EXPERIMENTAL INVESTIGATION INTO MICRO-GROOVING ON GLASS BY ELECTROCHEMICAL DISCHARGE TURNING PROCESS

By

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THESIS

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TABLE OF CONTENTS

Chapter: 1

1. INTRODUCTION

ECDM is basically a hybrid machining process, combining the principles of electric discharge machining (EDM) and electro chemical machining (ECM). So, this is a combination of two processes as the name suggests, in which one action will be by electrochemical action, which is very familiar to almost all of us in which a chemical action takes place, and that causes the dissolution of material into an electrolyte called a working fluid. And therefore, the material removal from the workpiece takes place. In addition to that combining another phenomenon is electrical discharge phenomena, in which the material removal takes place due to melting and evaporation of material because of high temperatures that develop as the sparks take place. Therefore, these two things are combined together, in this particular hybridization where basically the material removal will be done by the basic spark erosion process, which is known for rough machining or the stock removal or material removal process. The smoothing effect will be given by the electrochemical effect, which is known for producing smooth surfaces.

Thus it has been observed that in the electrochemical discharge machining (ECDM) process, the capabilities of ECM and EDM processes are combined with each other to expand the processing window from conductive to non-conducting materials as well as to fabricate deep micro holes, microchannels, etc. It is mainly used for micro machining and scribing hard and brittle, non-conductive materials. The process is basically for very small material removal, and not for bulk material removing applications. In ECDM, the discharge takes place between the tool electrode and workpiece. The circuit is completed by the auxiliary electrode having large surface area immersed in an aqueous solution of electrolyte bath.

1.1 HISTORY of ELECTROCHEMICAL DISCHARGE MACHINING (ECDM)

ElectroChemical Discharge Machining is also known by its other name as: Electrochemical Spark Machining (ECSM), Spark Assisted Chemical Engraving (SACE) and Electrochemical Anode Machining (ECAM). The first work on electrode effect, anode or cathode was first reported by Fizeau and his group of researchers and Foucault and his co researchers in the year 1844, thus as a principal. So, these principles are very old, that is of the nineteenth century. It was introduced in the year 1968 as electrochemical discharge drilling by Karafuji and Suda. ECDM is an unconventional machining technology which has the main advantage of its capability to machine non-conductive materials which is the basic drawback of ECM and EDM. The significant developments related to ECDM have been mentioned in Table 1.1.

Table 1.1 Year wise development of ECDM

1968	First report by Kurafuji and Suda
1973	First characterization by Cook et al.
1985	Extension to traveling wire ECDM by Tsuchiya et al.
1990	First functional devices
1997	First models by Ghosh et al and Jain et al.
2000	Study of SACE in light if electrochemistry
2004	SACE and NanoTechnology
2008	Systematic Studies on SACE 2D machining
2009	Machining structures less than 100µm
2011	Study of various tool geometries
2014	First commercial machine by Posalux SA

1.2 VARIANTS OF ELECTROCHEMICAL DISCHARGE MACHINING (ECDM) PROCESS

There are several types of Electro Chemical Discharge Machining (ECDM) processes used in industry. These processes differ in their specific configurations, electrode arrangements, and operational parameters. Here are some commonly used types of ECDM processes:

1.2.1 Electrochemical Discharge Drilling (ECDD)

Electrochemical Discharge Drilling (ECDD) is an advanced machining process that combines the principles of electrochemical machining (ECM) and electrical discharge machining (EDM) to create holes or bores in conductive materials. It offers unique advantages over conventional drilling techniques, especially for materials that are difficult to machine or have high hardness.

In the ECDD process, a tool electrode, typically in the form of a rotating tube or a rotating electrode with a hollow core, is brought into close proximity to the workpiece surface. An electrolyte is continuously supplied between the tool electrode and the workpiece, creating a conductive medium. A voltage is then applied between the tool electrode and the workpiece, resulting in the generation of an electrochemical reaction and electrical discharges. The electrochemical reaction causes localized dissolution of the workpiece material, while the electrical discharges facilitate the removal of the dissolved material and the creation of the hole. The combined action of the electrochemical dissolution and electrical discharges ensures efficient material removal and enables drilling holes with high precision and surface finish.

