	S/N (9)
Total						$\sum$	$\sum$	$\sum$	

5.6 EXPERIMENTATION

While performing various experiments, the following precautionary measures are taken:

1. To reduce the error due to experimental setup, each experiment is repeated three times in each of the trial conditions.
2. The order and replication of experiment was randomized to avoid bias, if any, in the results.
3. Each set of experiments was performed at room temperature in a narrow range (32±2°C).
4. The workpiece was cleaned with acetone before taking any measurement.

Three process parameters that were kept constant and varied are given in Table 5.4. Experiments were conducted according to the test conditions specified by the L_9 OA (Table 5.5).

Taguchi recommends the use of S/N ratio to measure the quality characteristics deviating from the desired values. The quality characteristic for MRR is taken "higher the better" and for TWR and SR, it is taken as "lower-the better". The S/N ratio for the "higher-the-better" and "lower-the-better" of response can be computed (Ross, 1988; Roy, 1990) as:

$$(S/N)_{HB} = -10 \log \left[\frac{1}{R} \sum_{j=1}^{R} (Y_j^{-2}) \right] \quad \text{….5.3}$$

$$(S/N)_{LB} = -10 \log \left[\frac{1}{R} \sum_{j=1}^{R} (Y_j^{2}) \right] \quad \text{….5.4}$$

Where, Y_j (j= 1, 2, 3…….n) is the response value under the trial condition repeated R times.

Analysis of Variance (ANOVA) is performed to identify the process parameters that are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters is predicted.

Each experiment is repeated three times in each of the trial conditions. In each of the trial conditions and for every replication, the MRR, TWR, SR is measured. The MRR response characteristics are given in Table 5.6, The SR response characteristics are given in Table 5.7 whereas TWR response characteristics are given in Table 5.8.

Table 5.6: Experimental trial conditions and results of response characteristics MRR

Exp. No	**Input Parameters**			**Responses**			
	A	**B**	**C**	**Raw Data**			**S/N Ratio (dB)**
	Type of Tool	**Current (A)**	**Time (min.)**	**Material Removal Rate *(mm^3/min)***			
				R1	**R2**	**R3**	
1	S_1	2	30	0.16	0.18	0.17	-15.42
2	S_1	6	40	2.39	1.94	1.76	5.94
3	S_1	10	50	3.35	3.9	4.54	11.69
4	S_2	2	30	0.46	0.54	0.29	-8.25
5	S_2	6	40	2.98	2.62	2.53	8.59
6	S_2	10	50	1.37	1.81	1.48	3.65
7	S_3	2	30	0.65	0.71	0.63	-3.59
8	S_3	6	40	1.39	1.47	1.53	3.28
9	S_3	10	50	5.01	6.57	6.97	15.55
Total				17.76	19.74	19.9	
				Overall Mean: 2.12			
S_1-1st Design of Tool, S_{2-} 2nd Design of Tool, S_3-3rd Design of Tool R1, R2, R3 represent Material Removal Rate response for three repetitions of each trial.							

Table 5.7: Experimental trial conditions and results of response characteristics SR

Exp. No	Input Parameters			Responses			
	A	B	C	Raw Data			S/N Ratio (dB)
	Type of Tool	Current (A)	Time (min.)	Surface Roughness *(μm)*			
				R1	R2	R3	
1	S_1	2	30	3.22	3.19	3.18	-10.09
2	S_1	6	40	5.05	5.234	5.08	-14.18
3	S_1	10	50	6.06	6.75	6.05	-15.98
4	S_2	2	30	2.90	2.91	2.98	-9.34
5	S_2	6	40	4.29	4.656	4.05	-12.75
6	S_2	10	50	5.31	5.27	5.31	-14.48
7	S_3	2	30	2.87	2.87	2.71	-8.99
8	S_3	6	40	4.13	4.25	4.10	-12.38
9	S_3	10	50	5.98	4.3	5.12	-14.28
Total				39.81	39.43	38.58	
				Overall Mean: 4.36			

S_1-1st Design of Tool, S_2- 2nd Design of Tool, S_3-3rd Design of Tool R1, R2, R3 represent Surface Roughness response for three repetitions of each trial.

Table 5.8: Experimental trial conditions and results of response characteristics TWR

Exp. No	Input Parameters			Responses			
	A	B	C	Raw Data			S/N Ratio (dB)
	Type of Tool	Current (A)	Time (min.)	Tool Wear Rate *(mm³/min)*			
				R1	R2	R3	
1	S_1	2	30	0.02	0.021	0.02	33.83
2	S_1	6	40	0.03	0.039	0.034	29.24
3	S_1	10	50	0.038	0.037	0.039	28.40
4	S_2	2	30	0.07	0.07	0.08	22.67
5	S_2	6	40	0.05	0.061	0.05	25.36
6	S_2	10	50	0.075	0.073	0.069	22.81
7	S_3	2	30	0.01	0.013	0.014	38.09
8	S_3	6	40	0.016	0.016	0.015	36.09
9	S_3	10	50	0.038	0.039	0.032	28.76
Total				0.347	0.369	0.353	
				Overall Mean: 0.0396			

S_1-1st Design of Tool, S_{2-} 2nd Design of Tool, S_3-3rd Design of Tool R1, R2, R3 represent Electrode Wear Rate response for three repetitions of each trial.

CHAPTER 6

ANALYSIS AND DISCUSSION OF RESULTS

6.1 ANALYSIS AND DISCUSSION OF RESULTS

The experiments were planned by using the parametric approach of the Taguchi's L_9 Orthogonal Array (OA). The response characteristics data are provided in chapter 5 (Table 5.6 to Table 5.8). The standard procedure to analyze the data, as suggested by Taguchi, is employed. The average values and S/N ratio of the response characteristics for each parameter at different levels are calculated from experimental data. The main effects of process parameters both for raw data and S/N ratio are plotted. The response curves (main effects) are used for examining the parametric effects on the response characteristics. The analysis of variance (ANOVA) of raw data and S/N ratio is performed to identify the significant parameters to quantify their effect on the response characteristics. The most favourable conditions (optimal settings) of process parameters in terms of mean response characteristic are established by analyzing response curves and the ANOVA Tables.

Further, the effect of HEDME process parameters i.e. type of Tool, Current and Time on the selected response characteristics (material removal rate, tool wear rate and surface roughness) have been discussed. The average value of response characteristics and S/N ratio (dB) for each parameter at level one, two and three (L1, L2 and L3) are calculated from Table 5.6 to Table 5.8 (Chapter 5).

