DEVELOPMENT OF MINI ELECTRO-DISCHARGE MACHINING (EDM) SETUP

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CHAPTER 1

INTRODUCTION

1.1 THE TRANSFORMATION OF THE MANUFACTURING PROCESS

The evolution of manufacturing processes spans ages, starting around 5000-4000 B.C. with the creation of tools for cave and rock markings. Early civilizations used various materials such as wood, ceramic, stone, and metals like copper, gold, iron, silver, and lead to create products through casting and hammering techniques. Steel production emerged around 600-800 A.D., leading to the development of machining methods for steel-based products. Before the Industrial Revolution, manual labor was the dominant method of production, resulting in batch production. The Industrial Revolution, which began in England in the 1750s, introduced textile machinery and advanced metal-cutting methods. The concept of interchangeable parts emerged in the United States, further revolutionizing manufacturing. In the past century, significant advancements, including computer-integrated manufacturing, have modernized manufacturing practices. Today, there are two main approaches to manufacturing: additive manufacturing (bottom-up) and subtractive manufacturing (top-down).

Additive manufacturing, or 3D printing, builds a three-dimensional object by layering material under computer control. Examples include Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM). These methods can produce products of various shapes and sizes using a single machine tool but are limited to specific materials.

Subtractive manufacturing, or the top-down approach, involves producing a three-dimensional object by removing material from a solid block through cutting processes. The top-down approach includes several steps: primary production, material removal, fabrication, and finishing.

In the primary production process, raw materials are shaped and sized to match the final product. The material removal process removes excess material to achieve the desired dimensions using techniques like turning, milling, and drilling. For larger or multi-part products, the fabrication process produces different parts that are later assembled.

To enhance surface smoothness and meet tolerance requirements, finishing processes like grinding, lapping, and honing are used. These processes contribute to achieving the desired surface roughness and dimensional precision of the final product.

Among these stages, the material removal process, or machining process, is crucial. Machining can be conventional or non-conventional. In conventional machining, a cutting tool engages in direct mechanical contact with the workpiece's surface to effect material removal and generate chips. Examples include turning, drilling, boring, and shaping. These processes require cutting tools that are harder than the workpiece, with traits of toughness and wear resistance.

1.2 REQUIREMENTS FOR USING NON-CONVENTIONAL TECHNIQUES

Meeting the increasing demand for complex-shaped products with enhanced characteristics such as superior quality, precision, and repeatability, amid the global challenges, requires the development of advanced manufacturing processes. Industries ranging from defense to medical sectors necessitate components made from a variety of challenging materials including high-strength temperature-resistant alloys, titanium alloys, stainless steel, cobalt-based alloys, fiber-reinforced composites, and ceramics.

Titanium and its alloys, renowned for their exceptional properties like corrosion resistance, high strength-to-weight ratio, and biocompatibility, offer vast potential for diverse applications. However, conventional machining of these materials using cutting tools presents significant challenges in terms of effectiveness and cost-efficiency. To overcome these obstacles, non-conventional machining methods are employed. These methods, often involving minimal or no direct contact between the tool and the workpiece (excluding tool-based machining or TBM), utilize energy in its direct form to process these difficult-to-machine materials.

Non-conventional machining processes are broadly categorized into four fundamental categories: mechanical, thermo-electrical, chemical, and electrochemical processes. Mechanical non-conventional processes achieve material removal from the workpiece by utilizing kinetic energy.

Table: 1.1 Different Advanced Machining Process (AMP)

Type of energy	Mechanism of material removal	Transfer medium	Energy source	Processes
Mechanical	Shear	Physical contact	Cutting tool	Tool based machining
	Erosion	High-velocity particles	Hydraulic or pneumatic pressure	Abrasive jet machining (AJM), Water jet machining (WJM), Ultrasonic machining (USM)
		Ion beam	Ionized material	Ion beam machining (IBM)
Electrochemical	Ion displacement	Electrolyte	High current	Electrochemical machining (ECM)
Chemical	Ablative reaction	Reactive environment	Corrosive agent	Chemical machining (CHM)
Thermoelectric	Fusion	Hot gases	Ionized material	Plasma arc machining (PAM)
		Electrons	High voltage	Electron beam machining (EBM), Electro-discharge machining (EDM)
	Ablation	Radiation	Amplified light	Laser beam machining (LBM)

Mechanical processes like Abrasive Jet Machining (AJM), Ultrasonic Machining (USM), and Water Jet Machining (WJM) utilize the kinetic energy of abrasives or water jets for metal removal. However, their effectiveness is limited by factors such as hardness, strength, and other physical and mechanical properties that affect performance. This limitation has driven the development of modern thermo-electrical machining processes.

Thermo-electrical processes involve material removal through applied energy forms like electric discharge (EDM), electron beam (EBM), heat (PAM), or light (LBM). For example, EDM is used for machining hard and tough electrically conductive materials, but it may have limitations in achieving a higher surface finish, material removal rate (MRR), and minimal damage to the work surface, which are often primary requirements.

Hybrid machining processes combine two or more methods to enhance efficiency. Examples include Electro Discharge Grinding (EDG), Electrochemical Grinding (ECG), and Electrochemical Discharge Machining (ECDG). These hybrid processes leverage the advantages of their constituent methods.

While modern machining processes don't entirely replace conventional techniques, they are crucial in specific situations. It's important to assess their suitability based on given conditions. Table 1.2 illustrates the capabilities of different modern machining methods. Selecting the right method for a specific machining task is crucial.

Table 1.2 Capabilities of different advanced machining processes

Process	**MRR** (mm^3 **/min)**	**Tolerance (µm)**	**Surface (µm) CLA e**	**Depth of surface damage (µm)**	**Power (Watts)**
USM	300	7.5	0.2-0.5	25	2400
AJM	0.8	50	0.5-1.2	2.5	250
ECM	15000	50	0.1-2.5	5.0	100000
CHM	15	50	0.5-2.5	50	--
EDM	800	15	0.2-1.2	125	2700
EBM	1.6	25	0.5-2.5	250	150
LBM	0.1	25	0.5-1.2	125	2 (average)
PAM	75000	125	Rough	500	50000
Conventional	50000	50	0.5-5.0	25	3000

1.3 SUITABILITY AND APPLICATIONS OF EDM

Electro Discharge Machining (EDM) has become an essential part of non-traditional machining due to several reasons:

Ability to Machine Hard Materials: EDM can efficiently machine very hard materials that are difficult or impossible to machine with traditional methods, such as hardened steel, titanium, and exotic alloys.

Precision Machining: EDM can achieve high levels of precision and intricate detail, making it suitable for manufacturing parts with complex shapes and tight tolerances.

No Contact Machining: EDM is a non-contact machining process, which means there is no direct mechanical force applied to the workpiece. This is advantageous for delicate or fragile materials.

No Tool Wear: Since EDM is based on thermal erosion rather than mechanical abrasion, there is minimal tool wear, leading to longer tool life and consistent machining accuracy over time.

Versatility: EDM can be used to machine conductive materials of varying thicknesses and shapes, making it a versatile process for a wide range of applications.

Automation and CNC Integration: EDM machines can be easily integrated with computer numerical control (CNC) systems, allowing for automated and highly repeatable machining processes.

Environmentally Friendly: EDM is a non-contact, non-abrasive process that does not use cutting fluids, making it environmentally friendly compared to traditional machining methods.

Cost-Effective for Small Batch Production: While EDM may not be as fast as some traditional machining methods for high-volume production, it can be very cost-effective for small to medium batch sizes due to its ability to machine complex shapes without the need for expensive tooling.

Overall, EDM's unique capabilities make it an essential part of modern manufacturing, especially for industries that require high precision, complex parts, and the machining of difficult materials.

CHAPTER 2

EDM - A BROAD SPECTRUM

2.1 INTRODUCTION

Electro Discharge Machining (EDM) is a non-traditional machining process where material removal is achieved through a series of electrical discharges between a tool (electrode) and a workpiece, separated by a dielectric fluid. EDM is used to machine conductive materials, including metals and alloys, that are difficult to machine with traditional methods due to their hardness or complex shapes.

The basic principle of EDM involves the generation of electrical discharges, or sparks, between the tool and the workpiece. These discharges create intense heat, which melts tiny portions of the workpiece material. The molten material is then flushed away by the dielectric fluid, leaving behind a machined cavity that corresponds to the shape of the tool.

The key components of an EDM system include:

Power Supply: Provides the electrical energy needed to generate the discharges. The power supply controls parameters such as voltage, current, and pulse duration.

Tool (Electrode): The tool, typically made of a conductive material such as copper or graphite, is used to create the desired shape in the workpiece. The tool is connected to the power supply's electrode terminal.

Workpiece: The workpiece, also made of a conductive material, is the part that is being machined. It is connected to the power supply's workpiece terminal.

Dielectric Fluid: The dielectric fluid acts as an electrical insulator and a coolant. It is used to flush away the debris and maintain a consistent gap between the tool and the workpiece.

The EDM process can be classified into two main types:

Wire EDM: In wire EDM, a thin wire electrode is used to cut the workpiece, following a programmed path. This method is commonly used for cutting intricate shapes and contours.

Sinker EDM: In sinker EDM, also known as ram EDM or die-sinking EDM, a shaped electrode is used to create a cavity in the workpiece. This method is often used for creating molds and dies.

EDM is known for its ability to machine complex shapes with high precision, excellent surface finish, and minimal tool wear. However, it is a relatively slow process compared to traditional machining methods, making it more suitable for applications where precision and surface finish are critical.

2.2 METAL REMOVAL MECHANISM

The material removal mechanism in Electro Discharge Machining (EDM) is primarily based on thermal erosion. When an electrical discharge occurs between the tool (electrode) and the workpiece, several key processes contribute to material removal:

Spark Generation: A high-voltage pulse is applied between the tool and the workpiece, ionizing the dielectric fluid and creating a conductive plasma channel. This channel allows current to flow, resulting in a spark.

Heat Generation: The electrical discharge generates intense heat, reaching temperatures as high as 8000 to 12000 degrees Celsius. This heat melts a small portion of the workpiece material.

Material Erosion: The high temperature causes localized melting of the workpiece material. The molten material is then removed from the workpiece surface by the flushing action of the dielectric fluid, carrying away debris and maintaining a consistent gap between the tool and the workpiece.

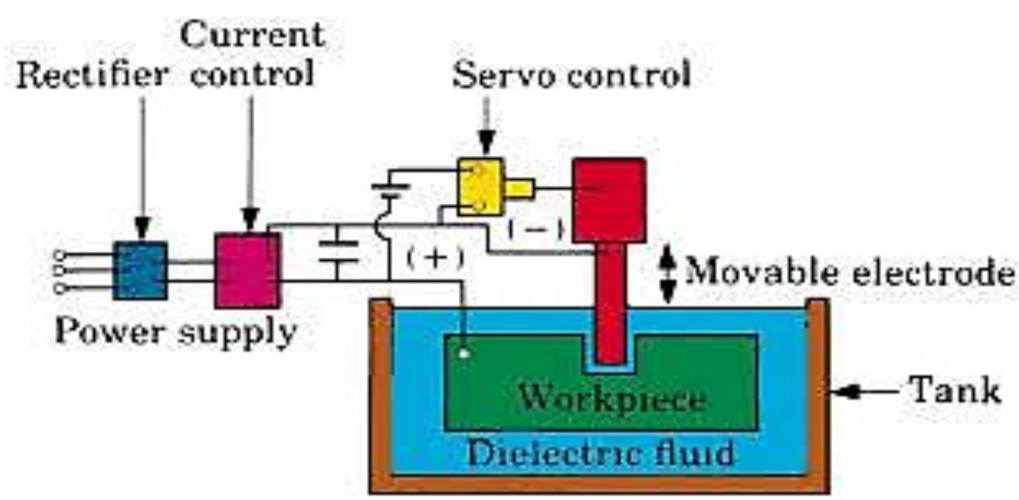

Figure 2.1 SCHEMATIC OF EDM- PROCESSES

Vaporization and Erosion: In addition to melting, some of the material may undergo vaporization due to the high temperatures and pressures generated during the discharge. This contributes to material removal.

Repetition and Layered Removal: The process is repeated thousands of times per second, gradually eroding the workpiece material layer by layer to create the desired shape.

Electrode Wear: As the material is removed from both the workpiece and the electrode, the electrode gradually wears away. To maintain dimensional accuracy, the electrode is continuously fed into the workpiece or replaced as needed.

Overall, the material removal mechanism in EDM is based on the controlled application of electrical discharges to melt and erode the workpiece material, resulting in precise machining of complex shapes with minimal mechanical force.

2.2 THEORY AND MATHEMATICAL DERIVATION

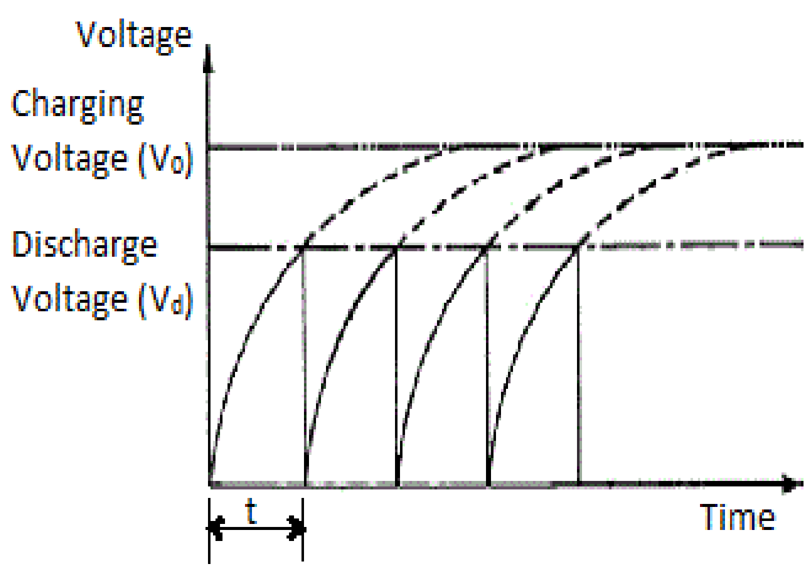

Figure 2.2 CHARGING AND DISCHARGING OF R C EDM

Discharge Voltage (V_d) is given by, $V_d = V_o (1- e^{-\frac{t}{RC}})$

Where V_o = Charging Voltage or Open Circuit Voltage

t = Charging time (t_c) + Discharging time (t_d)

But since t_d is negligible to t_c , $t = t_c$;

R = Resistance of the circuit and

C = Capacitance of the Circuit.