ECDD finds applications in various industries, including aerospace, automotive, medical, and electronics. It is used for the fabrication of cooling holes in turbine blades, fuel injector nozzles, heat exchangers, and other components requiring high-precision and high-quality holes.

1.2.2 Electrochemical Discharge Grinding (ECDG)

Electrochemical Discharge Grinding is an advanced form of ECDM that combines the principles of ECM, EDM and grinding. In ECDG, a conductive grinding wheel is used as the tool electrode, and a workpiece is placed opposite to it. An electrolyte is applied between the grinding wheel and the workpiece. By applying a voltage difference, electrochemical reactions occur, and material is removed from the workpiece due to electrical spark discharge and mechanical grinding. The grinding action provided by the rotating wheel assists in the material removal process. ECDG is particularly useful for machining hard and brittle materials, such as ceramics and carbides, with high precision and surface finish.

1.2.3 Electrochemical Discharge Milling (ECDM)

Electrochemical Discharge Milling (ECDM) is an advanced machining technique to perform milling operations on conductive as well as non-conductive materials. It offers several advantages over conventional milling processes, including the ability to machine complex and intricate shapes, improved surface finish, and reduced tool wear. In the Electrochemical Discharge milling process a conductive tool electrode, typically in the form of a rotating cylinder or a disk, is used along with a workpiece submerged in an electrolyte. By applying a controlled electric current and voltage between the tool electrode and the workpiece, localized sparks or discharges are generated. These discharges result in the controlled removal of material from the workpiece, allowing for precise milling operations.

1.2.4 Electrochemical Discharge Turning (ECDT)

In ECDT, a conductive tool electrode with the desired shape is used along with a workpiece submerged in an electrolyte. The tool electrode is brought into close proximity to the workpiece, when controlled voltage is applied between them. As a result, localized sparks or discharges occur at the interface between the tool electrode and the workpiece, causing material removal.

The ECDM process in turning involves the electrochemical dissolution of the reaction, combined with the thermal effects of the localized sparks. The electrolyte plays a vital role in facilitating the electrochemical reactions and carrying away the dissolved material, ensuring a stable machining environment. ECDT offers several benefits over conventional turning processes. It allows for the machining of intricate and complex shapes mainly having cylindrical shapes that are challenging to achieve with traditional turning methods like marking, grooving, knurling. The process also offers improved surface finish and dimensional accuracy due to the electrochemical dissolution and spark-induced material removal.

Furthermore, ECDT is particularly suitable for materials that are difficult to machine using conventional methods, such as hard and brittle materials. It reduces tool wear and minimizes the generation of heat-affected zones, resulting in improved machining efficiency and better surface integrity. Although ECDT is a relatively new and specialized technique, it holds promise for applications where high precision and complex geometries are required. Continued research and development in ECDT are expected to further enhance its capabilities and expand its industrial applications.

All the above methods are just a few examples of the different types of ECDM processes. Each process has its own advantages and is suitable for specific applications based on the desired machining outcomes, workpiece materials, and geometry.

1.3 NEED FOR ELECTROCHEMICAL DISCHARGE TURNING (ECDT)

Electrochemical Discharge Turning (ECDT) offers several advantages and fulfills specific machining requirements, making it a valuable technique in certain applications. Conventional turning methods may have limitations in terms of the complexity of the geometries that can be achieved. Mainly the need for ECDT arises due to the limitations of Electrochemical machining (ECM) and electro discharge machining (EDM) as the main condition for using these two is that the material must be a good conductor of electricity. Thus, these processes have major drawbacks that could be applied to only a limited number of workpieces having good conductivity only. Using ECM and EDM it is not possible to work on non-conductive materials and very difficult for machining of low conducting material. Also ECM and EDM have some other limitations like tool wear, low surface finish and high tool wear. One significant need for ECDT is the ability to machine complex and intricate shapes. ECDT overcomes these limitations by combining the principles of ECM and EDM, allowing for the precise removal of material from conductive as well as electrically non-conducting workpieces. This enables the production of intricate profiles, contours, and features that are difficult to achieve with traditional turning processes.