6.1.1 EFFECT ON MATERIAL REMOVAL RATE (MRR)

The raw data for average values of material removal rate and S/N ratio for each parameter was analyzed at three levels (L1, L2 and L3). The results so obtained are presented in Tables 6.1 and 6.2 respectively. The response curves for the individual effects of three process parameters for the average value of MRR and S/N ratio have been plotted as shown in Figure 6.1 to 6.3.

The pooled versions of ANOVA of the raw data and S/N ratios for MRR are also shown in Tables 6.3 and 6.4 respectively. The effect of process parameters on material removal rate for both the raw data and S/N ratio are analyzed using ANOVA.

Table 6.1: Main Effects of MRR (Raw Data) at various levels

LEVEL	Type of Tool	Current	Time
L1	2.043	0.42	1.06
L2	1.56	2.07	2.89
L3	2.77	3.89	2.43
L2-L1	-0.48	1.65	1.82
L3-L2	1.21	1.82	-0.45
L1, L2 and L3 represent levels 1, 2 and 3 respectively of parameters. Where L2-L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. Similarly, L3-L2 is the average main effect when the corresponding parameter changes from level 2 to level 3.			

Table 6.2: Main Effects of MRR (S/N Ratio) at various levels

LEVEL	Type of Tool	Current	Time
L1	0.74	-9.09	-2.83
L2	1.33	5.94	4.41
L3	5.08	10.29	5.56
L2-L1	0.59	15.03	7.24
L3-L2	3.75	4.35	1.15
L1, L2 and L3 represent levels 1, 2 and 3 respectively of parameters. Where L2-L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. Similarly, L3-L2 is the average main effect when the corresponding parameter changes from level 2 to level 3.			

Figure 6.1 show that MRR is more in case of 1st and 3rd design of Tool when compared with 2nd design of Tool.

The general increase in MRR is explained by the gain in better flushing, ease of ionization, high rate of pressure drop at the end of the discharge which causes more violent bulk boiling of the molten crater and also erosion of the workpiece due to cavitations. In case of 2nd design of Tool, it had a flushing problem which let Debris particles gather at the centre of electrode. Thus, 2nd design of Tool make the gap less to flush out the debris and subsequently improve the MRR due to better flushing as compared to 1st & 3rd design of Tool.

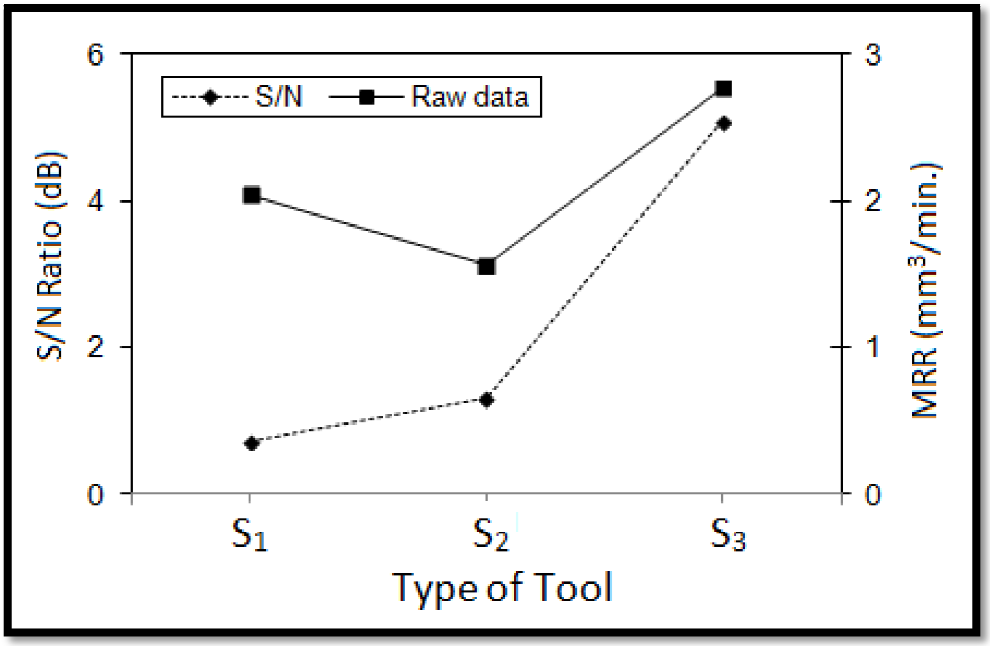

Figure 6.1: Effect of Design of Tool on MRR and S/N ratio

Figure 6.2 shows that MRR increases with the increase Current. The discharge energy is proportional to the peak current in any dielectric fluid. Thus, when increasing peak current, higher energy will be discharged and cause more obvious vaporizing and melting on the machining area. It will also create a larger impulsive force of discharge and obtain a higher MRR.