Hence, $e^{-\frac{t}{RC}} = (1 - \frac{V_d}{V_o})$

Or, $\frac{t}{RC} = \ln(\frac{V_o}{(V_o - V_d)})$

Or, $t = RC \ln(\frac{V_o}{(V_o - V_d)})$

The energy released per spark, $E = \frac{1}{2} CV_d^2$

Average Power, $P_{av} = \frac{E}{t}$

Or, $P_{av} = \frac{CV_o^2}{2t\,(1 - e^{-\frac{t}{RC}})^2}$

Or, $P_{av} = \frac{RCV_o^2}{2Rt\,(1 - e^{-\frac{t}{RC}})^2}$

Let, $\frac{t}{RC} = N$

Therefore, $P_{av} = \frac{CV_o^2}{2NR\,(1 - e^{-N})^2}$

For maximum average power, $\frac{dP_{av}}{dN} = 0$

Which implies for maximum power, N = 1.26

Hence for maximum power, $V_d = 0.72\ V_o$

2.4 ADVANTAGES OF DIE SINKING EDM

Die sinking EDM (Electrical Discharge Machining) is a non-conventional metal machining process used to create intricate and complicated cavities in workpieces. Let's explore the advantages of die-sinking EDM:

i) Materials Compatibility: Die-sinking EDM can cut all electrically conductive metals, regardless of their hardness. There are no material limitations, making it suitable for a wide range of applications.

ii) Preservation of Material Strength: Unlike traditional machining methods, die-sinking EDM does not affect the material hardness. As a result, the workpiece retains its original strength even after machining.

iii) No Mechanical Forces: Die-sinking EDM operates without direct contact between the electrode (tool) and the workpiece. This absence of mechanical forces allows delicate shapes to be machined with high precision.

iv) High-Dimensional Accuracy: The process offers exceptional dimensional accuracy, allowing complex shapes and tight tolerances to be achieved. Surface finishes mirror the electrode, resulting in smooth and precise cavities.

v) No Burrs or Chatter Marks: Die-sinking EDM produces cavities without burrs, chatter marks, or mechanical damage. This clean machining process ensures high-quality results.

Overall, die-sinking EDM is advantageous for creating complex shapes that would be challenging to produce using conventional cutting tools. It is commonly used in applications such as injection molds, prototypes, and forming blind cavities.

2.5 DISADVANTAGES OF DIE SINKING EDM

Die-sinking EDM (Electrical Discharge Machining) offers several advantages over traditional machining methods, but it also has some limitations. Let's explore the disadvantages of die-sinking EDM:

i) **Slower Material Removal**: Die-sinking EDM is relatively slower for removing large volumes of material compared to conventional machining methods. The process involves a series of electric spark discharges, which can be time-consuming when significant material needs to be removed.

ii) **Limited to Conductive Materials**: Die-sinking EDM is restricted to electrically conductive materials. It cannot be used on non-conductive materials, which limits its applicability in certain cases.

iii) **Erosion of Electrodes**: The electrode used in die-sinking EDM must be erosion-resistant with a conductive core. However, during the machining process, the electrode gradually wears out due to the repeated spark discharges. This erosion necessitates periodic replacement or reworking of the electrode.

iv) **Special Power Supply and Dielectric System**: Die-sinking EDM requires a specialized power supply and dielectric system. The electrical parameters need to be carefully controlled to achieve accurate results. This additional complexity can increase setup time and maintenance requirements.

v) **Time and Cost for Electrode Design and Fabrication**: Creating custom electrodes for ram/sinker EDM involves additional time and cost. The design, fabrication, and preparation of electrodes contribute to the overall lead time for die-sinking EDM projects.

Despite these limitations, die-sinking EDM remains a valuable technique for creating complex shapes, molds, and precision components.

2.6 DI-ELECTRICS FOR EDM PROCESS

In Electrical Discharge Machining (EDM), the dielectric serves as an electrical insulator and semiconductor between the electrode and the workpiece. It plays a crucial role in the machining process. Let's explore some common dielectrics used in EDM:

i) **Kerosene**: Kerosene is a widely used dielectric in EDM. It provides good insulation properties and helps remove debris from the machining surfaces of the workpiece.

ii) **Mineral Oil**: Mineral oil is another common dielectric. It offers stability and consistent performance during the EDM process.

iii) **Water-Based Dielectrics**: Some water-based dielectrics are used in EDM. However, water is an electrical conductor, so its use results in a lower metal removal rate compared to other dielectrics like paraffin.

iv) **Gas Dielectrics**: Gases such as oxygen and helium can also serve as dielectrics in specific EDM applications. They provide insulation and help control the spark discharge.

v) **Edible Vegetable Oils**: Recent research has explored using edible vegetable oils (such as sunflower oil, rapeseed oil, and peanut oil) as dielectrics to improve the sustainability of EDM. These oils offer advantages over traditional kerosene, including better machinability and reduced environmental impact. For example, rapeseed oil has been found to have higher material removal rates (MRR) and energy efficiency per unit volume (EEV) compared to sunflower oil and peanut oil.

The choice of dielectric depends on factors such as material compatibility, environmental considerations, and machining requirements. Each dielectric has its advantages and limitations, and manufacturers select the most suitable one based on their specific needs.

2.7 PROCESS PARAMETERS OF THE DIE-SINKING EDM PROCESS

In Electrical Discharge Machining (EDM), the die-sinking process parameters play a crucial role in achieving optimal results. Let’s explore these parameters:

i) **Discharge Voltage:** This voltage is produced between the workpiece and the tool when a DC power supply is connected. It influences the spark formation and material removal rate (MRR).

ii) **Peak Current:** Peak current is a critical factor in EDM. It represents the amount of power used during the process. Higher peak current results in faster material removal but also increases electrode wear.

iii) **Average Current:** The average current available for each pulse from the power supply. It affects the overall energy input during EDM.

iv) **Pulse On Time:** The duration for which current flows during each cycle. Longer pulse on time increases material removal but may also lead to higher electrode wear.

v) **Pulse Off Time**: The duration between each spark. Proper control of pulse off time ensures efficient flushing of debris from the gap.

vi) **Polarity**: The tool can be connected either positively or negatively. MRR tends to be higher when the tool is connected to positive polarity.

vii) **Pulse Frequency**: The number of cycles produced at the gap per second. Higher pulse frequency allows more sparks and faster material removal.

viii) **Duty Factor**: The percentage ratio of pulse duration to the total cycle time. The duty factor affects the overall energy input and material removal efficiency.

ix) **Electrode Gap (Spark Gap)**: The distance between the tool and workpiece during EDM. Proper gap control ensures stable sparking and accurate machining.

Optimizing these parameters depends on the specific application, material, and desired outcomes. Adjusting them appropriately can lead to efficient and precise die-sinking EDM processes.

2.8 VARIOUS ADVANCED DIE SINKING EDM PROCESSES

Some advanced die-sinking EDM (Electrical Discharge Machining) processes beyond the basics:

2.8.1 MULTI-AXIS DIE SINKING EDM

In addition to the standard X, Y, and Z axes, multi-axis die-sinking EDM machines incorporate additional rotational axes (A, B, and C). These rotational movements allow for complex 3D machining, including tapered surfaces, undercuts, and intricate contours.

Figure 2.3 MULTI AXIS DIE SINKING EDM

2.8.2 HIGH SPEED DIE SINKING EDM

High-speed die-sinking EDM machines use optimized pulse generators and advanced servo systems to achieve faster material removal rates. These machines are ideal for applications where productivity and efficiency are critical.

Figure 2.4 HIGH SPEED DIE SINKING EDM

2.8.3 ADAPTIVE CONTROL DIE SINKING EDM

Some die-sinking EDM machines feature adaptive control systems that dynamically adjust machining parameters based on real-time feedback. These systems optimize cutting conditions, reduce electrode wear, and enhance surface finish.

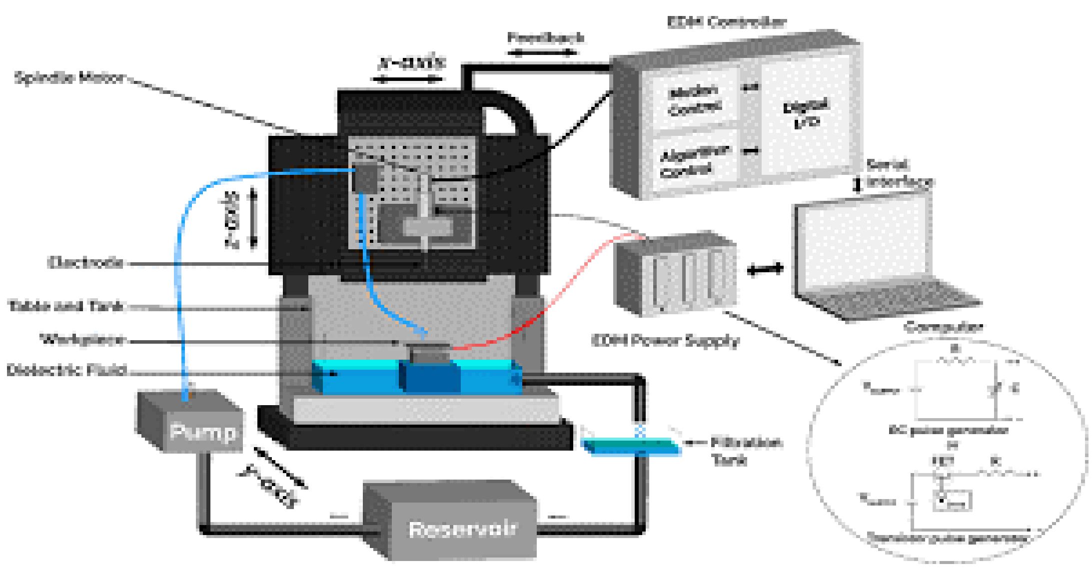

Figure 2.5 ADAPTIVE CONTROL EDM

2.8.4 GRAPHITE DIE SINKING EDM

Graphite electrodes are commonly used in die-sinking EDM due to their excellent electrical conductivity and low wear rate. Graphite EDM allows for high-speed machining and precise cavity creation.

2.8.5 CNC OPERATED DIE SINKING EDM

Computer Numerical Control (CNC) operated die-sinking EDM machines offer automated toolpath generation and precise control over electrode movement. CNC systems enhance accuracy, repeatability, and ease of programming.

Figure 2.6 CNC OPERATED DIE SINKING EDM

2.8.6 MICRO DIE SINKING EDM

Micro EDM focuses on creating extremely small features, such as micro-holes, micro-cavities, and intricate patterns. These machines use fine electrodes and specialized dielectric fluids to achieve sub-micron accuracy.

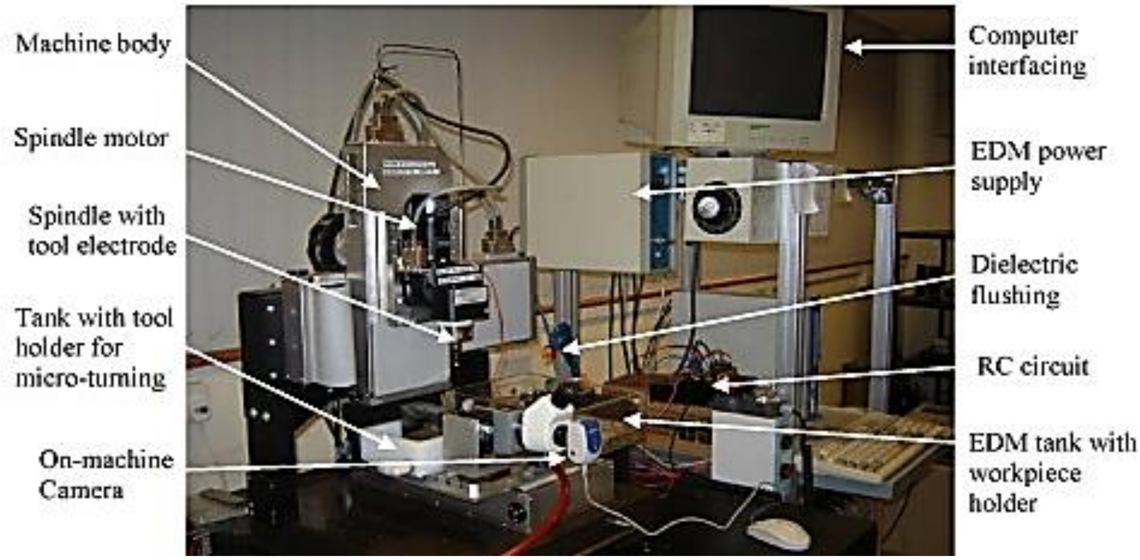

Figure 2.7 MICRO DIE SINKING EDM

2.8.7 WIRELESS MONITORED ADVANCED DIE SINKING EDM

Advanced die-sinking EDM machines incorporate wireless sensors and monitoring systems. These allow real-time tracking of process parameters, electrode wear, and machine health. Predictive maintenance and diagnostics improve overall efficiency.