Another need for ECDT is the demand for improved surface finish. The combination of electrochemical reactions and spark-induced material removal in ECDT results in a smoother surface finish compared to conventional turning. This is particularly advantageous for applications where a high-quality surface is crucial, such as in aerospace, medical, and optical industries. ECDT can achieve finer surface textures and reduce the need for subsequent finishing operations. ECDT also addresses the machining challenges posed by hard and brittle materials. Such materials are difficult to machine using conventional turning methods due to their high hardness and susceptibility to cracking. ECDM offers a controlled and precise material removal process, reducing tool wear and minimizing heat-affected zones. This makes it a suitable option for machining materials like ceramics, carbides, and hardened steels.

Additionally, ECDT offers the potential for improved dimensional accuracy. The controlled electrochemical reactions and spark-induced material removal allow for precise material removal rates and dimensional control. This is especially beneficial for applications where tight tolerances and precise dimensions are required.

In summary, ECDT addresses the need for machining complex shapes, achieving improved surface finish, handling hard and brittle materials, and ensuring dimensional accuracy. By leveraging the advantages of ECM and EDM, ECDM turning provides a unique approach to turning operations and offers benefits in specific industries and applications where these requirements are essential.

1.4 PROSPECT OF ELECTROCHEMICAL DISCHARGE (ECDT) AS μ-GROOVING

The prospects of Electrochemical Discharge Turning (ECDT) as a μ-machining and grooving technique are highly promising. ECDM offers unique capabilities and advantages for micro-scale machining applications of cylindrical shapes work pieces where precision, intricate features, and high-quality surface finish are crucial.

One key prospect of ECDT in micro-machining is its ability to achieve sub-micron level precision. The controlled electrochemical reactions and localized sparks enable precise material removal, allowing for the creation of intricate and complex micro-features. This makes ECDT well-suited for applications in microelectronics, MEMS

(Micro-Electro-Mechanical Systems), and microfluidics, where miniaturized components and structures are required.

Another prospect of ECDT in micro-machining is its versatility in machining a wide range of materials. ECDT can effectively machine conductive materials, including metals, alloys, and semiconductors. This enables the production of micro-features and grooves in various workpiece materials, providing flexibility for different application requirements. Furthermore, ECDT offers a non-contact and stress-free machining process for micro-scale components. Since ECDT is based on electrochemical reactions and spark-induced material removal, there is minimal mechanical force applied to the workpiece, reducing the risk of deformation or damage. This is advantageous for delicate microstructures and materials prone to distortion, ensuring the integrity of the machined parts. As research and development in ECDM continue to advance, there is potential for further improvements and innovations in micro-machining and grooving applications. The optimization of process parameters, development of specialized tooling, and advancements in control systems will contribute to enhancing the precision, efficiency, and range of achievable features in ECDT.

In conclusion, ECDT holds significant prospects as a micro-machining, grooving and turning technique. Its ability to deliver sub-micron precision, excellent surface finish, material versatility, and non-contact machining makes it a valuable tool in the microfabrication field.

1.5 APPLICATION OF μ-ELECTROCHEMICAL DISCHARGE TURNING (ECDT) PROCESS

As discussed earlier Micro-Electrochemical Discharge Turning (Micro-ECDT) is a specialized machining technique that combines the principles of electrochemical machining (ECM) and electrical discharge machining (EDM) to perform turning operations at the micro-scale level. It finds applications in various industries where precise machining of miniature components is required. Some specific applications of Micro-ECDT turning include:

Micro-machining of Precision Components: Micro-ECDT turning is employed in the fabrication of precision components with intricate geometries and miniature features. It is used to create small-scale parts for industries such as aerospace, medical devices, electronics, and micro-optics. Examples include microfluidic devices, miniature gears, medical implants, and microelectrodes.

Fabrication of Microfluidic Channels and Devices: Microfluidics is a field that deals with the manipulation and control of small volumes of fluids. Micro-ECDT turning is utilized to produce microchannels, microgrooves, and other structures in microfluidic devices. These devices find applications in biomedical diagnostics, chemical analysis, and lab-on-a-chip systems. Micro-Optics and Photonics: Micro-ECDT turning is crucial in the manufacturing of micro-optical components and devices. It enables the fabrication of precise optical surfaces, lens arrays, diffractive optics, and microstructures used in imaging systems, telecommunications, and photonic devices.