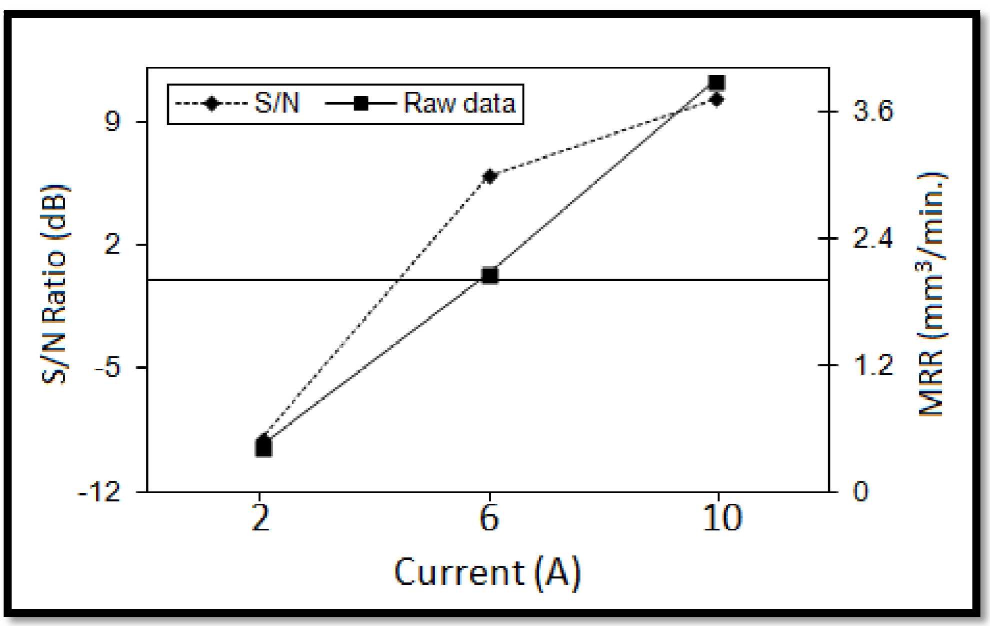

Figure 6.2: Effect of Current on MRR and S/N ratio

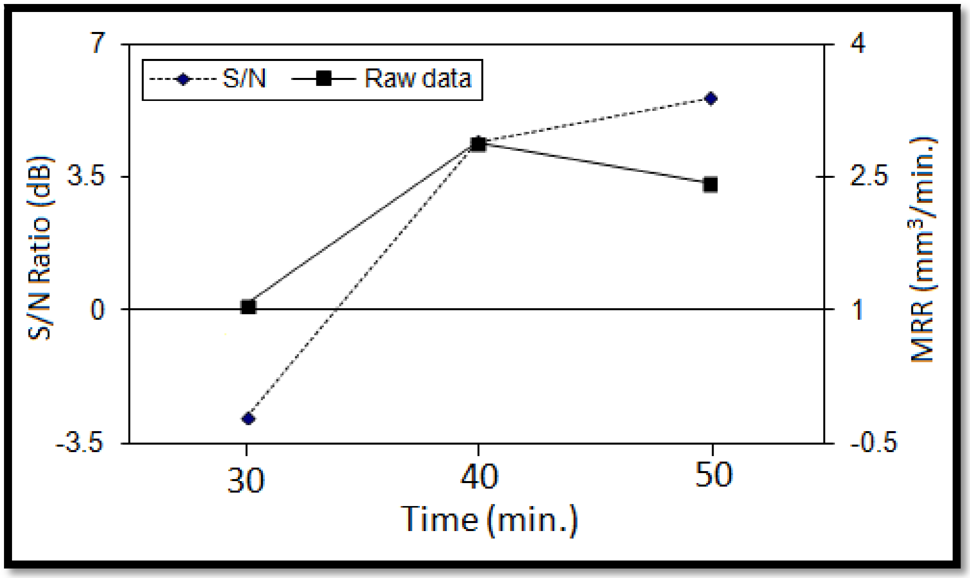

Figure 6.3: Effect of Time on MRR and S/N ratio

Figure 6.3 shows that MRR increases from 2A to 6A and decreases from 6A to 10A. Increase in the time of machining will increase the pulse discharge energy which in turn can improve the MRR.

The reason for decreasing MRR at more machining time may be attributed due to the fact of gap conditions. At higher range of time, gap conditions may become unstable with improper combination of pulse-on time, pulse off time, peak current settings.

To determine which factors significantly affects the response characteristics, ANOVA has been performed. The pooled version of ANOVA for average values of raw data as well as S/N ratio is given in Tables 6.3 and 6.4 respectively.

These Tables indicate that all the parameters significantly affect both the average values and the S/N ratio. The percentage contribution of parameters as quantified under column P% in Tables 6.3 and 6.4 indicate that the Time & peak current are the most influential in controlling the average values as well as S/N ratio.

Table 6.3: ANOVA of MRR (Raw Data)

SOURCE	SS	DOF	V	F-Ratio	P
Type of Tool	6.63	2	3.32	4.31*	7.18
Current	54.16	2	27.08	35.19*	58.64
Time	16.17	2	8.09	10.51*	17.51
Error	15.39	20	0.77	---	16.66
Total	92.36	26	---	---	100
*Significant at 95% confidence level, SS = Sum of Squares, DOF= Degree of Freedom, V=Variance, F-ratio tabulated: 3.493, P%- Percentage contribution.					

Table 6.4: ANOVA of MRR (S/N Ratio)

SOURCE	SS	DOF	V	F-Ratio	P
Type of Tool	33.25	2	16.63	24.98*	4.27
Current	620.69	2	310.35	466.19*	79.63
Time	124.16	2	62.08	93.26*	15.93
Error	1.33	2	0.66	---	0.17
Total	779.44	8	---	---	100
*Significant at 95% confidence level, SS = Sum of Squares, DOF= Degree of Freedom, V=Variance, F-ratio tabulated: 19, P%- Percentage contribution.					

Figure 6.1 to 6.3 reveals that the optimum levels of machining parameters for MRR of the Hybrid EDM Electrode are: Type of Tool (level 3), Current (level 3) and Time (level 2) which provide maximum MRR from workpiece when machined by HEDME process. It can be further noticed that in case of all the parameters, the higher values of average response characteristics correspond to highest values of S/N ratio. It is clear that parameters Type of Tool, Current and Time significantly affect both the mean and the variation in the MRR values. The percentage contribution of machining parameters in decreasing order is Current (58.64%), Time (17.51%) and Type of Tool (7.18%).

6.1.1.2 ESTIMATION OF OPTIMUM PERFORMANCE CHARACTERISTICS.

The optimum value of MRR (mm^3/min.) is predicted at the selected levels of significant parameters $A_3B_3C_2$. The estimated mean of the response characteristic MRR is determined (Ross 1988; Roy 1990) as

$$\mu_{MRR} = \overline{A}_3 + \overline{B}_3 + \overline{C}_2 - 2 \times \overline{T} \quad \text{....6.1}$$

Where

T: Overall mean of MRR = 2.12,

A_3: Average MRR at the third level of type of Tool = 2.77

B_3: Average MRR at the third level of Current = 3.89,

C_2: Average MRR at the second level of Time = 2.89

(Ref. to Table 6.1 and Figure 6.1 to 6.3)

Substituting the values of various terms in the above equation

$$\mu_{MRR} = 2.77 + 3.89 + 2.89 - 2 \times 2.12 = 5.28$$

The 95% confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{pop}) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \text{.....6.2}$$

$$CI_{POP} = \sqrt{\frac{F_{\alpha}(1, f_e)V_e}{n_{eff}}} \quad \text{....6.3}$$

Where $F_{\alpha}(1,f_e)$: The F ratio at the confidence level of (1-α) against DOF 26 and error DOF f_e= 20,

N: Total number of results = 27 (Treatment=9, Repetition=3),

R : Sample size for confirmation experiments = 3,

V_e: Error variance = 0.77 (Ref. Table 6.3),

f_e (error DOF) = 20.

$$n_{eff} = \frac{N}{1 + [\text{ DOF associated in the estimate of mean response })} = 3.86 \qquad \ldots.6.4$$

$F_{0.05}(1, 20)$= 3.493 (tabulated F value) ,

So $CI_{CE} = \pm 1.26$, $CI_{POP} = \pm 0.835$

The predicted optimal range (for a confirmation runs of three experiments) is :

$$\mu_{MRR} - CI_{CE} < \mu_{MRR} < \mu_{MRR} + CI_{CE} \;;\; 4.02 < \mu_{MRR} < 6.54 \qquad \ldots.6.5$$

The 95% conformation interval of the predicted mean is as follows:

$$\mu_{MRR} - CI_{POP} < \mu_{MRR} < \mu_{MRR} + CI_{POP}; \qquad 4.44 < \mu_{MRR} < 6.11 \qquad \ldots.6.6$$

The optimal value of process parameters for the predicted range of optimal MRR are as follows:

Type of Tool (A, 3^{rd} level),

Current (B, 3^{rd} level) = 10 A,

Time (C, 2^{nd} level) = 40 min.