Remember that the choice of an advanced die-sinking EDM process depends on the specific application, material, and desired outcomes. Each process offers unique advantages and challenges, allowing manufacturers to tailor their approach to meet specific requirements.

CHAPTER 3

LITERATURE SURVEY

3.1 INTRODUCTION

In this chapter, some selected EDM-related research papers on the effect of workpiece material on MRR, TWR, OC, and surface roughness (SR) of metals are reviewed. We broadly classified all papers into five different categories, i.e., workpiece and tool material-related paper, tool structure related paper, multiple discharge-related paper, and the rest are CNC- controlled EDM related paper.

3.2 REVIEW OF THE PAST LITERATURE

3.2.1 WORKPIECE AND TOOL MATERIAL RELATED REVIEW

Dhar and Purohit [1] evaluated the effect of current (c), pulse time (p), and gap voltage (v) on the MRR, TWR, and ROC of EDM with -10wt% Al-4Cu-6Si alloy. % SiCP composites. A PS LEADER ZNC-EDM machine and a cylindrical brass electrode diameter of 30 mm can be used for this test. Three factors, three levels, used and analyzed a full factorial design. A second-order nonlinear mathematical model is developed to determine the relationship between processing parameters. Significant models were tested using ANOVA and found to be non-linear significant increases in MRR, TWR, and ROC with increasing flow.

Karthikeyan et al [2] presented mathematical modeling of EDM with aluminum-silicon carbide particle compositions. The mathematical equation is Y=f(V, I, T). The effect of MRR, TWR, and SR with the observed process parameters were current (I), pulse duration (T), and volume percentage of SiC (size 25 μ). There was a choice between a third-level full author design. Finally, the significance of the models was tested using ANOVA. MRR was found to decrease with increasing SiC volume, while TWR and surface roughness increased with increasing SiC volume.

El-Taweel [3] introduced Tool electrode materials such as Al-Cu-Si-Tic composite manufactured by powder metallurgy technique (P/M) and using CK45 steel as workpiece material. A centered composite second-order rotational design was used to design the experiments, and RSM was used to develop the experimental models. The composite

electrode is found more sensitive to peak current and pulse than the conventional electrode.
B. Mohan and Satyanarayana [4] develop EDM current, electrode marriage polarity, pulse duration, and electrode rotation to metal removal rate, TWR and SR, and Al-Sicin EDM 20-25 vol% SiC, electrode polarity, and silicon. fuel volume, MRR increased with increasing discharge current and specific current decreased with increasing pulse duration. Increasing the speed of the rotating electrode gave a positive effect with MRR, TWR, and better SR than static. An electric motor can rotate the electrode (tool) AV belt was used to transmit the motor force to the electrode EDM drilling optimization parameters were also developed to summarize the effect of machining characteristics such as MRR, TWR, and SR.

Yan-Cherng et al [5] investigated the effect of EDM machine parameters (MRR, TWR, and SR) on the machining properties of SKH 57 high-speed steel. An experimental design was used to reduce the total number of trials. Part of the experiment was performed on an orthogonal L18 array based on the Taguchi method. In addition, the signal-to-noise ratios associated with the values observed in the experiments were determined by ANOVA and F-test. During the experiment, MRR increases with peak current MRR initially peaked around 100 μs and then decreased.

J. Simao et al [6] developed surface modification using EDM. Detailed information is given on operations involving powder metallurgy (PM) tool electrodes and powders suspended in a dielectric fluid, typically aluminum, nickel, titanium, etc. Test results are presented on AISI H13 heat-treating tool steel surfaces during an alloy dipping operation using partially sintered WC/Co electrodes operating in a hydrocarbon oil dielectric. The L8 fractional factor Taguchi test was used to identify the effect of the main operating factors on the power measurement (electrode wear, workpiece surface hardness, etc.). As for microhardness, the percentage of peak current (PCR), electrode polarity, and pulse are times. However, the very low error PCR value (micro crossover ~6%) suggests that all important effects have been accounted for.

P. Narender Singh et al. [7] discuss the effect of EDM current (C), pulse on time (P), and flow pressure (F) on MRR, TWR, taper (T), ROC and surface roughness (SR)) machining cast Al -MMC 10% SiCp. And the use of metal matrix compounds. ELEKTRAPULS fire erosion machine and dielectric fluid, kerosene, and jet washing were used for this purpose.

A brass tool with a diameter of 2.7 mm was chosen to drill the sample. For experiments, L27 OA was selected for three processing parameters at three levels. ANOVA was performed and optimal levels to maximize responses were determined. Scanning electron microscope (SEM) analysis was performed to investigate the surface properties.

A. Soveja et al [8] defined an experimental study on laser surface texturing of TA6V alloy. The effect of operating factors on the laser texturing process was investigated using two experimental approaches: Taguchi methodology and RSM. Empirical models have been developed. These allowed us to determine the correlation between process operating factors and performance parameters such as surface roughness and MRR. Analysis of the results shows that laser pulse energy and frequency are the most important operating factors. The developed mathematical models can be used to choose the correct values of the work factors to obtain the desired values for the objective functions.

Bing Hwa et al. [9] discussed the feasibility and optimization of rotary EDM with ball polishing of Al_2O_3/6061Al to check the machinability of the composite using the Taguchi method. Three ZrO_2 balls mounted as attachments to the back of the electrode tool ensure immediate polishing after electrode treatment. To ensure optimization of the machining technique, the three considered values machine speed, surface roughness, and surface roughness improvement are introduced. The tool electrode structure is an annular BEDM as shown in Figure 2.4. This B-EDM process approaches both higher machining speed and finer surface roughness. In addition, the B-EDM process can reach approximately constant machine speed.

Lee and X.P.Li [10] showed the effect of machining parameters on machining characteristics in tungsten carbide EDM. The EDM process, where tungsten carbide has better machining results, is usually achieved when the electrode acts as the cathode and the workpiece acts as the anode. The negative polarity tool allows for higher material removal rates, less tool wear, and better surface quality. Tungsten carbide requires high open circuit voltage because of its high melting point and high hardness, and copper tungsten is the tool electrode material because of the negative pole material of the tool electrode. This study confirms that there are optimum conditions for precision machining of tungsten carbide, although conditions may vary depending on battlespace configuration, machining accuracy, and other external factors.

Wang and Lin [11] discuss the optimization of W/Cu composite battle using Taguchi method. W/Cu compounds are a type of cooling material that is highly resistant to thermal corrosion caused by powder metallurgy. Taguchi method and orthogonal matrix L18 to obtain polarity, peak current, pulse duration, duty cycle, rotating electrode rotation speed, and average voltage to study material removal rate, electrode wear, and surface roughness. The effect of each variable and the optimal processing parameter are obtained using ANOVA analysis, experimenting to improve the process.

Tsai et al [12] functionalized graphite, copper, and copper alloys are widely used in EDM because these materials have high melting points and excellent electrical and thermal conductivity. Electrodes made from special powders using powder metallurgy technology have been used in recent years to modify EDM surfaces to improve wear and corrosion resistance. The electrodes are manufactured at low pressure (20 MPa) and temperature (200 °C) in a hot setting machine According to the experimental results, the mixing ratio of Cu–0wt%Cr and sintering pressure of 20 MPa gave an excellent MRR. In addition, this work also shows that the composite electrodes achieved a higher MRR than the Cu metal electrodes. The redone layer was thinner and the machined surface had fewer cracks.

Habib, Sames S [13] investigated EDM parameters using RSM, parameters such as MRR, TWR, void size, and SR, and related experimental data were obtained through experimentation. They use an Al/Sic composite material and show that the relationships between cutting speed, surface finish, and material physical parameters complicate this process. An optimal combination of these parameters was achieved to achieve controlled EDM of the workpiece and observe an increase in MRR with increasing pulse time, peak current, and gap voltage, and a decrease in MRR with increasing Sic%.

3.2.2 TOOL ELECTRODE RELATED REVIEW

Saha and Choudhury [14] investigated the dry EDM process using a tubular copper tool electrode and a mild steel workpiece. Experiments were carried out in the air and the effects of DC discharge current, pulse on time, duty factor, air pressure, and spindle speed on MRR, surface roughness (Ra), and TWR were investigated. Empirical models of MRR, Ra, and TWR are then developed by conducting a designed experiment based on a centralized synthetic design of experiments. The analysis of the response surface is performed with the developed models. ANOVA tests were performed to identify significant parameters. The dry EDM installation showed the test result in Figure 2.5 and find the airflow characteristic in the electrode gap affects the MRR and surface roughness (Ra). There is an optimal number of air holes (in the tool) with the highest MRR and lowest Ra. Growth of six percent.

Bley et al. [15] demonstrated the EDM machining of complex cavities with simple cylindrical or tubular electrodes. [17]. EDM milling requires tool electrode wear compensation. Current wear compensation methods are mostly based on offline prediction of tool wear. A new wear compensation method that includes real-time wear based on discharge pulse estimation. Tool wear is continuously estimated during machining and the actual wear compensation is adjusted based on this real-time wear estimate. As a solution to this problem, a new wear compensation method based on real-time detection of tool wear is under development. Simulations and experiments show the potential of the new method.

Sohani et al. [16], who discussed the effect of tool shape and size factor on the sink EDM process, must be considered in the process using RSM process parameters such as discharge current, pulse on time, pulse of time, and tool area. RSM-based mathematical models for MRR and TWR are developed using information from central synthetic design. Analysis of variance was used to check the relevance and appropriateness of the developed models. Research has shown that the best tool shape for higher MRR and lower TWR is round, followed by triangular, rectangular, and square cross-sections. The parametric analysis also found that the interaction between discharge current and pulse is highly significant for MRR and TWR, while key factors such as pulse-off time and tool area are statistically significant for MRR and TWR.

Zhou and Han [17] worked on the EDM servo system, a new adaptive EDM control system developed by the adaptive control of the self-rotation controller, which directly and automatically controls the tool delay time. Based on the real-time estimated parameters of the EDM process model using the minimum variance control strategy, a process controller, a self-tuning controller, was designed to control the machining process so that the void conditions follow the defined void condition. With properly selected elimination modes, this adaptive system improves processing speed by about 100%, and at the same time achieves stronger and more stable processing than conventional processing without adaptive control. This adaptive control system helps to achieve the expected goal of optimal machining process.

3.2.3 MULTIPLE DISCHARGE RELATED REVIEW

The workpiece of an EDM process, which is created by the superimposition of multiple discharges as occurs during the actual EDM operation, is written by Izquierdo et al. [22] the discharge channel diameter and material removal efficiency can be estimated by inverse detection of numerical model results. An original numerical model is presented to simulate the EDM process. The model generates the EDM surfaces by calculating the temperature fields inside the workpiece using a finite difference approach and considering the effect of successive discharges.

Wei et al. [18] investigated electrical discharge machining of multiple holes in an electrically conductive workpiece that includes an electrical discharge machine for rotating the first electrode and at least one electrical discharge device for rotary mounting at least one-second electrode. The electric discharge machine includes a controller and a controller, the controller is preferably connected to the electric discharge machine, and an electric discharge device is a device for rotating the first electrode and at least one second electrode, and the controller is preferably connected to the electric discharge machine and at least one electrical discharge device to control the supply of electrical energy from the first electrode and the second electrode to the workpiece.

Kung et al. [19] evolution of MRR and EWR study effect on cobalt bonded tungsten carbide (WC-Co) powder mixture electrical discharge machining (PMEDM) was carried out. In the PMEDM process, the aluminum powder particles suspended in the dielectric liquid break down and uniformize the discharge energy distribution. It shows multiple burst effects within a single input pulse. This study was done only for the final steps and is carried out with four machining parameters: discharge current, pulse time, grain size, and aluminum powder particle content to evaluate the machinability of MRR and EWR. RSM was used to design and analyze experiments. Note that the residuals tend to fall on a straight line, which means that the errors are normally distributed. In addition, it supports least squares adjustments. MRR generally increases with increasing aluminum powder concentration.

2.2.4 CNC OPERATED EDM RELATED REVIEW

Ding and Jiang [20] presented their work on CNC-EDM machining of freeform surfaces requires toolpaths different from those used in mechanical milling, although in geometry both processes are described by the same rotary surface cutting model. Special requirements for toolpaths required in CNC-EDM machining are investigated, and a two-step method of generating toolpaths for 4-axis CNC-EDM rough grinding with a cylindrical electrode is researched and developed. The process of creating a tool must consider the fixed model of the workpiece and the electrode connection as shown in Figure 2.6, as well as finding the discharge gap compensation, electrode wear compensation, and many other factors.

Bley et al. [21] discussed a CNC-designed EDM with a rotating cylinder and or tubular electrode, which requires compensation of tool electrode wear during CNC milling based on offline tool wear simulation before machining. Therefore, tool wear can be compensated in one dimension by continuously moving the tool down. Coherent tool wear estimation is used to combine predictive compensation with real-time compensation. This extends the scope of EDM milling to machining parts whose exact shape is not previously known.

A study about a Variable structure system (VSS) with large proportional gains can suddenly hold the electrode at the appropriate position was shown by **Fang Chang [22]** for the design process of the VSS is presented according to a practical gap control system for an EDM. This advantage can provide high performance on the nonlinear and time-varying gap condition during the eroding process. The practical experimental results of an EDM with the VSS controller show a decrease in machining time, compared to the time required by the conventional proportional controlled EDM. And experimental result obtained from the commercial CNC EDM indicates that the eroding speed of control EDM with VSS is faster than the speed with force P control system.

Chang and Chiu [23] presented an electrode wear scanning process for EDM, using robust slot control to compensate for electrode wear in the process of electrical discharge scanning (ED Scanning). This control compensates for wear without considering the wear ratio of the electrodes. As the tool moves horizontally from part (a) to part (b) as shown in Figure

2.7, they are discharged in the slot to compensate for the wear, and the material is removed. The electrode must be moved from Z2 to Z1 and the removal depth in the layer maintained. Finally, a robust controller can compensate for the wear of the electrode base during scanning without complex calculations.