MEMS (Micro-Electro-Mechanical Systems): MEMS devices require intricate structures with high precision and accuracy. Micro-ECDT turning is employed in the fabrication of MEMS components such as microsensors, microactuators, microvalves, and micro-electrodes. These devices find applications in automotive sensors, biomedical devices, and consumer electronics. Micro Grooving and Texturing: Micro-ECDT turning is utilized to create microgrooves and textures on various materials. This technique is employed in industries such as mold making, where the surface textures of molds play a crucial role in the replication of fine details and patterns.

Micro-ECDT turning offers unique advantages for these applications, including the ability to achieve sub-micron precision, excellent surface finish, and the capability to machine complex geometries. As ECDT is a turning process therefore it is most suitably used for cylindrical shapes of workpiece. With further advancements in process optimization and tooling, the application of Micro-ECDT turning is expected to expand further in the future.

1.6 LITERATURE REVIEW OF PAST RESEARCH

ECDM was discovered in 1968 by Kara Fuji and Suda for drilling operations, however since then a lot of researchers had worked on ECDM to explore the various opportunities related to ECDM as well as ECDT operation.

Basak *et al.* [1] proposed a theoretical model of the discharge phenomena. They reported that with the help of the model, the critical voltage and current required to initiate discharge between the electrode and the electrolyte are estimated. The theoretically-predicted values compare quite well with experimental observations. The process of ECD is a very complex phenomenon involving a number of processes taking place simultaneously. The simplified model based on an idealistic mechanism leading to switching, however, provides reasonably good estimates of the conditions leading to the onset of discharge. The mechanism also suggests a number of interesting characteristics, which are supported by the experimental observations. Therefore, it would be appropriate to conclude that the idealized mechanism of ECD represented the actual physical phenomenon with reasonable accuracy.

Kozak *et al.* [2] analyzed pulsed electrochemical micromachining (ECMM) processes for generating complex 2½ and possibly 3-D microcomponents of high accuracy. A mathematical model was developed based on the first principle of the process mechanism and experimentally verified using a designed and developed ECMM system. Factors affecting ECMM process performance are voltage, feed rate, frequency, and duty factor. The results at higher frequency (1 MHz) indicated smaller side and frontal gaps with sharper edges than the results at 250 KHz. A mathematical model to predict frontal and side gaps was developed and experimentally verified. A close agreement between the theoretical estimated and experimental values at the frontal gap was observed. Similarly, a close agreement for side gap values was observed for applied voltage pulses below 8 V, supporting the hypothesis of model applicability at small voltage.

Wuthrich *et al.* [3] developed an experimental method for measuring the thickness of the gas film using the inspection of the current–voltage characteristics of the process to solve the problem of reproducibility. It was demonstrated that there was a decrease in the gas film thickness by changing the wettability of the tool electrode and resulted in significantly higher machining repeatability. By adding liquid soap into the electrolyte, it was demonstrated that more reproducible machining was achieved (at the time better than 5 μm). The reduction of the gas film thickness resulted in smaller fluctuations and therefore more reproducible and repeatable machining. Another conclusion was that the consequence in gas film thickness reduction was the lowering of the critical voltage.

Maillard *et al.* [4] developed a qualitative model for SACE machining by gravity-feed. It was observed that micro-hole drilling by gravity-feed with spark assisted chemical engraving was characterized as a function of the drilling depth and machining voltage. It was observed that the variation of the mean diameter increased from 15 μm up to 100 μm with machining voltage. The relative roundness error increased with drilling depth from 10% to 20% and depends only slightly on the machining voltage. Best results for drilling were obtained with voltages slightly higher than the critical voltage when the discharge activity was in the so-called transition regime.

Jain *et al.* [5] analyzed Electrochemical spark machining (ECSM) process for cutting of quartz using a controlled feed and a wedge edged tool. It was observed that (Electrochemical spark machining with reverse polarity (ECSMWRP)) cut quartz plate at faster rate as compared to Electrochemical spark machining with direct polarity (ECSMWDP), but produced higher overcut, higher tool wear and higher surface roughness. Chemical analysis of reaction products confirmed the dissolution of quartz into NaOH solution. It was observed that auxiliary electrodes could also be made small in the ECSM process. It was observed that to use only one electrode at a time as a tool, the size of the other electrode should be such that the sparking zone always confines near the small electrode, so that sparking zone (high potential) would always be available at the tool.