6.1.1.3 CONFIRMATION EXPERIMENT

The three confirmation experiments for MRR are conducted at the optimum setting of the process parameters. The type of Tool is set at 3^{rd} level, Current at 3^{rd} level and Time at 2^{nd} level. From the confirmation experiments the average MRR is found to be 5.21mm^3/min, which falls within the 95% confidence interval of the predicted optimum parameter.

6.1.2 EFFECT ON TOOL WEAR RATE (TWR)

The raw data for average values of material removal rate and S/N ratio for each parameter was analyzed at three levels (L1, L2 and L3). The raw data for average values of TWR and S/N ratio for each parameter was analyzed at three levels (L1, L2 and L3) which are given in Table 6.5 and 6.6 respectively. The response curves for the individual effects of three process parameters for the average value of TWR and S/N ratio have been plotted as shown in Figure 6.4

to 6.6. The pooled versions of ANOVA of the raw data and S/N ratios for TWR are also shown in Table 6.7 and 6.8 respectively. The effect of process parameters on TWR for both the raw data and S/N ratio are analyzed using ANOVA.

Table 6.5: Main Effects of TWR (mm^3/min) at various levels (Raw Data)

LEVEL	Type of Tool	Current	Time
L1	0.031	0.035	0.036
L2	0.066	0.035	0.048
L3	0.021	0.049	0.035
L2-L1	0.036	-0.001	0.012
L3-L2	-0.045	0.014	-0.013

L1, L2 and L3 represent levels 1, 2 and 3 respectively of parameters. Where L2-L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. Similarly, L3-L2 is the average main effect when the corresponding parameter changes from level 2 to level 3.

Table 6.6: Main Effects of TWR (S/N Ratio) at various levels

LEVEL	Type of Tool	Current	Time
L1	30.491	31.535	30.913
L2	23.617	30.233	26.892
L3	34.319	26.658	30.622
L2-L1	-6.874	-1.303	-4.021
L3-L2	10.702	-3.575	3.730

L1, L2 and L3 represent levels 1, 2 and 3 respectively of parameters. Where L2-L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. Similarly, L3-L2 is the average main effect when the corresponding parameter changes from level 2 to level 3.

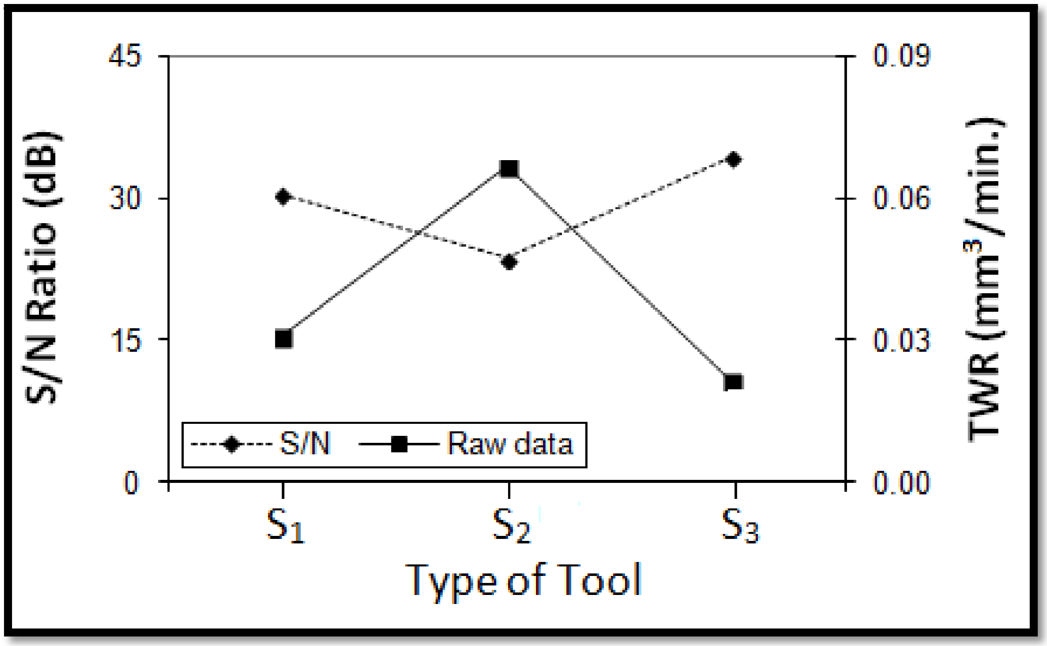

Figure 6.4: Effect of type of Tool on TWR and S/N ratio

In Figure 6.4, second Design of Tool has more TWR as compared to first and third Design of Tool, the possible reason is more erosion of the tool's Abrasive front surface whilst under presence of Debris generated if it is compared to first and third Design of Tool.