Ziada and Koshy [24] Process Investigation Rotary Convex Tools for Electromagnetic Modification of Polygonal Sharp Corners. Flushing the inter-electrode gap is important in electrical discharge immersion operations. If it is impractical to create flow holes in the tool or workpiece, actual flow is best achieved by inducing relative motion between the electrodes. This innovative design allows the processing of regular and irregular polygonal shapes with sharp corners. Experimental results of the implementation of this concept on a 4-axis CNC-EDM machine are presented.

Shieh and Lee [25] showed a study on CNC EDM error reduction, they are designed to control, the system consists of three parts. First, stepping starts a position loop controller for each axis. Second, appropriate control error calculations are used for control system analysis and design, and third, cross-coupling control is used to control contour error. In the control of the proposed scheme, the stability of the system is studied for both linear and circular paths. CNC EDM test results show that the proposed model improves contour performance effectively and is ready for practical application.

Sushil Kumar Chaudhary and Dr. R.S. Jadoun [26] have made a research review on the current advancement of EDM machines. They stated that Electrical discharge machining (EDM) is a process for shaping hard metals and forming deep complex shaped holes by arc erosion in all kinds of electroconductive materials. The erosion of Materials occurs due to the pulse of the Current. Researchers have explored several ways to improve EDM Process parameters such as Electrical parameters, Non- Electrical Parameters, tool Electrode-based parameters & and powder-based parameters. This Paper gives research work done on the development of die-sinking EDM, Water in EDM, dry EDM, and Powder mixed electric Discharge Machining. In this review paper, the Researcher works on enhancement of Material removal rate (MRR), reduction of tool wear rate (TWR), improve Surface Quality (SQ)

by the experimental investigation is expressed. Various approaches like Vibration, rotary and Vibro-rotary mechanisms based on EDM, and water-based EDM have been employed to increase EDM efficiency, Dry EDM use of gas instead of oil electrolyte, and PM-dielectric Electric Discharge Machining.

Sandeep Kumar [27] has published a research paper status of recent developments in EDM machines. He stated that it is based on the thermoelectric power between the workpiece and tool. The process includes controlled erosion of the electrically conductive workpiece by introducing the rapid and repetitive spark discharge between the tool and workpiece by the use of the dielectric medium. He also gives various applications in EDM machines in automobile, nuclear, and surgical industries, and thin and fragile parts. He concluded that EDM can be used as viable machining operations for producing complex parts, EDM is independent of the mechanical properties of the workpiece and in order to remain competitive as a micromanufacturing technology, the EDM process should use computer numerically controlled.

C. Bhaskar Reddy et al [28] has conducted research on the growth of EDM machines and their various applications. Experiments with wire EDM on reciprocating dry sliding pin on plate revealed that the Zro2-WC composite exhibits better tribological characteristics over Zro2-TiCN and Zro2-TiN. The recent observation is the application of the Wire-EDM in Granite Mining, operations to avoid the heavy manual involvement. The technique starting from a simple means of making tools and dies has reached the stage as the best alternative for producing micro-scale parts. He concluded that EDM is flexible enough to meet the requirements of the global metal-cutting industries. Thus, the ultimate goal of the Wire EDM process is to achieve an accurate and efficient machining operation combined with quality with most best machining performance by the various factors affecting the process and identifying the optimal machining condition from several combinations.

Manpreet Singh et al [29] conducted research on recent developments in wire EDM machines. They stated that EDM is used to manufacture geometrically intricate shapes with great accuracy and good surface finish that are difficult to machine with the help of conventional machining processes. They also considered the various affecting parameters on the EDM machine. They concluded that wires with greater tensile strength can be made but they face adverse effects in terms of increase in resistance to breakage. Some work is also done on cryogenics treatment on various pieces of materials. Thus, WEDM can serve the purpose of high-speed machining with good quality products in a short time period and at reduced costs.

D.T. Pham et al [30] published research papers on Micro-EDM and its development. As MRR is in micro and due to the high precision and good surface quality that it can give, EDM is potentially an important process for the fabrication of micro tools, micro-components, and parts with micro-features. Researches are conducted on micro EDM on wire, drilling, milling, and die-sinking. The focuses are laid on the planning of the EDM process and the electrode wear problem. Special influences are made to achieve high accuracy, including positioning approaches during EDM and electrode grinding.

They concluded that while assigning process tolerances for micro EDM all aspects of the process, such as type of electrode grinding, type of positioning, and duration of the operation, should be considered, overall machining efficiency based on empirical methods and to remain competitive as a micro-manufacturing technology, micro-EDM processes should use reliable algorithms and strategies with repeatable results.

Khushmeet Kumar and Sushma Singh [31] have conducted an experimental study of Al-Sic (30%) composite on an EDM machine. Engineering Composite Materials are gradually becoming very important materials for their scope due to their high fatigue strength, thermal shock resistance, high strength-to-weight ratio, etc. Hence, it is essential for searching an advanced machining method by which the machining of the composite can be performed with ease and accuracy. For effective machining of AL6061/ Sic (30%) composite, an electrochemical discharge machining (EDM) has been developed.

The developed EDM has been utilized to machine holes on AL6061/Sic (30%). Material removal rate and tool wear rate were obtained experimentally for Brass and Copper tool. Materials with different tool diameters and different levels of current. They concluded that Based on the experimental results it may be concluded that MRR and TWR are directly proportional to the current. They saw that MRR for 8mm tool diameter at 5-amp current is 2.22mg/min for a brass tool whereas it is 2.38 mg/min for a copper tool which is 0.16mg/min (7.21%) more than that of the brass tool. Also, the corresponding tool wear rate (TWR) was observed as 1.43mg/min for the brass tool, and the copper tool is 1.57mg/min which indicates the TWR of the copper tool is higher by 9.79% than that of the brass tool.

Kuldeep Ojha et al [32] has published review papers on MRR improvement in sinking

Electrical Discharge machines. They published that Material removal rate (MRR) is an important performance measure in the EDM process. Despite a range of different approaches, all the research work in this area shares the same objectives of achieving more efficient material removal coupled with a reduction in tool wear and improved surface quality. Apart from all these, various parameters, dielectric, and ultrasonic performance are also considered.

They concluded that found that the basis of controlling and improving MRR mostly relies on empirical methods. This is largely due to the stochastic nature of the sparking phenomenon involving both electrical and non-electrical process parameters along with their complicated interrelationship. Being an important performance measure, the MRR has been getting overwhelming research potential since the invention of the EDM process and requires more Study /experimentation/modeling in the future.

3.3 OBJECTIVES OF PRESENT RESEARCH WORK:

From the review of the past literature, it is quite clear that rigorous research work has been being carried out to enhance the performance characteristics in Electro discharge Machining processes. Workpiece material-related or tool-related paper, tubular electrode, tool structure, multiple discharge-related paper, and the rest CNC EDM related paper were found. Despite such improvements, EDM setups are still very costly and in fact, affordable EDM setups are not available in the market. This aspect poses a barrier, particularly for small-scale industries. From the review of the past literature as well as market research, it is very clear that to date compact-size, lightweight EDM setups are not available in the market. Keeping these aspects in mind, the objective of the research work is to indigenously develop an affordable mini EDM setup having the following features:

- **(i)** Compact in size
- **(ii)** Light in weight
- **(iii)** Portable
- **(iv)** User-friendly and possibility for future upgradation.

(v) Very cheap in comparison to other commercial machines available in the market in order to make it suitable for application in small-scale applications

3.4 SCOPES OF THE RESEARCH:

(i) To develop a mechanical setup in which a hollow tool in an appropriate tool holder can be moved Z-axes. The setup must be very compact, light in weight and can be carried from one place to another very easily.

(ii) To use appropriate motors, drivers, and sensors so that the feedback control system works in a very precise manner.

(iii) To use appropriate resistors and capacitors in the power supply circuit to achieve the desired performance of the setup.

(iv) To create provision for using both de-ionized water and hydro-carbon oil interchangeably for observing the change in performance.

(v) To design and fabricate the setup so that both hollow/tubular tool as well as solid tools can be used in order to use external di-electric flow as well as internal di-electric flow through the hollow/tubular tools.

(vi) To incorporate suitable transformer-based RC power supply modules for powering the electrodes and the workpiece, In EDM there is always the possibility gap short.

(vii) To carry out experiments with the prototype in order to estimate the performance of the proposed EDM setup in real life working environment.

CHAPTER 4

HARDWARE COMPONENTS IN THE EDM SETUP

To ease the understanding of mini-Electro discharge machining setup, all the hardwarecomponents used are classified into 4 groups.

1. Components used for the development of vertical sliding mechanism and machine base setup.
2. Components used for the development of di-electric circulation system setup.
3. Components used for the development of power supply system setup.
4. Components used for the development of feedback control system setup of the vertical sliding mechanism.

Now, let us consider each group separately.

4.1 COMPONENTS USED FOR VERTICAL SLIDING MECHANISM SETUP:

(i) A 320 mm X 250 mm X 2.5 mm mild steel plate is used as the base of the machine.

(ii) A 45 mm X 45 mm X 140 mm L section is attached to the base plate with a nut and bolt drilled thoroughly through the L section and the base plate. The part is designed in such a manner so that the assembly can be dismantled at any time upon required.

(iii) A hollow square pipe of 25 mm X 25 mm cross-section and 400 mm in length is welded over the central part of the L section which is erected vertically and is used as the main column for holding Z axis drive with the help of external attachment.

(iv) A specially designed 3-D Printed L-shaped external attachment is fastened to the vertical column through a drilled hole in the column. This attachment will hold the D.C. servo motor to its upper side and will hold the Z-axis drive over another side of it.

(v) A 2-ampere D.C geared (60: 1) servo motor is attached over the attachment with 4 no. 3-D printed 10 mm external diameter and 1.5 mm internal diameter and 10 mm high washer invertedly.

(vi) A Z-axis slide consists of one lead screw (8 mm diameter and 2 mm pitch) of 250 mm length, 3 linear bearings of 8 mm diameter and 250 mm length, a nut and slider attached to the rear side of the special attachment for vertical (up and down) sliding motion of the slider.

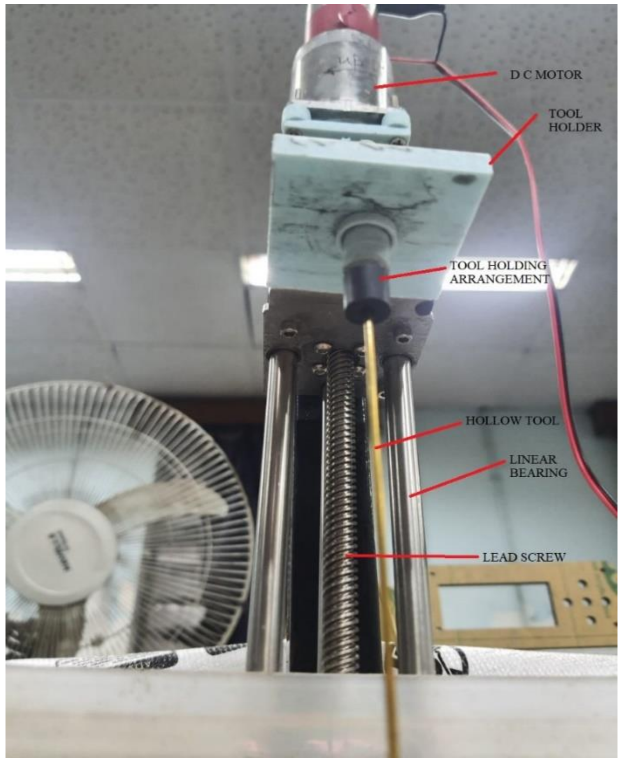

Figure 4.1(1) STRUCTURAL Z AXIS DRIVE ASSEMBLY

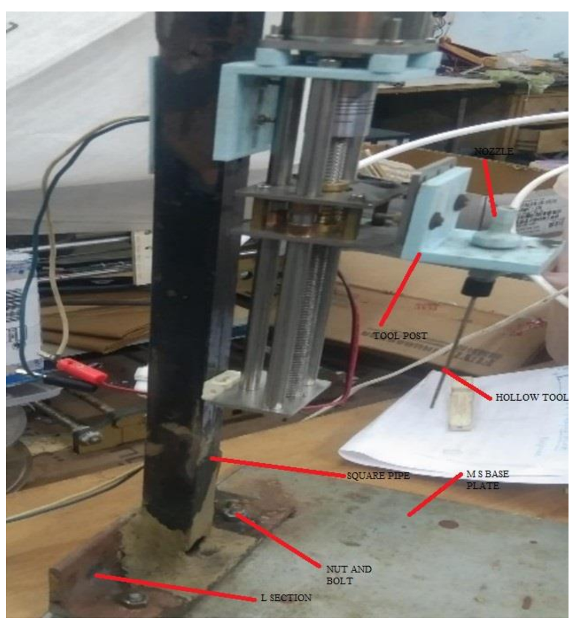

Figure 4.1(2) STRUCTURAL Z AXIS DRIVE ASSEMBLY

Figure 4.1(3) STRUCTURAL Z AXIS DRIVE ASSEMBLY

(vii) The lead screw is attached to the servo motor shaft with the help of a coupler.

(viii) Tool holder is attached to the Z-axis slide with a screw.

(ix) Two holding arrangements are made over the tool holder one for internal di-electric flow arrangement and the other for only tool holding purpose for external flow.

(x) A specially designed nozzle is made by 3-D printing with a rubber seal for holding the hollow (1.5 mm diameter) tool for internal flow.