Liu *et al.* [6] analyzed the discharge mechanism in electrochemical discharge machining (ECDM) of a particulate reinforced metal matrix composite and developed a model to reveal the electric field acting on a hydrogen bubble in ECDM process. The model was found capable of predicting the position of the maximum field strength on the bubble surface as well as the critical breakdown voltage for spark initiation, for a given processing condition. A set of experiments was performed to verify the model and the experimental results agreed well with the predicted values. The experimental results also showed that an increase in current, duty cycle, pulse duration or electrolyte concentration would promote the occurrence of arcing action in ECDM. Moreover, by studying the waveform of ECDM and surface craters, it was confirmed that the spark action was in the form of an arc. Compared to EDM, the volume of an arc eroded crater of ECDM was less than that of EDM. It was observed that when current, duty cycle, pulse duration and electrolyte concentration increased sparking action occurring in ECDM also increased. The experimental breakdown voltage was found to lie between 26 V and 30V.

Yang *et al.* [7] examined machining performance and extent of wear under gravity-feed micro-hole drilling of tool material. It was concluded that the optimal voltage of different tool electrodes affected the machining performance. Moreover, wettability of tool electrodes was determined by surface roughness of tool material, which in turn affected the coalescence status of gas film, machining stability and micro-hole diameter achieved. In addition, differences in tool material also resulted in variations in machining speed. During ECDM, energy discharge varied with the tool material of the electrode. It was noticed that different tool materials had different optimal voltages, which determined the gas film formation, and hence the hole diameter and average current achieved. Poor wettability had increased surface tension of gas bubbles adhered on the electrode surface, causing them to coalesce and form a thicker gas film, resulting in the largest hole diameter machined. Although It was seen that the tungsten electrode had the highest average current and hence the fastest machining speed, its current response was relatively less stable, resulting in non-uniform etching marks found in the HAZ.

Kolhekar *et al.* [8] investigated the effect of concentration of electrolyte in ECDM on the integrity of a micro machined hole surface. Surface roughness and micro-defects, microstructure by EDAX testing and hardness testing by nanoindentation was analyzed. It was found that lower electrolyte concentrations in ECDM enhanced chemical etching that caused surface wrinkling. Experiments were conducted with 1M, 0.8M, 0.6M, 0.4M and 0.2M concentration of electrolyte. It was found that with higher concentration of electrolyte thermal mechanism was observed dominant as high energy sparks vaporizes the surface. Vickers hardness values were found to decrease for lower concentration of electrolyte. With lower concentration of electrolyte, the critical voltage increased.

Sarnaya ***et al*****. [9]** carried out the detailed experimental investigations to study the electrical and 2-D machining characteristics of an ECDM. The influential process parameters considered were electrolyte type, electrolytic concentration, tool travel rate (TTR) and applied voltage on the process. Two different electrolytes under varied concentration were used. For KOH it was noticed that KOH requires a higher critical voltage than NaOH solution due to its relatively lesser conductivity. When any specific electrolyte was used the higher concentration of electrolyte caused reduced critical voltage and increased critical current. Further it was also noticed that the critical voltage and critical current were increased for an increase in tool immersion depth and tool diameter and for KOH it was noticed that KOH requires a higher critical voltage than NaOH solution due to its relatively lesser conductivity.

Elhami ***et al.*** **[10]** analyzed the effect of ultrasonic vibrations on the ECDM. For this purpose ultrasonic vibration is concentrated on the tooltip which directly and continuously affects the machining zone and avoids global undesirable effects. A modal analysis was used to design a special configuration which could achieve the maximum amplitude of vibration in the tool tip. Also, an analytical model was developed for both the electro-chemical discharge machining (ECDM) and ultrasonic assisted electro-chemical discharge machining (UAECDM) to study the effect of ultrasonic vibration on the thickness of gas film. Results showed that ultrasonic vibration could increase MRR up to 82%. Also, tapering zone and entrance overcut deviation as accuracy parameters improved 50% and 40%, respectively. It was noticed that UAECDM produced smaller gas film thickness compared to ECDM, it was the result of electrolysis as an electrochemical phenomenon and hence more time for discharge activities causing higher MRR and higher machining depth.