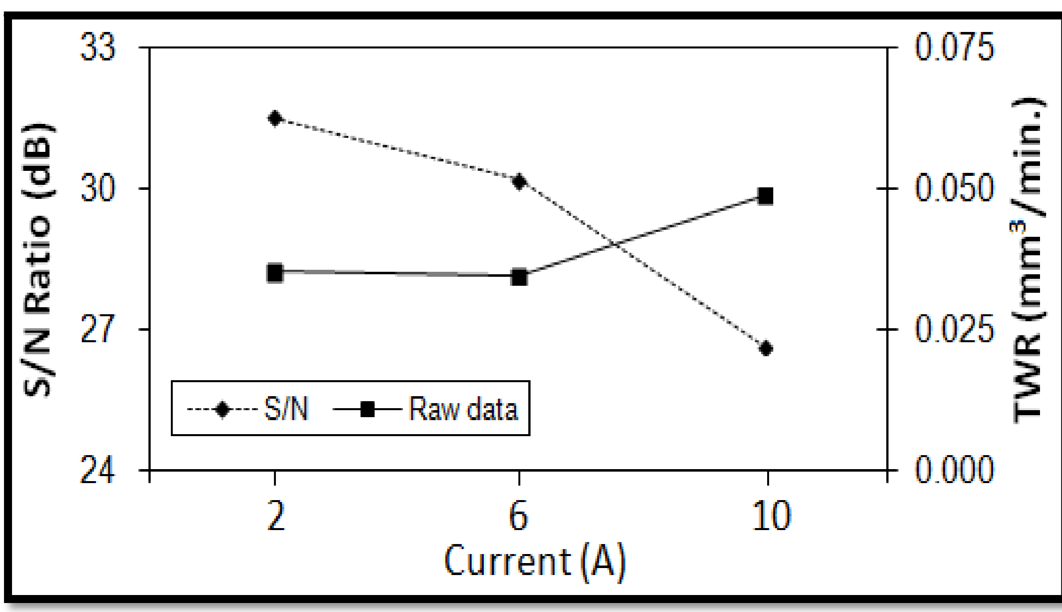

Figure 6.5: Effect of Current on TWR and S/N ratio

Figure 6.5 shows the effect of Current on TWR. It has been observed that TWR significantly decreases from 6A to 10A, and remains constant from 2A to 6A. This happened due to more electrical energy is conducted into the machining zone within a single pulse; more tool materials are removed within the single pulse.

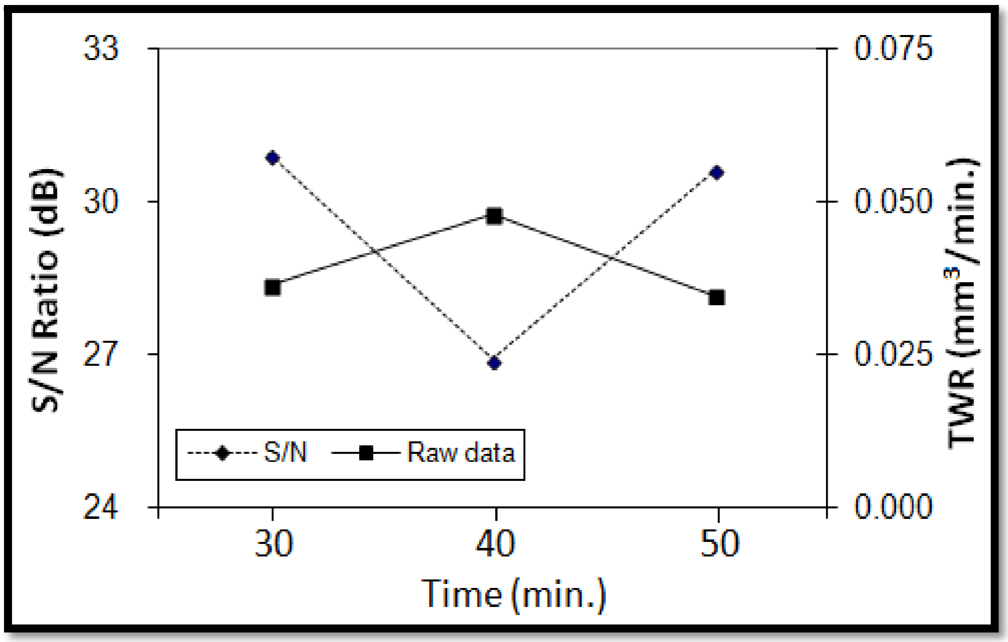

Figure 6.6: Effect of time on TWR and S/N ratio

Figure 6.6 shows the effect of peak-current on TWR, it is lesser at 30min., slightly increased at 40 minute and minimum at 50 Minute.

6.1.2.1 SELECTION OF OPTIMAL LEVELS

In order to determine the factors significantly affecting the TWR, ANOVA has been performed. The pooled version of ANOVA for average values of raw data as well as S/N ratio is given in Table 6.7 and 6.8 respectively. These Tables indicate that all the parameters significantly affect both, the average values and the S/N ratio. The percentage contribution of parameters as quantified under column P% in Table 6.7 and 6.8 indicate that the Tool is the most influential in controlling the average values of TWR as well as S/N ratio.

Table 6.7: ANOVA Raw Data (TWR)

SOURCE	SS	DOF	V	F-Ratio	P
Type of Tool	0.0101	2	0.0051	262.37*	80.09
Current	0.0012	2	0.00058	30.272*	9.24
Time	0.0009	2	0.00048	24.945*	7.62
Error	0.0004	20	0.000019	---	3.05
Total	0.0126	26	---	---	100
*Significant at 95% confidence level, SS = Sum of Squares, DOF= Degree of Freedom, V=Variance, F-ratio tabulated: 3.493, P%- Percentage contribution.					

Table 6.8: ANOVA S/N Ratio (TWR)

SOURCE	SS	DOF	V	F-Ratio	P
Type of Tool	176.440	2	88.220	112.113*	71.592
Current	38.271	2	19.135	24.318*	15.529
Time	30.167	2	15.084	19.169*	12.241
Error	1.574	2	0.787	---	0.639
Total	246.451	8	---	---	100
*Significant at 95% confidence level, SS = Sum of Squares, DOF= Degree of Freedom, V=Variance, F-ratio tabulated: 19, P%- Percentage contribution.					

Figure 6.4 to 6.6 reveal that the optimum levels of machining parameters for least TWR are: Type of Tool (level 3), 2A Current (level 1) and 50 minute Time (level 3) which provide minimum TWR from workpiece when machined by HEDME process. It can be further noticed that in case of all the parameters, the lower values of average response characteristics correspond to highest values of S/N ratio are taken. It is clear that parameters Type of Tool, Current and Time significantly affect both the mean and the variation in the TWR values. The percentage contribution of machining parameters in decreasing order is Type of Tool (80.09%), Current (9.24%) and Time (7.62%).

6.1.2.2 ESTIMATION OF OPTIMUM PERFORMANCE CHARACTERISTICS.

The optimum value of TWR is predicted at the selected levels of significant parameters $A_3B_1C_3$. The estimated mean of the response characteristic TWR is determined (Ross 1988; Roy 1990) as

$$\mu_{TWR} = \overline{A}_3 + \overline{B}_1 + \overline{C}_3 - 2\overline{T} \quad \ldots 6.7$$

Where

T: Overall mean of TWR = 0.039,

A_3: Average TWR at the third level of type of Tool = 0.021,

B_1: Average TWR at the first level of Current = 0.035,

C_3: Average TWR at the third level of Time = 0.035,

(Ref. to Table 6.5 and Figure 6.4 to6.6)

Substituting the values of various terms in the above equation

μ_{TWR} = 0.021 + 0.035 + 0.035 – 2 x 0.039 = 0.0118

The 95% confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{pop}) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_\alpha(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \ldots .6.8 \text{ and}$$

$$CI_{POP} = \sqrt{\frac{F_\alpha(1, f_e)V_e}{n_{eff}}} \quad \ldots ..6.9$$

Where,

$F_\alpha(1,f_e)$: The F ratio at the confidence level of (1-α) against DOF 26 and error DOF f_e=20,

N: Total number of results = 27 (Treatment=9, Repetition=3),

R : Sample size for confirmation experiments =3,

V_e: Error variance = 1.93×10^{-5} (Ref. Table 6.7),

f_e error DOF = 20.