(xi) A 10 mm drill chuck can also be fitted with the tool post for holding the tool for external

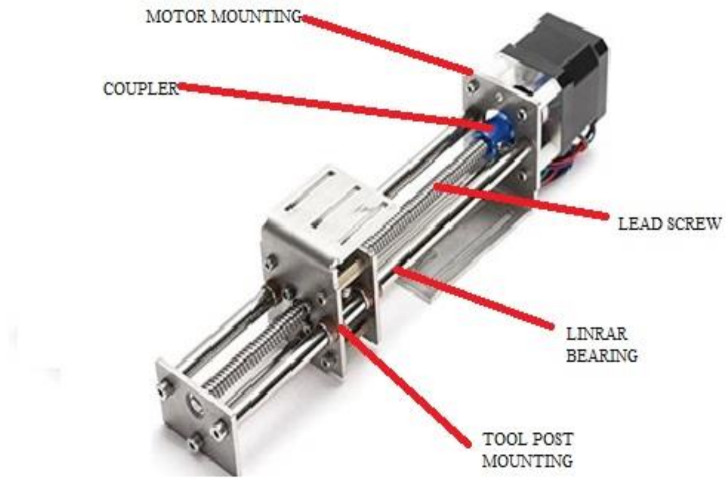

Figure 4.2   Z AXIS DRIVE

4.2 COMPONENTS USED FOR DEVELOPING ELECTROLYTE CIRCULATION SYSTEM

(i) 230V brush-less submersible centrifugal water pump:

Technical specifications:

- Style: Submersible
- Item dimensions: 80 mm X 80 mm X 50 mm
- Power source: Corded electric
- Item weight: 0.25 kg
- Input AC voltage: 230 V
- Power: 19 W
- H-max: 1.9 m
- Flow: 1400 l/hour
- Applications: Used in aquariums, water cooling systems, and circulation systems.

In a submersible pump, the motor is hermetically sealed and close-coupled to the body of the pump. The pump pushes water to the surface by converting rotary energy into kinetic energy into pressure energy. This is done by the water being pulled into the pump, first in the intake, where the rotation of the impeller pushes the water through the diffuser. Submersible pumps are also very efficient because they don't really have to spend a lot of energy moving water into the pump. Water pressure pushes the water into the pump, thus saving a lot of energy. The main advantage of using this pump lies in the fact that all its parts are non-metallic and the motor is sealed, hence corrosive nature of the electrolytes will not be a threat to its longevity. A plastic box will serve as an electrolyte holder in the setup, the submersible pump will be placed in it as shown flow model.

Figure 4.3 ZIGMA SUBMERSIBLE PUMP

(ii) 5-micron spun filter with filter housing:

Process filtration is a critical activity for many industrial or manufacturing organizations. The effectiveness of solid separation has impacts on downstream processes and can determine quality standards. A filter removes solid contaminants by capturing and retaining theseparticles as they pass through the filter media. Filters can consist of many different materials, and they are presented in different formats, such as cartridges, bags, and sheets. Each of these consumable filters fits within a permanent housing or vessel. Cartridges are often the most popular format of filter. Spun Filter is made of fine melted polypropylene, which is blownand spun in a cylinder-like form. The micron rating is the size at which particles are retained by the filter. For example, a five-micron filter will stop particles of five microns or larger from passing through the media.

In this application, the main function of the 5-micron spun filter is sludge removal, or else the narrow passage in the hollow tool can be clogged leading to a decrease in electrolyte pressure.To ensure proper functioning,

RO tubing made of polypropylene having a diameter of $1/4^{th}$ of an inch is used to connectthe components in the circulation system. Input and output terminals of the components are connected with the pipe by threaded polypropylene elbow connector and push fit type elbow connector of $1/4^{th}$ inch inner diameter.

Figure 4.4 SPUN FILTER WITH FILTER HOUSING

4.3 COMPONENTS USED FOR DEVELOPING POWER SUPPLY SYSTEM

STEP DOWN TRANSFORMER

1. **Definition and Working Principle**:

- A **step-down transformer** is an electrical device that reduces the voltage of an alternating current (AC) power supply.
- It consists of the following components:

- **Primary winding**: The coil where the AC voltage is applied.
- **Secondary winding**: The coil where the transformed voltage is induced.
- **Iron core**: The magnetic core that facilitates energy transfer.
- When an AC voltage is applied to the primary winding, it creates a fluctuating magnetic field in the iron core.
- This changing magnetic flux induces an electromotive force (emf) in the secondary coil by the law of electromagnetic induction.

The induced emf in the secondary coil is lower than the emf in the primary coil, hence the name "step-down" transformer.

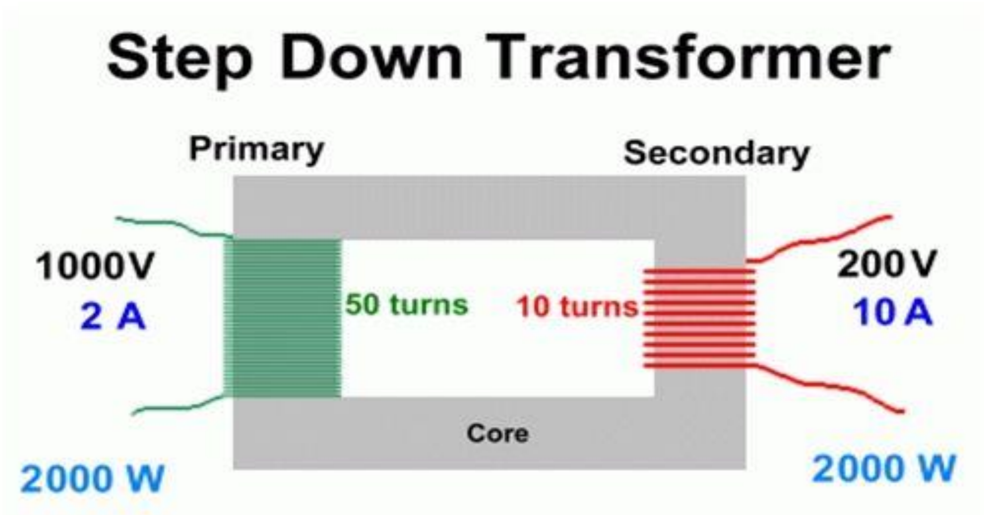

Figure 4.5 STEP DOWN TRANSFORMER CONSTRUCTION

2. **Voltage Transformation**:

- A step-down transformer converts high-voltage (HV) and low-current input from the primary side into low-voltage (LV) and high-current output on the secondary side.
- The transformer turns ratio ((n)) for a step-down transformer is approximately proportional to the voltage ratio: [n = {V_P}/{V_S}] where (V_P) and (V_S) are the voltages on the primary (HV) and secondary (LV) sides, respectively.

- The primary side (HV side) has more turns than the secondary side (LV side), allowing energy to flow from HV to LV.
- The voltage is stepped down from the primary voltage (input voltage) to the secondary voltage (output voltage). The step-down transformer formula for the output voltage is: [V_S = {V_P}/{n}]

3. **Applications**:

Step-down transformers play a crucial role in various applications:

- **Electronic devices**: They provide low voltages (e.g., 5V) suitable for powering electronic circuits.
- **Battery chargers**: Daily-use chargers often use step-down transformers.
- **Power systems:** They adapt voltage levels for energy consumers.

BRIDGE RECTIFIER

A bridge rectifier plays a crucial role in electronic circuits by converting alternating current (AC) into direct current (DC). This process is known as rectification. The bridge rectifier is composed of four diodes arranged in a bridge configuration, which allows it to convert both the positive and negative halves of the AC waveform into DC voltage.

Here's a simplified explanation of its operation:

1. **Construction**: The bridge rectifier circuit consists of four diodes (D1, D2, D3, D4) and a load resistor (RL). The diodes are connected in a closed-loop 'bridge' configuration to efficiently convert AC to DC.

2. **Working Principle**: During the positive half-cycle of the AC input, diodes (D1) and (D3) become forward-biased and allow current to flow through them, while (D2) and (D4) are reverse-biased and block current. During the negative half-cycle, (D2) and (D4) become forward-biased and conduct, while (D1) and (D3) are reverse-biased.

3. **Output**: The result is that the load resistor (RL) sees a unidirectional current flow during both half-cycles, which creates a pulsating DC output. This output can then be smoothed into a more stable DC voltage using additional components like capacitors.

The bridge rectifier is widely used because it does not require a center-tapped transformer, making it a cost-effective and compact solution for many power supply applications.

A bridge rectifier plays a crucial role in electronic circuits by converting alternating current (AC) into direct current (DC). This process is known as rectification. The bridge rectifier is composed of four diodes arranged in a bridge configuration, which allows it to convert both the positive and negative halves of the AC waveform into DC voltage.

Figure 4.6 BRIDGE RECTIFIER

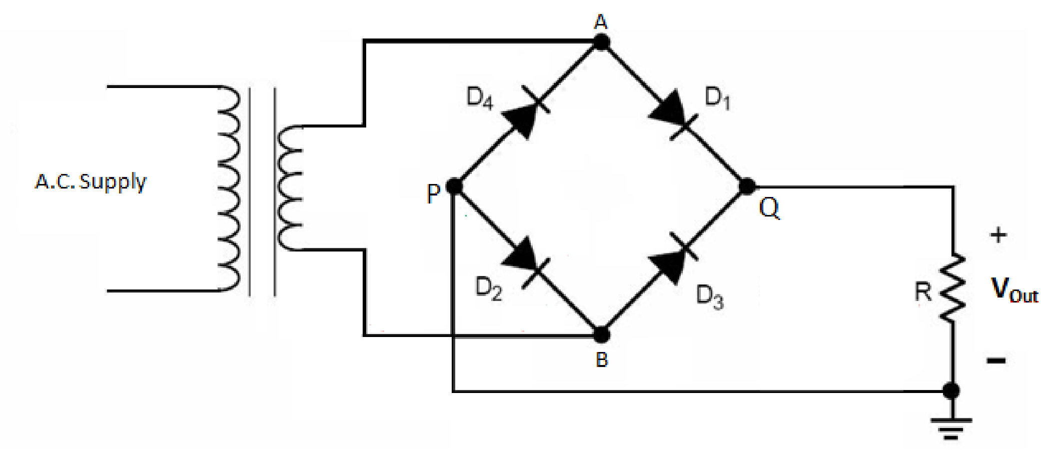

Figure 4.7 BRIDGE RECTIFIER CIRCUIT

CAPACITORS

In an RC (Resistor-Capacitor) circuit, the capacitor serves several important functions, particularly in the context of an EDM (Electronic Discharge Machining) circuit:

1. **Energy Storage**: The capacitor stores electrical energy in an electric field when it is charged. This stored energy can be released to the circuit when needed, which is crucial in EDM for providing the discharge energy required for machining[1].

2. **Timing Control**: The capacitor, in conjunction with the resistor, determines the timing characteristics of the circuit. The time constant (τ), which is the product of the resistance (R) and capacitance (C), dictates how quickly the capacitor charges and discharges. This is essential in EDM to control the duration and frequency of the discharges.

3. **Voltage Smoothing**: During the charging phase, the voltage across the capacitor increases, while during discharging, it decreases. This helps to smooth out voltage fluctuations, which is important for the stable operation of the EDM process.

4. **Filtering**: In combination with resistors, capacitors can form filter circuits that can eliminate unwanted frequencies from the signal. This can be used to shape the pulse waveform in EDM, affecting the machining characteristics.

Overall, the capacitor's role in an RC EDM circuit is vital for energy storage, controlling the timing of discharges, smoothing voltage variations, and filtering the signal to achieve the desired machining performance.

Figure 4.8 CAPACITORS

RESISTORS

Resistors in an RC (Resistor-Capacitor) circuit, especially in the context of EDM (Electronic Discharge Machining), have several key roles:

1. **Current Limiting**: Resistors limit the current that can flow through the circuit. This is crucial in EDM to prevent excessive current that could damage the components or affect the precision of the machining process.

2. **Timing Control**: The resistor affects the rate at which the capacitor charges and

discharges, which is important for controlling the timing of the electrical discharges in EDM. The time constant (tau) of the circuit is the product of the resistance (R) and the capacitance (C)(tau= RC), and it determines how quickly the capacitor can charge to a certain percentage of its maximum voltage.

3. **Voltage Divider**: In combination with capacitors, resistors can act as voltage dividers, determining the voltage levels across different parts of the circuit. This can be used to create specific voltage conditions required for the EDM process.

4**. Filtering**: When used with capacitors, resistors can help filter out unwanted frequencies from the signal. This is particularly useful in EDM to ensure that only the desired frequencies are used for machining.

5**. Energy Dissipation**: Resistors convert electrical energy into heat. In an EDM circuit, this can be used to dissipate excess energy safely, which is important for maintaining the stability and safety of the system.

Overall, resistors are essential for managing the electrical characteristics of an RC EDM circuit, ensuring that the circuit operates within safe parameters and achieves the desired machining outcomes.

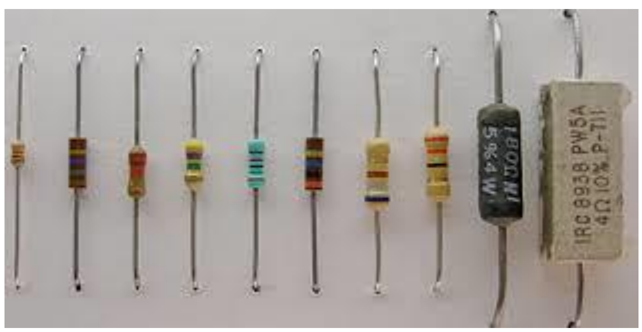

Figure 4.9 RESISTORS

POWER RESISTORS

A **power resistor** is a type of resistor specifically designed to handle and dissipate large amounts of power. They are typically used in applications where there is a need to convert excess electrical energy into heat. Here are some key points about power resistors:

1.Power Rating: Power resistors can handle a significant amount of power, often rated at watt or higher.