Sabahi ***et al.*** **[11]** analyzed the effect of wettability of tool electrodes and surface tension between the bubble and electrolyte on the thickness of gas film. In the presence of surfactant reduced thickness of gas film was observed. The depth of micro channels increased due to increasing the current and the thermal energy of the process. The surface quality of micro channels was improved due to the increase in the viscosity of electrolyte and decrease in the thermal conductivity. It was concluded that due to surfactant micro channels with higher material removal rate (MRR), lower overcut and heat affected zone (HAZ) could be produced.

Gupta [12] focused on the effect of the level of electrolyte in the machining of glass by ECDM. It was observed that there was variation in the thickness of gas film, which was due to the variation in level of electrolyte and due to variation in gas film thickness which affected the machining quality. To prevent this electrolyte variation a separate electrolyte was supplied to maintain constant electrolyte level. The glass workpiece was machined keeping the workpiece in a Perspex chamber which was filled by electrolyte and the level of electrolyte was controlled by stepper motor. It was concluded that lower electrolyte level resulted in higher MRR, depth of cut and lower HAZ and overcut. When the level of electrolyte reaches less than 1mm, deteriorated edges of the hole were obtained due to high discharge concentration. With increased electrolyte level up to 4mm lower HAZ and overcut were obtained, however MRR and depth of cut were lowered. Therefore, it was concluded that for an optimum electrolyte level around 1mm better quality, high MRR, depth of cut with decreased HAZ and overcut was obtained.

Xu *et al.* [13] developed a hybrid electrochemical discharge drilling method in which a metal tube was used as a cathode tool and a workpiece was used as anode. Liquid with weak conductivity made to flow at high speed between the metal tube and workpiece. Electrical discharge occurred mainly at the frontal gap, and electrochemical process at both the frontal gap and side gap. The recast layer generated by electrical discharge at the side gap can be removed electrochemically. The machining phenomenon at the gap was observed through a designed transparent clamping fixture, voltage and current waveforms during machining were recorded, and the machining products and removal effect of the recast layer were analyzed. The lateral wall of the hole in ECDD was almost free of recast layer, and the tool wear in ECDD was found to be much lower than that in EDM. A deep hole of 0.5-mm diameter was successfully produced with high efficiency, low tool wear, and better surface quality.

Elhami *et al.* [14] analyzed the process of ECDM concentrating on single discharge and effects due to ultrasonic vibrations on ECDM. To get the desired output special configuration and equipment were used to produce ultrasonic vibrations and for generating single discharge. Material removal and tool wear were considered as two important characteristics of the drilling process to determine the machining efficiency. It was also observed that ultrasonic vibration helped in the cooling (convection) mechanism on the tool, so lower material melt and smaller tool wear occurs. Results showed that the application of ultrasonic vibration changed the current signal pattern to increase discharge numbers in constant condition. Also, ultrasonic vibration increased the material removal up to 35%, while tool wear reduced between 3% and 14%.

Singh *et al*. [15] studied the development of pressurized feeding systems for effective control on working gaps during ECDM. In a pressurized feeding system, the exerted pressure maintains a constant working gap (almost zero) during machining, and that was provided by the development of a workpiece holding fixture. The existence of micro cavities between abrasive coated tool and work material generated thin and stable gas films underneath the tool electrode. It was observed that the application of exerted pressure reduced the critical voltage and provided high-frequency consistent discharges that made ECDM very effective even at high applied voltages. This ensured enhancement of MRR and depth of machining. Also the pressurized feeding system did not require any feedback system to control the feed motions. Thus it helped in reducing the complications in the ECDM setup for drilling and deep depth machining. It was seen that the higher values of exerted pressure exhibited superior accuracy as compared to lower values of the exerted pressure.

Antil *et al.* [16] observed that the conventional machining of polymers matrix composite materials causes high tool wear due to presence of abrasive particles, so ECDM applied for the desired purpose. Voltage, electrolyte concentration and duty factor were considered as process parameters whereas material removal rate and taper were observed as output quality characteristics. The regression equation and coefficients were obtained using regression analysis. Using the regression equations, further solutions were obtained by genetic algorithm. It was observed that voltage and electrolyte concentrations were the most significant parameters which affected the output quality characteristics (OQCs) of ECDM process. Also, it was seen that material removal rate was directly proportional to voltage and electrolyte concentration whereas taper was directly proportional to voltage and inversely proportional to electrolyte concentration. However, the duty factor had limited effect on OQCs of ECDM. The mathematical models for OQCs were developed by the regression analysis. Genetic Algorithm was successfully employed for the ECDM process optimization. The comparative analysis proved that Genetic Algorithm was in good agreement with the result obtained through Taguchi's methodology.