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean response})} = 3.86 \qquad ..6.10$$

$F_{0.05}(1, 20)$= 3.493 (tabulated F value)

So, CI_{CE}= ±0.00632; CI_{POP}= ±0.0042

The predicted optimal range (for a confirmation runs of three experiments) is:

$\mu_{TWR} - CI_{CE} < \mu_{TWR} < \mu_{TWR} + CI_{CE}$;

$0.0055 < \mu_{TWR} < 0.0181$ ….6.11

The 95% conformation interval of the predicted mean is as follows:

$\mu_{TWR} - CI_{POP} < \mu_{TWR} < \mu_{TWR} + CI_{POP}$;

$0.0076 < \mu_{TWR} < 0.0159$ …..6.12

The optimal value of process parameters for the predicted range of optimal TWR are as follows:

Type of Tool (A, 3rd level),

Current (B, 1st level) = 2A,

Time (C, 3rd level) = 50 min.

6.1.2.3 CONFIRMATION EXPERIMENT FOR TWR

The three confirmation experiments for TWR are conducted at the optimum setting of the process parameters. The type of Tool is set at 3rd level, Current at 1st level and Time at 3rd level. From the confirmation experiments the average TWR is found to be $0.0105mm^3/min$, which falls within the 95% confidence interval of the predicted optimum parameter.

6.1.3 EFFECT ON SURFACE ROUGHNESS (SR)

The raw data for average values of Surface Roughness (SR) and S/N ratio for each parameter was analyzed at three levels (L1, L2 and L3). The raw data for average values of SR and S/N ratio for each parameter was analyzed at three levels (L1, L2 and L3) which are given in Table 6.9 and 6.10 respectively.

The response curves for the individual effects of three process parameters for the average value of SR and S/N ratio have been plotted as shown in Figure 6.7 to 6.9. The pooled versions of ANOVA of the raw data and S/N ratios for SR are also shown in Table 6.11 and 6.12 respectively. The effect of process parameters on SR both the raw data and S/N ratio are analyzed using ANOVA.

Table 6.9: Main Effects of SR (µm) at various levels (Raw Data)

LEVEL	Type of Tool	Current	Time
L1	4.87	2.98	4.22
L2	4.19	4.54	4.39
L3	4.04	5.57	4.48
L2-L1	-0.69	1.56	0.18
L3-L2	-0.15	1.04	0.08

L1, L2 and L3 represent levels 1, 2 and 3 respectively of parameters. Where L2-L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. Similarly, L3-L2 is the average main effect when the corresponding parameter changes from level 2 to level 3.

Table 6.10: Main Effects of SR (µm) at various levels (S/N Ratio)

LEVEL	Type of Tool	Current	Time
L1	-13.42	-9.48	-12.32
L2	-12.19	-13.11	-12.61
L3	-11.89	-14.92	-12.58
L2-L1	1.23	-3.63	-0.28
L3-L2	0.30	-1.81	0.03

L1, L2 and L3 represent levels 1, 2 and 3 respectively of parameters. Where L2-L1 is the average main effect when the corresponding parameter changes from level 1 to level 2. Similarly, L3-L2 is the average main effect when the corresponding parameter changes from level 2 to level 3.

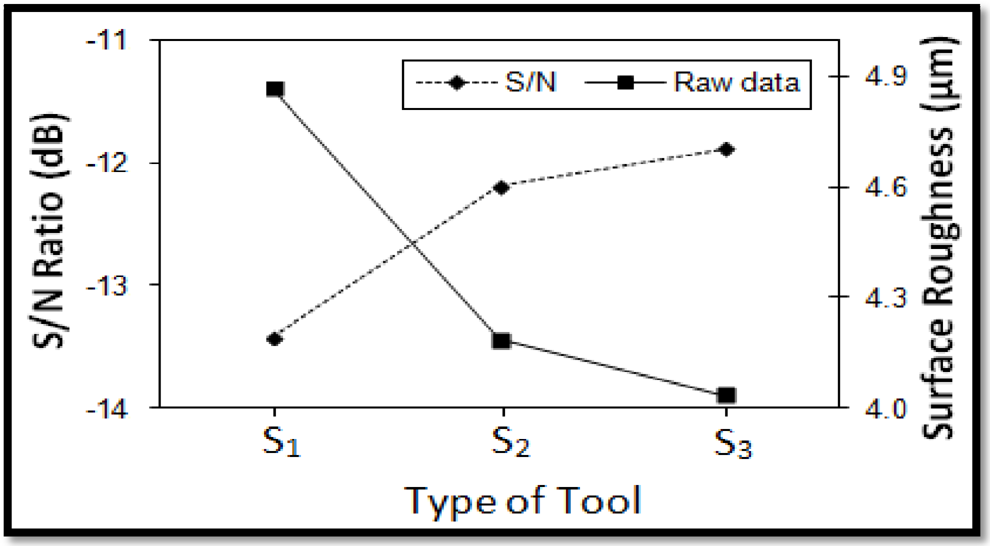

Figure 6.7: Effect of Type of Tool on SR and S/N ratio

Figure 6.7 shows the effect of type of Tool on surface roughness. Lower surface roughness is observed in case of 2nd & 3rd design of tool in as comparison to 1st design of tool. Due to the spark, material is melted and softened below the melt zone.

The molten material is removed during pulse off-time of EDM process. Then the material is removed due to the abrasive action of the ceramic particles. These two actions are repeated due to rotation of the electrode and material is removed due to the individual effect of spark erosion and abrasion processes.