2.Construction: They are made from materials with high thermal conductivity and are often larger than standard resistors to manage heat dissipation effectively.

3.Type: Common types include wire wound, metal alloy, ceramic, carbon film, and metal oxide resistors.

4.Applications: Power resistors are found in power supplies, power conversion circuits, and power amplifiers, where managing high power and thermal conditions is crucial.

Figure 4.10 POWER RESISTOR

The power rating of a resistor describes its ability to dissipate power safely without damage. The formula for power dissipation is given by,

$$P = VI$$

where (P) is the power in watts, (V) is the voltage across the resistor, and (I) is the current flowing through it. To prevent overheating, power resistors may be mounted on heat sinks or require forced air or liquid cooling systems when operating at maximum load. It's important to select a power resistor with an appropriate power rating for the intended application to avoid issues like overheating or failure.

DIODES

In an RC (Resistor-Capacitor) EDM (Electronic Discharge Machining) circuit, diodes have several important roles:

1. **Rectification**: Diodes are used to convert alternating current (AC) into direct current (DC), a process known as rectification. This is essential in EDM circuits that require a stable DC voltage for operation.
2. **Protection**: Diodes can protect sensitive components in the circuit from potential damage caused by reverse voltage spikes. They allow current to flow in one direction and block it in the opposite direction, safeguarding against reverse current flow.
3. **Voltage Regulation**: Zener diodes can be used to regulate voltage within the circuit. They maintain a constant voltage level as a reference or a stable supply for the control circuits in the EDM machine.
4. **Signal Shaping**: Diodes can be used to shape the pulse waveform in the EDM process. By clipping or steering the current, they can modify the waveform to achieve the desired machining characteristics.
5. **Discharge Control**: In some EDM circuits, diodes may be used to control the discharge timing. They can ensure that the capacitor discharges at the correct moment, contributing to the precision of the machining process.
6. **Rapid Discharge**: Diodes can help in the rapid discharge of capacitors when power is switched off, ensuring that the circuit is quickly reset and ready for the next operation cycle.

Overall, diodes play a critical role in ensuring the EDM circuit functions correctly, providing protection, control, and stability to the machining process.

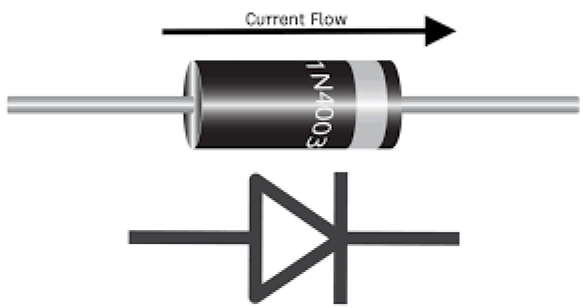

Figure 4.11 DIODE AND DIODE SYMBOL

4.4 COMPONENTS USED FOR DEVELOPING SERVO CONTROL SYSTEM

SWITCH MODE POWER SUPPLY

A Switch Mode Power Supply (SMPS) is an electronic power supply that incorporates a switching regulator to efficiently convert electrical power. Unlike a linear power supply, the pass transistor of an SMPS continually switches between low-dissipation, full-on and full-off states, spending very little time in high dissipation transitions. This minimizes wasted energy. Voltage regulation is achieved by varying the ratio of on-to-off time, known as duty cycles.

SMPS can be substantially smaller and lighter than a linear supply due to the high switching frequency, which allows for a much smaller transformer. However, they can be more complex and may produce electrical noise if not carefully suppressed.

Figure 4.12 SWITCH MODE POWER SUPPLY (SMPS)

Here's a basic explanation of how an SMPS works:

1. Input Rectifier Stage: Converts AC to DC if the input is from an AC source.

2. Inverter Stage: The DC from the previous stage is switched on and off rapidly by a transistor operating as a high-frequency oscillator.

3. Voltage Converter and Output Rectifier: The switched DC voltage is converted to the desired output voltage using a transformer and then rectified to produce a stable DC output.

4. Regulation: Feedback is used to adjust the duty cycle to maintain a stable output voltage despite changes in load or input voltage.

SMPS are widely used in various applications due to their efficiency and size advantages over traditional linear power supplies.

The construction of a Switch Mode Power Supply (SMPS) involves several key components and stages. Here's a brief overview of the main elements involved in the construction of an SMPS:

1. Input EMI Filter: This stage helps in reducing electromagnetic interference from the power supply.

2. Rectifier Filter Circuit: It converts the incoming AC power to DC power.

3. Power Conversion Circuit: This includes a high-frequency switch (like a transistor or MOSFET) that rapidly turns the DC on and off, creating a high-frequency signal.

4. PWM Controller Circuit: It controls the pulse width modulation which regulates the output voltage.

5. Output Rectifier Filter Circuit: This stage stabilizes the output by converting the high-frequency signal back to DC and filtering it.

Each of these components plays a crucial role in ensuring that the SMPS operates efficiently and provides a stable power output to the devices it powers. The construction of SMPS is designed to optimize for size, efficiency, and noise reduction

COMPARATOR INTEGRATED CIRCUIT

In an RC (Resistor-Capacitor) EDM (Electronic Discharge Machining) circuit, a driver IC (Integrated Circuit) is essential for controlling the power electronics that manage the machining process. Here's the role it plays:

1**. Signal Amplification**: The driver IC amplifies the control signals to levels that can switch the power transistors or thyristors in the circuit. This is necessary because the control signals are often too weak to drive the power components directly.

2**. Interface Between Control and Power Stages**: It acts as an interface between the low-power control electronics and the high-power output stages. This ensures that the delicate control circuitry is isolated from the high voltages and currents present in the power stage.

3. **Protection**: Driver ICs often include features that protect the power transistors from overcurrent, overheating, and other potentially damaging conditions. This is crucial in EDM, where the power electronics are subjected to harsh operating conditions.

4**. Controlled Discharge**: In EDM, the driver IC controls the timing and duration of the discharges to the workpiece. It ensures that the energy delivered during each pulse is consistent with the desired machining parameters.

5**. Efficiency**: By optimizing the switching of the power transistors, the driver IC can improve the overall electrical efficiency of the circuit. This can lead to more efficient machining and lower operational costs.

Overall, the driver IC is a key component that ensures the EDM circuit operates effectively, safely, and efficiently, contributing to the precision and quality of the machining process.

Figure 4.13 LM 339 COMPARATOR IC

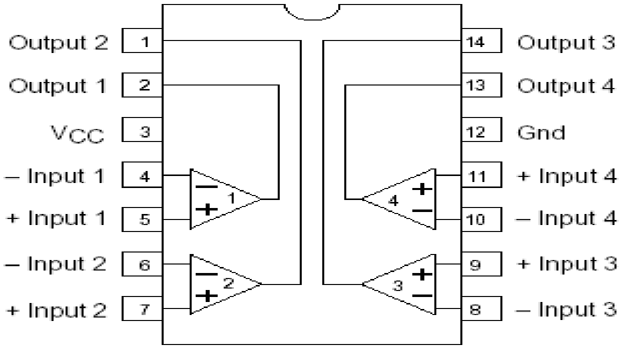

Figure 4.14 LM 339 COMPARATOR IC CIRCUIT

OPERATIONAL AMPLIFIER COMPARATOR CIRCUIT

An **op-amp comparator** is an electronic circuit that utilizes an operational amplifier to compare two voltage levels. It operates in its open-loop state, meaning there is no feedback resistor. The primary purpose of a comparator is to determine which of the two input voltages is larger and produce an output signal based on this comparison. Here are the key points about op-amp comparators:

1. **Basic Operation:**

- The op-amp comparator compares an **analogue voltage level** (usually the input voltage) with another **analogue voltage level** (often a preset reference voltage, denoted as V_{REF}).
- It determines which input voltage is greater and produces an output signal accordingly.

- Unlike standard op-amp circuits with negative feedback, comparators either use **positive feedback** or operate in an **open-loop mode**.

2. **Output Behavior:**

- The output of an op-amp comparator switches between two saturated states:
- When the input voltage on the **non-inverting** terminal is greater than the voltage on the **inverting** terminal, the output swings **fully to the positive supply rail** (+Vcc).
- When the input voltage is less than the reference voltage, the output switches to the **negative supply rail** (-Vcc).
- Essentially, the comparator behaves like a **digital bistable device**, having two possible output states.

3. **Difference Between Op-Amps and Comparators:**

- While operational amplifiers and comparators may look similar, they serve different purposes.
- An op-amp can be used as a comparator, but a voltage comparator cannot be used as an op-amp due to its non-linear output stage.

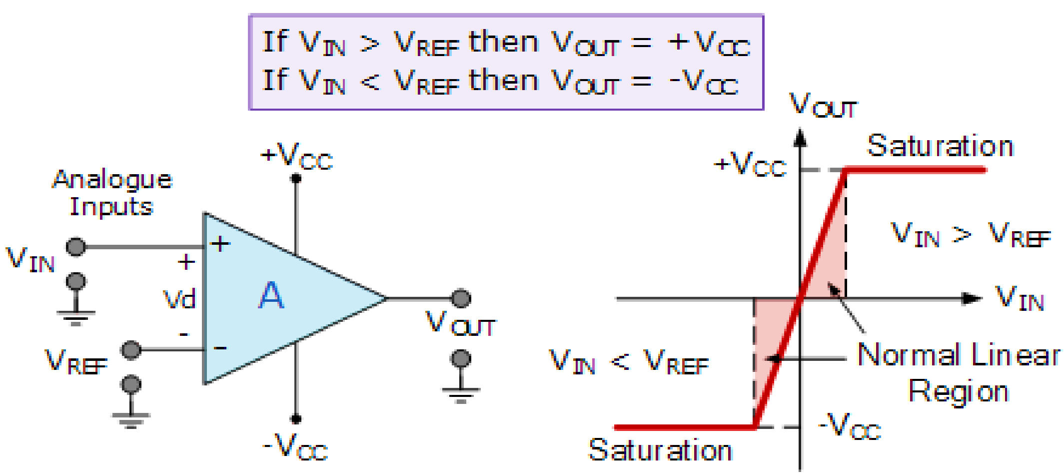

Figure 4.15 OP-AMP COMPARATOR CIRCUIT

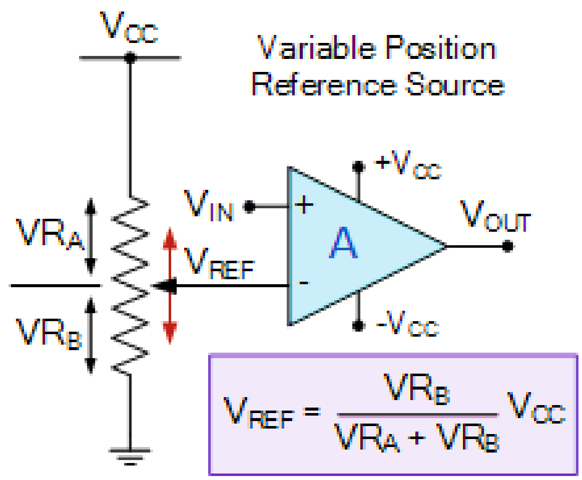

Figure 4.16 OP- AMP REFERENCE VOLTAGE

SERVO MOTOR DRIVER INTEGRATED CIRCUIT

The **L293D** motor driver IC is a versatile integrated circuit that allows you to control the rotation direction and speed of **two DC motors** simultaneously

Functionality:

- The L293D acts as a **dual-channel H-bridge motor driver**. It enables you to drive DC motors in either direction (forward or reverse) and also control their speed.
- An H-bridge is an electrical circuit that allows bidirectional control of a load (in this case, the DC motors).
- The L293D provides continuous bidirectional direct current (DC) to the motors, making it ideal for various applications.

Features:

- **Dual H-Bridge**: The L293D has an internal H-bridge for controlling two motors independently.
- **Voltage Range**: It can handle a voltage range of **4.5 to 36 Volts**.
- **Current Handling**: The L293D can control up to **600mA** of current per channel.
- **Back EMF Protection**: Diodes within the IC protect the controlling device and the IC itself from back electromotive force (EMF).

Pinout:

- The L293D is a 16-pin IC, with 8 pins on each side.
- You can use a single L293D to drive up to two DC motors.

Usage:

- **Robotics:** L293D is commonly used in robotics projects to control motorized wheels or arms.
- **Cars**: It's also useful for controlling motors in toy cars, remote-controlled vehicles, and other similar applications.
- **Speed Control:** By varying the input voltage, you can adjust the motor speed.
- Direction Control: Simply change the polarity of the input to reverse the motor direction.

The L293D simplifies motor control by providing an easy-to-use interface for driving DC motors.