Mehrabi *et al.* [17] analyzed the effect of impact of external electrolyte injection on output characteristics such as drilling depth, hole and chemical etching of optical glass material with variation in voltage, electrolyte pressure, hollow electrode with different diameter electrodes. For this purpose, hollow electrodes with high-pressure electrolyte injection systems were employed to provide the electrolyte to the machining area in deep holes. It was concluded that drilling depth and chemical etching both increased with increase in injection pressure of the electrolyte. By injection of electrolyte through the hollow cathode to the drilling area, material removal rate (MRR) and drilling speed increased. Also, MRR and drilling speed rose by increasing the electrode diameter and injection pressure. Improvement of the hole depth versus the effective pressure for different electrode diameters was about 50–70%. More injection pressure resulted in larger hole diameter and creation of conical shape holes. It was concluded that increasing the electrode diameter the differential of hole diameters also increased. Injection of electrolyte through the electrode to the deep section of the hole prevented the accumulation of removed material in the deep hole and caused the increased rate of discharges and material removal.

Gohil *et al.* [18] investigated the electrical discharge turning of titanium Ti-6Al-4 V alloy. The objective was to analyze the influence of machining parameters including peak current, pulse-on time, gap voltage, spindle speed and flushing pressure on performance characteristics at reverse polarity. Taguchi-grey relational approach based on multi objective optimization has been used to optimize material removal and surface roughness simultaneously. It was observed that based on grey relational analysis pulse-on time at level 5 μs, peak current at level 5 A, gap voltage at level 40 V, spindle speed at level 40 RPM. Among input parameters, voltage and Flushing pressure found to be the most influencing parameter for output performance parameters i. e. material removal rate and surface roughness. The results of the confirmation experiment are compared with the findings of the orthogonal array and predicted grey relational grade. Surface roughness was improved by 2.23 times and material removal decreased from 41.55 to 12.36 mg/min.

Hajian *et al.* [19] investigated to present a thermal model based on the finite element method (FEM) to predict the machining depth in ECD milling and estimate the equivalent temperature (Teq) in electrochemical discharge milling (ECD milling). The input parameters of the FEM model were calculated based on different machining conditions such as machining voltages and electrolyte concentrations. Two proposed temperatures, 600 °C and 850 °C were chosen as the temperature criterion (Teq) for the material removal temperature in the finite element modeling and the results were compared with the experimental data. The comparisons between FEM results and experimental data showed that by considering Teq = 600 °C and 850 °C the evaluated machining depths were determined a little over or under estimation, respectively. It was found that the best temperature for Teq could be estimated at the softening point of 720 °C.

Arab *et al.* [20] investigated the Effect of the tool electrode surface roughness upon the overcut and the HAZ width of the through-holes formed in the glass substrate by ECDM. Tool electrodes having varying surface roughness were successfully fabricated by wire-EDM and electrochemical finishing. Tool surface roughness influenced the gas film thickness in the ECDM process. Gas bubbles of larger size and larger contact angles were formed on the tool electrodes having higher surface roughness due to the deeper valleys present on the surface. Larger gas bubbles eventually coalesced to create a thicker gas film which resulted in larger overcut and HAZ widths. Tool electrodes with lower surface roughness showed a thinner gas film which resulted in through-holes having lower overcut and HAZ widths. The mean discharge current having the maximum and the minimum magnitude of 2.026 A and 0.850 A, was measured when the tool electrodes having the highest surface roughness and lowest surface roughness were used.