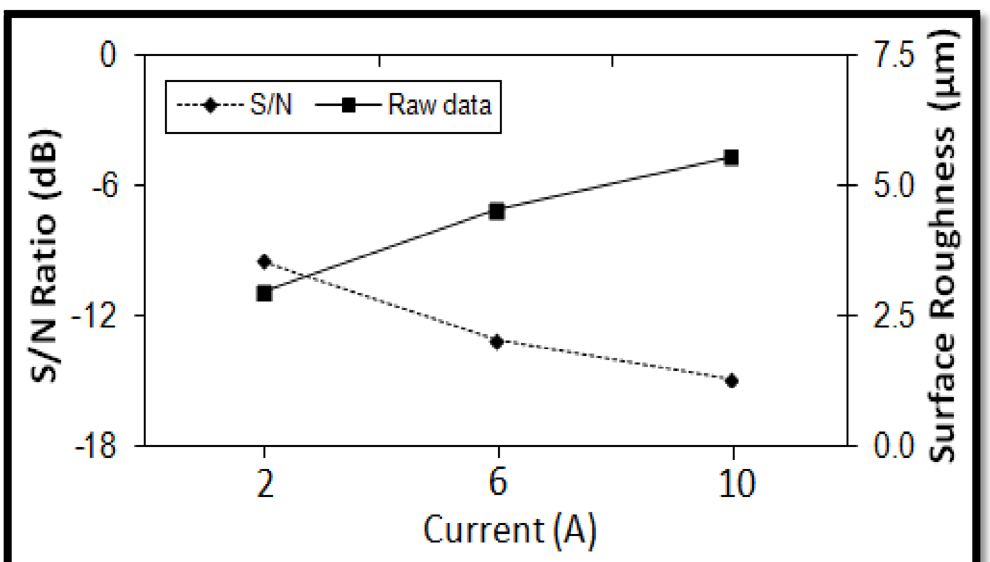

Figure 6.8: Effect of Current on SR and S/N ratio

Figure 6.8 shows the effect of current on surface roughness. Higher surface roughness is observed in case of 2nd & 3rd level of current in as comparison to 1st level of current. This happened due to more electrical energy is conducted into the machining zone within a single pulse; more tool materials are removed within the single pulse.

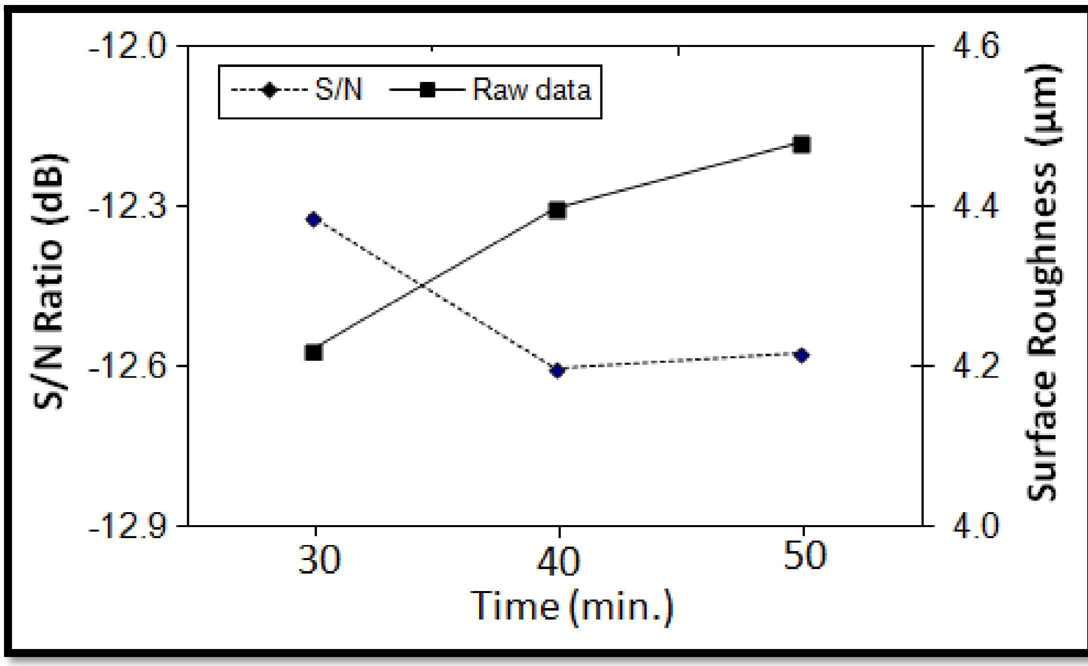

Figure 6.9: Effect of Time on SR and S/N ratio

Figure 6.9 shows the effect of time on surface roughness. It has been observed that time has insignificant effect on surface finish from the ANOVA analyzation.

6.1.3.1 SELECTION OF OPTIMAL LEVELS

In order to determine the factors significantly affecting the SR, ANOVA has been performed. The pooled version of ANOVA for average values of raw data as well as S/N ratio is given in Table 6.11 and 6.12 respectively. These Tables indicate that Type of Tool & Current significantly affect both, the average values and the S/N ratio, whereas Time is not significant. The percentage contribution of parameters as quantified under column P% in Table 6.11 and

6.12 indicate that the Current is the most influential in controlling the average values of SR as well as S/N ratio.

Table 6.11: ANOVA Raw Data (SR)

SOURCE	SS	DOF	V	F-Ratio	P
Type of Tool	3.53	2	1.76	15.60*	9.61
Current	30.61	2	15.30	135.30*	83.36
Time	0.32	2	0.16	1.41*	0.87
Error	2.26	20	0.11	---	6.16
Total	36.72	26	---	---	100
*Significant at 95% confidence level, SS = Sum of Squares, DOF= Degree of Freedom, V=Variance, F-ratio tabulated for Type of Tool: 3.493, P%- Percentage contribution.					

Table 6.12: ANOVA S/N Ratio (SR)

SOURCE	SS	DOF	V	F-Ratio	P
Type of Tool	3.95	2	1.97	59.79*	7.88
Current	45.99	2	22.99	695.78*	91.69
Time	0.15	2	0.07	2.24*	0.29
Error	0.07	2	0.03	---	0.13
Total	50.16	8	---	---	100
*Significant at 95% confidence level, SS = Sum of Squares, DOF= Degree of Freedom, V=Variance, F-ratio tabulated for Type of Tool: 19, P%- Percentage contribution.					

Figure 6.7 to 6.9 reveal that the optimum levels of machining parameters for least SR are: Type of Tool (level 3) and 2A Current (level 1) which provided minimum SR for workpiece when machined by HEDME process. It can be further noticed that in case of all the parameters, the lower values of average response characteristics correspond to highest values of S/N ratio are taken. It is clear that parameter Type of Tool and Current significantly affect both the mean and the variation in the SR values, whereas Time is not significant. Thus any level of Time can be

selected based on user requirements and economy. The percentage contribution of machining parameters in decreasing order is Tool Current (91.69%), Type of Tool (7.88%) and Time (0.29%).