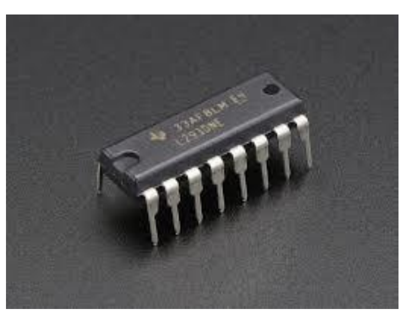

Figure 4.17 L293D DRIVER IC

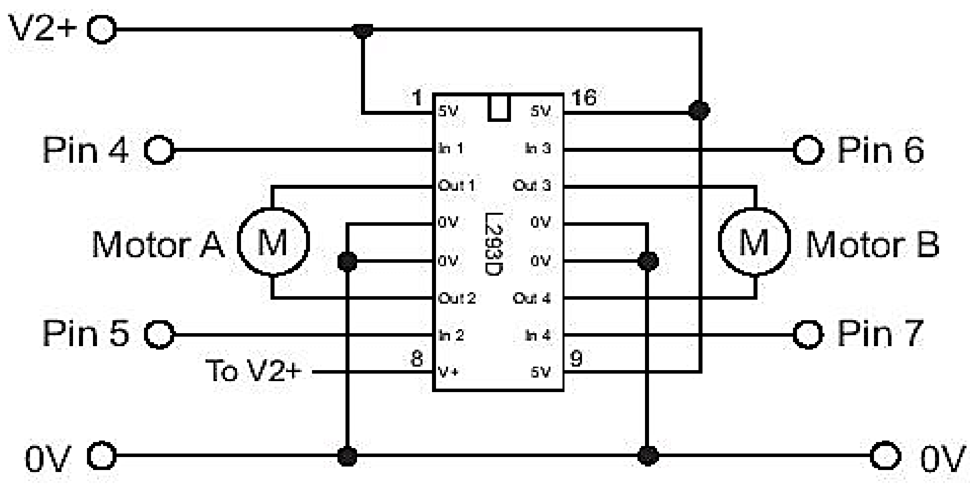

Figure 4.18 L293D DRIVER IC CIRCUIT

DC GEARED MOTOR

1. **Components of a DC Geared Motor**:

A **DC-geared motor** consists of several essential components:

- **DC motor**: The core motor responsible for generating rotational motion.
- **Gear assembly**: The gears play a crucial role in controlling speed, torque, and precision.
- **Load**: Connected to the motor's mechanical shaft (e.g., a simple fan or industrial load).
- **Position sensor**: Provides feedback equivalent to the current position of the load. Usually, a potentiometer generates a voltage proportional to the motor shaft's absolute angle through the gear mechanism.
- **Comparator**: Compares the position sensor's output with a reference point, producing an error signal.
- **Amplifier**: Amplifies the error signal from the comparator and feeds it to the DC motor. It acts as a proportional controller, minimizing steady-state error.
- **PWM (Pulse Width Modulator)**: Modulates the motor's input based on feedback signals, ensuring precise control.

2. **Working Principle**:

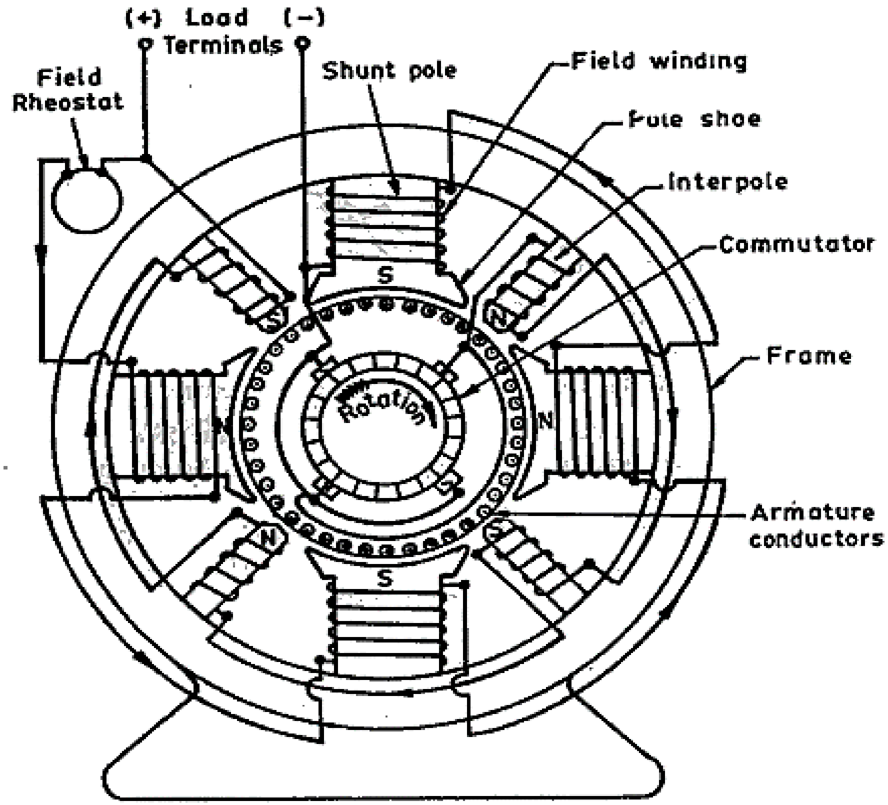

Figure 4.19 DC MOTOR CONSTRUCTION

- When a DC voltage is applied to the motor's coil, current flows through it, generating an electromagnetic field.
- The magnetic field interacts with that produced by the stator (field system), inducing torque and causing the motor to start spinning.
- The gearbox modifies the motor's output (acceleration, position, or velocity) based on the application.
- The position sensor provides feedback on the load's current position.
- The comparator compares the position sensor's output with a reference point, generating an error signal.
- The amplifier amplifies the error signal and feeds it to the DC motor, ensuring precise control.

- The PWM modulates the motor's input for accurate performance.
- DC-geared motors find use in various applications:

i) Small robotic joints
ii) Camera auto-focus systems
iii) Antenna positioning
iv) RC vehicles

4.5 CONSTRUCTION DETAIL OF THE POWER SUPPLY

- A 230 V 50 Hz AC to 75 V 50 Hz AC step-down transformer is used for stepping down the main power supply voltage to the required voltage for the EDM power supply.

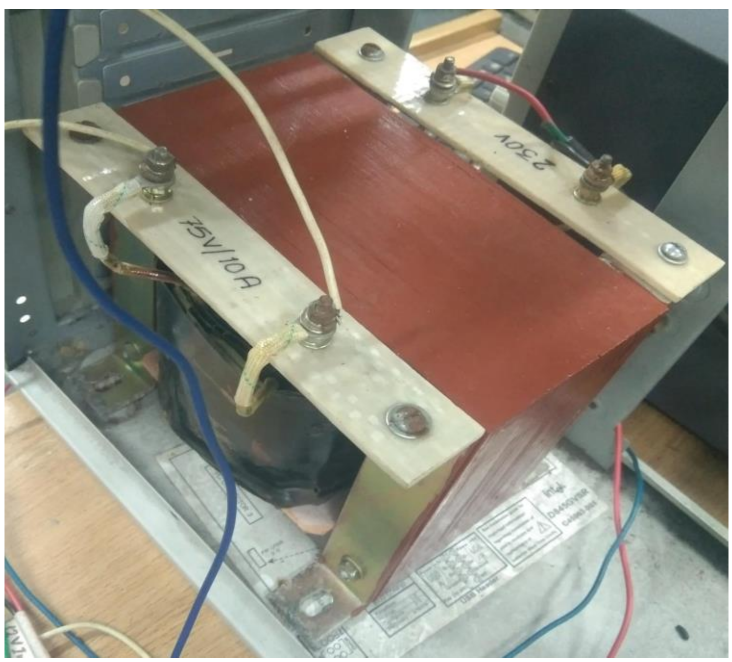

Figure 4.20 TRANSFORMER

- A 10 Ampere MCB with an MCB holder is attached to the transformer to protect the circuit from certain unwanted voltage spikes.

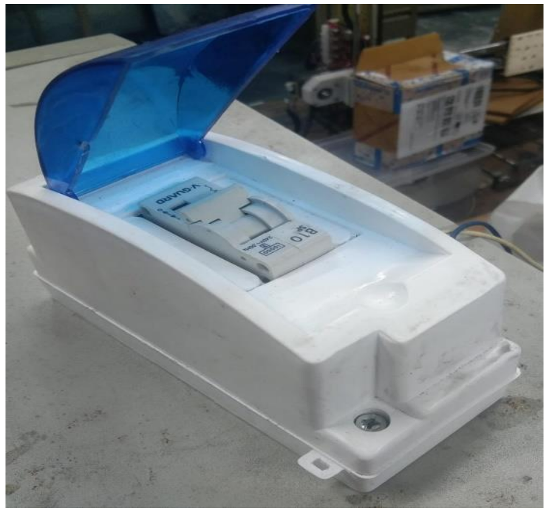

Figure 4.21 10-A MCB

- A 6-ampere bridge rectifier is employed in the circuit to convert AC to DC.
- A 1000 microfarad rectifier capacitor is used in the circuit to rectify the DC.
- A 22-microfarad capacitor is connected to the circuit in parallel for supplying capacitor discharge to the circuit.
- Another 22-microfarad capacitor is employed with the circuit in parallel and attached to a switch (SW1). The switch when in on position will discharge a total of (22+22) 44 microfarad charge to the circuit.
- Another 220-microfarad capacitor is also attached to the circuit in parallel with another switch (SW2). If both SW1 and SW2 are on then the total capacitive discharge to the circuit is (22+22+220) 264 microfarad.
- The output is attached to the cathode (tool) and anode (job) through diodes for completing the Power supply circuit.

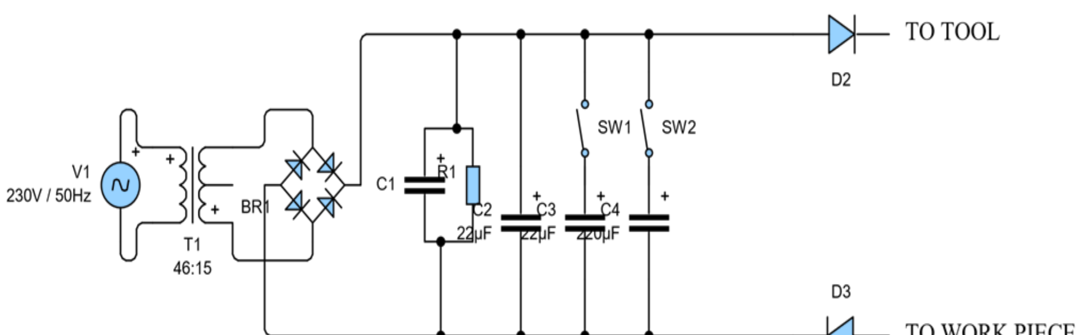

Figure 4.22 SCHEMATIC OF EDM POWER SUPPLY

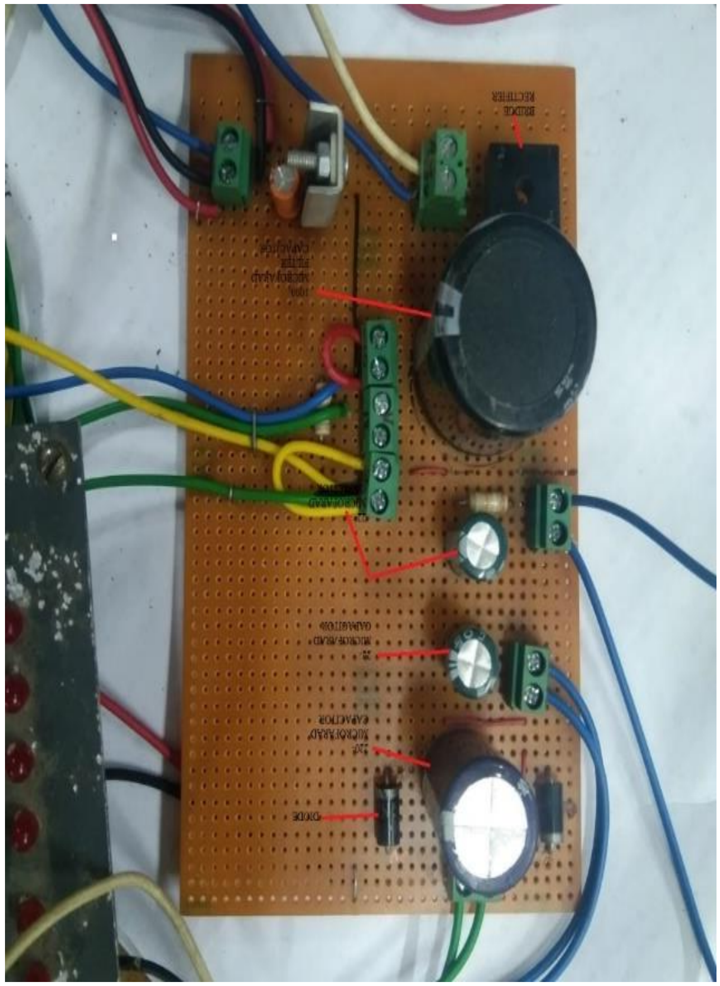

Figure 4.23 POWER SUPPLY CIRCUIT

4.6 CONSTRUCTION DETAIL OF THE FEED BACK CONTROL CIRCUIT

- Two taps for reference voltage are made from the anode terminal of the power supply circuit through potential divider and connected to the comparator so that the comparator IC can compare the gap voltage with the reference voltage set by a potentiometer.
- Comparator IC compares the reference voltage and the gap voltage and sends signal to the driver IC.
- The driver IC in turn receiving the signal from comparator IC and sends signal to the DC servo motor to rotate it clockwise and anticlockwise accordingly.

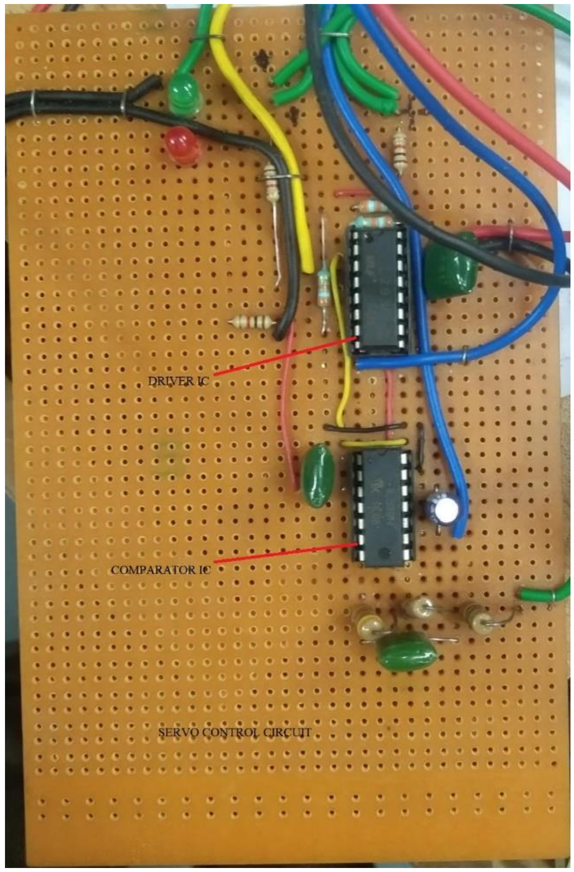

Figure 4.24   FEED BACK CONTROL CIRCUIT

4.7 CONSTRUCTION DETAILS OF THE DI-ELECTRIC CIRCULATION SYSTEM

- An AC submersible pump is fitted inside the machining chamber which is a 220 mm X 160 mm X 85 mm PVC box. Inside the machining chamber there is a job holding arrangement also.
- The whole arrangement is immersed into deionized water / hydrocarbon oil.
- While machining the removed debris is mixed with the dielectric.
- The submersible pump pumps the contaminated dielectric from the chamber and with suitable piping arrangement it sends the dielectric to the filter first and from there again discharge the filtered dielectric to the machining chamber.
- Two separate arrangement is made for discharging one through an external nozzle and the other through a hollow tool.

- The discharging action washed out the debris from the machining zone as well as cools the spot.

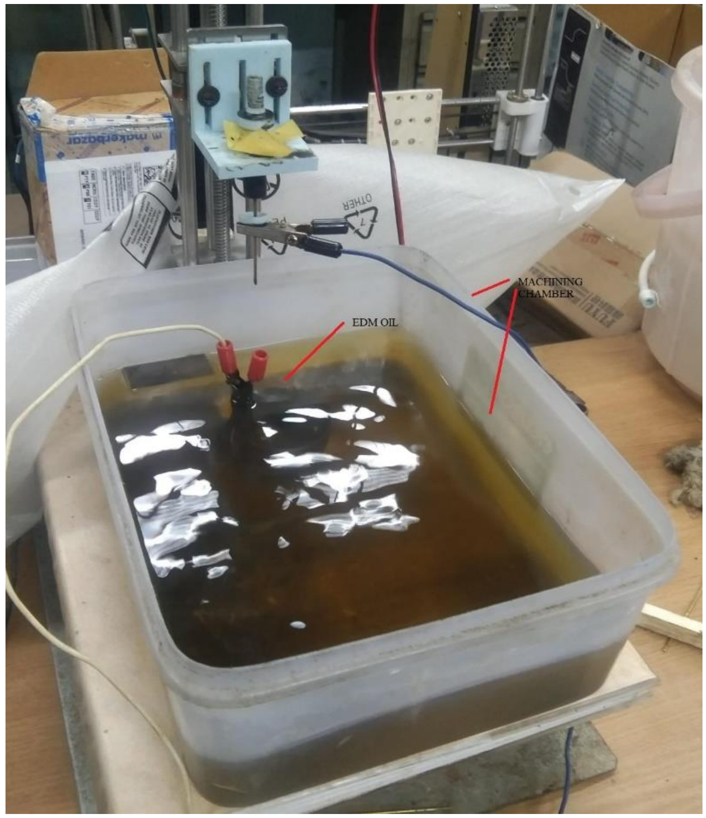

Figure 4.25 MACHINING CHAMBER

CHAPTER 5

PRILIMINARY PERFORMANCE TESTING OF THE DEVELOPED EDM SETUP

This report presents the findings from a series of experiments conducted to evaluate the performance of a newly developed prototype of an RC circuit Electrical Discharge Machining (EDM) system. The experiments focused on drilling through holes using a 1.5 mm diameter hollow copper tool over a 5 mm thick aluminum workpiece. Deionized water was employed as the dielectric medium. Two flushing systems were tested: internal flow through the hollow tool and external flow through an indigenously designed nozzle. The results indicated a significant improvement in the size of the drilled hole with the use of internal flow. Additionally, the rigidity of the tool when coupled with the tool holder was found to be a critical factor in achieving precision, with overcut being notably visible when the tool was loosely fitted with the tool holder.

The RC circuit EDM is a non-conventional machining process that utilizes electrical discharges to erode material from the workpiece. In this study, we explore the capabilities of a prototype EDM machine designed to optimize the drilling process through enhanced flushing systems and tool rigidity.

Materials and Methods:

- **Workpiece**: 5 mm thick aluminum.
- **Tool**: 1.5 mm diameter hollow copper electrode.
- **Dielectric**: Deionized water.
- **Flushing Systems**: Internal flow through the tool and external flow through a custom nozzle.

Procedure:

1. Setup the prototype RC circuit EDM machine with the aluminum workpiece and copper tool.

2. Conduct drilling operations using both internal and external flushing systems.

The internal flushing system demonstrated a clear advantage over the external system, producing holes with improved size accuracy. The rigidity of the tool was paramount; a loosely fitted tool resulted in noticeable overcut, affecting the hole's precision.
The internal flushing system's effectiveness can be attributed to the direct removal of debris from the cutting zone, which is consistent with findings from other studies. The importance of tool rigidity is well-documented, as it directly influences the stability and accuracy of the EDM drilling process. Overcut is a common issue in EDM drilling, often resulting from inadequate flushing or tool instability.
The newly developed prototype of the RC circuit EDM has shown promising results in drilling precision holes in aluminum workpieces. The internal flushing system outperforms the external system, and tool rigidity is crucial for minimizing overcut and achieving high-quality holes. Further research is recommended to optimize these parameters for industrial applications.

- Optimize the internal flushing system for consistent debris removal.
- Ensure high tool rigidity to prevent overcut and improve hole quality.
- Investigate the scalability of the prototype for larger industrial applications.

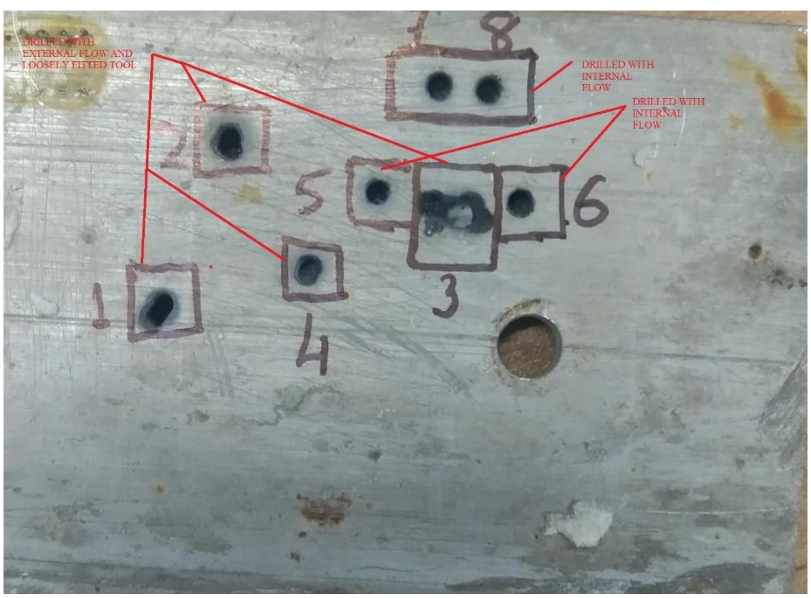

Figure 5.1 ALUMINUM PLATE WITH DRILLED HOLES

A Case Study: Removal of a Broken Tap by Using the developed EDM setup

A common issue in the manufacturing industry is the breaking of taps within drill holes during the machining process. This not only halts production but also risks damaging the workpiece. Traditional methods of removal can be time-consuming and may not always be successful, leading to increased downtime and costs.

The challenge was to remove a broken tap from a drill hole without causing further damage to the workpiece. The tap was made of high-speed steel (HSS), known for its hardness and resistance to conventional drilling methods.

Figure 5.2 JOB WITH INSERTED BROKEN TAP

The solution involved the use of an RC circuit die sinking Electrical Discharge Machining (EDM) process. This method utilizes electrical discharges to erode material from the workpiece. In this case, the broken tap acted as the workpiece, and a specially designed electrode was used as the tool.

The broken tap was submerged in a dielectric fluid, and the EDM machine was set up with the above parameters. The electrode, designed to match the negative imprint of the tap, was then brought close to the tap without making physical contact.

The RC circuit EDM effectively removed the broken tap from the drill hole. The process parameters were optimized to achieve a balance between efficient material removal and minimal tool wear. The workpiece was preserved without any additional damage, and production was able to resume with minimal delay.

The use of RC circuit EDM proved to be an effective method for removing broken taps from drill holes. It provided a precise, non-contact method of material removal that saved the workpiece from potential damage and reduced downtime significantly.

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE

7.1 CONCLUSIONS

A mini EDM setup with a feedback-controlled tool feed mechanism has been developed. Scraped M.S plate and hollow square pipe section has been used as machine's base and main frame of the machine. A 12 V, 2 A DC geared servo motor with a gear ratio 60:1 has been used in the machine. The motor mount, the tool holder, the internal flow nozzle are all designed using 3-D modelling software *'Free cad'* and fabricated using Fused deposition model type 3D Printing machine.

In order to develop the closed-loop feedback control system a comparator IC is used which senses the gap voltage at the job tool interface and sends corrective signal to the servo motor driver. Based on the reference input voltage setting and gap voltage feedback, the comparator IC sends signal to the driver IC. The DC motor driver IC will then rotate the DC motor clockwise and anticlockwise depending on the signal from the comparator IC. Based on the present research studies the following observations can be made:

1. The developed dielectric circulation system is made of corrosion-resistant components. the submersible centrifugal pump is a cheap and quite suitable solution for this setup. The dielectric supply system is equipped with a replaceable filter to remove the machining product from the machining zone. Apart from external flushing, the dielectric flow system was also designed to establish flow through tubular/hollow tool electrodes for enhanced machining performance.
2. The tool holder was designed and fabricated in such a way that the streamlined flow is maintained and also tool replacement can easily be done without changing the alignment.
3. Switched Mode Power Supplies (SMPS) was used for supplying DC power to the

electronic motion control module and the geared DC motor. The SMPS is also equipped with overcurrent and short-circuit protection.

4. It is observed that the developed analog controller with on off control strategy is quite fast and capable of proving quite stable electro-discharge machining in most of the cases. However, it is felt in some adverse machining conditions additional controller for controlling the speed of the DC motor may be added to ensure improved stability.
5. Based upon the results of the preliminary trial run, it can be concluded that the developed setup is quite useful in real-life applications. The EDM setup is compact and very much affordable for any kind of small-scale use.

There is still lot of scope for future upgradation for this basic version of this developed EDM setup. Drilling positions can be moved along X and Y axes simultaneously thereby creating a drilling pattern on the XY plane of the workpiece. Also pulsed DC power supply module can be developed instead of using a Resistance Capacitance based power supply module for improving the machining performances. There is a possibility for exploring other analog control strategies like PID (proportional–integral–derivative) control strategy for enhanced stability during machining. Besides, there is also scope for developing microcontroller-based power supply and control systems in future.

As already pointed out the performance of this basic version of the EDM setup is quite encouraging. The developed EDM setup is very cheap in comparison to other commercial machines available in the market. Yet, this setup offers a feedback control strategy and non-corrosive components promise good endurance of the setup with very little maintenance. In fact, at present this kind of small affordable EDM setup is not available in the Indian market. Thus, it is quite imperative that this mini EDM setup can become a promising solution for practical uses in small-scale industries, research institutions and has lot of other potential applications in modern manufacturing industries.

7.2 FUTURE SCOPE OF RESEARCH

The future scope of research for mini R-C circuit die-sinking EDM (Electrical Discharge Machining) setups involves several exciting areas. Let's explore some potential directions:

1. **Material Removal Rate Enhancement**: Investigate advanced electrode materials and their impact on material removal rate (MRR). For instance, exploring novel composite electrodes or surface-modified electrodes could lead to improved MRR. Optimize process parameters such as pulse duration, current, and electrode geometry to enhance MRR without compromising surface finish.
2. **Surface Integrity Improvement**: Study the effects of different dielectric fluids (including environmentally friendly options) on surface integrity. Researchers can explore how specific dielectric properties influence surface roughness, microhardness, and residual stresses. Investigate post-processing techniques (e.g., shot peening, laser shock peening) to enhance surface integrity after die-sinking EDM.
3. **Tool Wear Reduction**: Develop wear-resistant tool materials or coatings to extend electrode life. This could involve using advanced ceramics, diamond-like carbon (DLC) coatings, or other wear-resistant materials. Explore adaptive control strategies to dynamically adjust process parameters based on real-time tool wear monitoring.
4. **Energy Efficiency and Sustainability**: Investigate energy-efficient EDM setups by optimizing discharge parameters and reducing energy consumption. Explore eco-friendly dielectric fluids and their impact on machining performance.
5. **Hybrid Approaches**: Combine die-sinking EDM with other manufacturing processes (e.g., laser machining, ultrasonic machining) to achieve synergistic effects. Investigate hybrid setups that integrate EDM with additive manufacturing (e.g., 3D printing) for complex part fabrication.
6. **Advanced Modeling and Simulation**: Develop accurate numerical models to predict process outcomes, including surface roughness, recast layer thickness, and heat-affected zone. Use simulations to optimize process parameters and electrode design.

7. **Micro- and Nano-EDM**: Extend die-sinking EDM to micro- and nano-scale applications. Investigate the challenges and opportunities in machining miniature features. Explore new electrode fabrication techniques for micro-EDM.
8. **Industry-Specific Applications**: Focus on specific industries (e.g., aerospace, medical devices, electronics) and tailor die-sinking EDM research to their unique requirements.

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