6.1.3.2 ESTIMATION OF OPTIMUM PERFORMANCE CHARACTERISTICS

The optimum value of SR is predicted at the selected levels of significant parameters $A_1B_1C_2$. The estimated mean of the response characteristic SR is determined (Ross 1988; Roy 1990) as

$$\mu_{SR} = \overline{A}_1 + \overline{B}_1 - \overline{T} \qquad \ldots 6.13$$

Where

T: Overall mean of SR = 4.364,

A_1: Average TWR at the third level of type of Tool = 4.037,

B_1: Average TWR at the first level of Current = 2.982,

C_2: Average TWR at the second level of Time = Not Significant,

(Ref. to Table 6.9 and Figure 6.7 to 6.9)

Substituting the values of various terms in the above equation

μ_{TWR} = 4.037 + 2.982 – x 4.364 = 2.655

The 95% confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{pop}) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_\alpha(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \qquad \ldots.6.14 \qquad \text{and}$$

$$CI_{POP} = \sqrt{\frac{F_\alpha(1, f_e)V_e}{n_{eff}}} \qquad \ldots..6.15$$

Where

$F_\alpha(1,f_e)$: The F ratio at the confidence level of (1-α) against DOF 26 and error DOF f_e=20, N: Total number of results = 27 (Treatment=9, Repetition=3),

R : Sample size for confirmation experiments =3,

V_e: Error variance = 0.1131 (Ref. Table 6.11),

f_e error DOF = 20

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean response})} = 3.86 \qquad ..6.16$$

$F_{0.05}(1, 20)$= 3.493 (tabulated F value)

So, $CI_{CE}= \pm 0.484$; $CI_{POP}= \pm 0.319$

The predicted optimal range (for a confirmation runs of three experiments) is:

$\mu_{TWR} - CI_{CE} < \mu_{TWR} < \mu_{TWR} + CI_{CE}$;

$2.172 < \mu_{TWR} < 3.139$ ….6.17

The 95% conformation interval of the predicted mean is as follows:

$\mu_{TWR} - CI_{POP} < \mu_{TWR} < \mu_{TWR} + CI_{POP}$;

$2.336 < \mu_{TWR} < 2.975$ …..6.18

The optimal value of process parameters for the predicted range of optimal SR are as follows:

Type of Tool (A, 3rd level),

Current (B, 1st level) = 2A,

Time (C, 1st level) = 30 min.

6.1.3.3 CONFIRMATION EXPERIMENT FOR SR

The three confirmation experiments for SR are conducted at the optimum setting of the process parameters. The type of Tool is set at 3rd level, Current at 1st level and Time at 2nd level (Even if it was not significant). From the confirmation experiments the average SR is found to be 2.89, which falls within the 95% confidence interval of the predicted optimum parameter.

CHAPTER 7

CONCLUSION AND SCOPE FOR FUTURE WORK

The investigation of Hybrid Electric Discharge Machining process (HEDME) for exploring the possibility of improvement in surface morphology by adding a abrasive grinding material in electrode (tool) leads to useful results. HEDME a hybrid machining process suggested in this research work can be considered as one of the important process in the field of machining components having regular plane surfaces with high surface finish.

The important conclusions from this research work are listed in section 7.1. The scope for further work that may be helpful to the manufactures, users and the researchers engaged in this technology is presented in section 7.2.

7.1 CONCLUSION

In experiment Taguchi L_9 orthogonal array was used with 3 designs of copper and abrasive material as Hybrid EDM Electrode and it is explored with EN-31 high carbon alloy steel. Within the range of test conditions employed in the exhaustive experimental investigations, the following major conclusions can be drawn:

I. The higher surface finish gained by the employment of Abrasive material to EDM Electrode (Tool) is mainly attributed to improvement in grinding effect of electrode (tool).

II. As compared to Normal Copper electrode The Hybrid EDM Electrode improve the MRR by causing better debris evacuation from the spark gap better fluid renewal. Also the rotational Electrode leads to better surface finish of workpiece.

III. The optional value of process parameters for the predicted range of optimal MRR are as follows: Type of Tool (A, 3^{rd} level), Current (B, 3^{rd} level) = 10 A and Time (C, 2^{nd} level) = 40 min.. The predicted optimal interval of predicted mean for MRR is CI_{pop}: $4.44 < \mu_{MRR} <$

6.11. The 95% confidence interval of the predicted mean for MRR is CI_{CE}: $4.02 < \mu_{MRR} < 6.54$. The confirmation optimum experimental value is found to be as 5.21mm^3/min.

IV. In case of MRR, the percentage contribution of Current, Time and Type of Tool is 58.64%, 17.51%, 7.18% respectively.

V. The optional value of process parameters for the predicted range of optimal TWR are as follows: Type of Tool (A, 3rd level), Current (B, 1st level) = 2A, Time (C, 3rd level) = 50 min.. The predicted optimal interval of predicted mean for MRR is CI_{pop}: $0.0076 < \mu_{TWR} < 0.0159$. The 95% confidence interval of the predicted mean for MRR is CI_{CE}: $0.0055 < \mu_{TWR} < 0.0181$. The confirmation optimum experimental value is found to be as 0.0105mm^3/min.

VI. In case of TWR, the percentage contribution of Type of Tool, Current and Time is 80.09%, 9.24% and 7.62% respectively.

VII. The optional value of process parameters for the predicted range of optimal SR are as follows: Type of Tool (A, 3rd level), Current (B, 1st level) = 2A, Time = not significant. The predicted optimal interval of predicted mean for SR is CI_{pop}: $2.336 < \mu_{TWR} < 2.975$. The 95% confidence interval of the predicted mean for SR is CI_{CE}: $2.172 < \mu_{TWR} < 3.139$. The confirmation optimum experimental value is found to be as 2.89 µm.

VIII. In case of SR, the percentage contribution of Current, Type of Tool and Time is 91.69%, 7.88% and 0.29% respectively.

IX. As compared to traditional electrode, the new developed Hybrid Electrode produces high quality surface finish.

7.2 SCOPE OF FUTURE WORK

HEDME machining is new and has not been thoroughly investigated hence there is scope of further investigation. The following suggestions may be useful for future work:

1. The effect of process parameters on different HEDME Abrasive Materials may also be investigated.
2. The Set-Up can be upgraded to give High RPM’s to Electrode Holder.
3. Further work may be carried out to explore other techniques integrating to HEDME so that enhancement of material removal rate may be achieved on a wide range of workpiece shapes.
4. This hybrid technique may be tried for new material combinations. As no work is reported on composite and harder materials like alumina and ceramic.
5. Higher order OA may be considered to incorporate all the possible interactions of the process parameters.
6. The effect of machining parameters like over cut and debris analysis may be investigated.

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