Pawar *et al.* [21] developed the ECDM experimental setup for machining of non-conducting materials. ECDM process was used for machining of silicon carbide which is very brittle and hard in nature. Two output responses were investigated viz. machined depth and hole diameter by considering the three input factors such as voltage, electrolyte concentration, and rotation. The experiments were done with the help of Taguchi L27 orthogonal array method and analyzed by using MINITAB 17 software. The hole diameter and machined depth results were inspected after ECDM drilling on silicon carbide material while considering the input machining parameters such as electrolyte concentration, voltage, and rotation. The experimental observation results showed electrolyte concentration as the major parameter for hole diameter and machining depth followed by voltage and rotation of the tool electrode. The optimum input factors combination for maximum machined depth and the nominal value for hole diameter are voltage 81.81V, electrolyte concentration 16.16%, and rotation 50 rpm.

Charak *et al.* [22] investigated continuous improvements in ECDM machining of glass and effect of process parameters on material removal (MR). A Taguchi analysis on machining of borosilicate glass was carried out, where it was illustrated that increase in feed rate and electrolyte concentration increases the MR. It was reported that the machining performance of ECDM depends on the stability and uniformity of gas film around the tool. The most influencing factor was the feed rate of work for material removal and the electrolyte concentration came out as a secondary factor. It was observed that for highest material removal the suitable electrolyte found was 25% by weight concentration.

Bijon *et al.* [23] analyzed the influencing mechanism of the process parameters on tool wear, and a suitable voltage range for the processing when the tungsten carbide spiral cathode with a diameter of 400 μm was used. The influence of the cathode’s loss behavior on the film formation time and the average current of spark discharge was discussed based on the current signal. The results showed that the tool wear mainly appeared from the bottom to the end and edge tip of the protrusion and the loss was mainly in the form of local melting or the vaporization of the material at a high temperature. It was observed that the tool wear increased sharply as the voltage increased. Tool wear was also directly proportional to frequency, duty cycle, and electrolyte concentration, but the speed has little effect on tool wear. The gas film formation time was significantly shortened with the increase in voltage, and the tool wear caused the gas film formation time to decrease.

Goyal [24] analyzed the consequences of practical voltage, dilution of electrolyte & gap between electrodes parameters in micro machining of ceramics using Electro Chemical Discharge Machining. It has been observed that the most significant result for MRR with reverse polarity was obtained at voltage 50 V, concentration of NaOH 20 M and a gap between electrodes of 40 mm. Also it can be observed that different concentrations of the electrolyte NaOH and gap between tool electrode and an auxiliary electrode have more effect on material removal rate MRR (mg/min) than voltage.

Palival *et al.* [25] analyzed a variety of process parameters involved in ECDM. It was concluded that the material removal rate, machining depth, accuracy etc get affected by various process parameters such as voltage, current, electrolyte concentration, feed rate, pulse duration etc. Electrochemical Discharge Machining was the distinguished method to fabricate micro holes, microgrooves, microchannel etc. ECDM proved to be one of the prestigious techniques, which ameliorated the surface quality of miniaturized components and also reduced the machining time.

Bravo *et al.* [26] Presented the three models using fuzzy logic, backpropagation network, and radial basis function network for the prediction of the material removal rate (MRR). The gap voltage (Vg), peak current (Ip), and frequency (f) were taken as input parameters. A 3-factor full factorial design was developed with 2 levels (23), two replicas, and four central points. The model with the higher accuracy according to experimental result was radial basis function artificial neural network with 97.25% of accuracy.Anderson Darling test with a probability value less than 0.05; based on the test, we could determine with a 95% confidence level that residuals of MRR (P=0.022) do not fit a normal distribution. The soft computing techniques used were considered that a model adequately predicts if the accuracy with respect to the experimental results would be more than 90%, which corresponds to an error of less than 10%. An accuracy of 90.67% was obtained with the proposed fuzzy model, which corresponds to a MAPE of 9.33% approximately. For the backpropagation ANN model, obtained accuracy was 89.50% which corresponds to a MAPE of 10.15%, while the results for the RBF model showed an accuracy of 97.25% which corresponds to a MAPE of 2.75%. It was observed that both fuzzy logic as artificial neural networks are a feasible option to model the ECDM process.

Tayade *et al.* [27] analyzed the feasibility of drilling micro-holes on Ti6Al4V by applying a Sequential Electro-Micro Machining (SEMM) process. A novel sequential combination of micro electro-chemical discharge machining (μECDM) and micro electro-chemical machining (μECM) was applied for drilling a micro-hole in titanium alloy (Ti6Al4V). The best-suited electrolyte for drilling by μECDM was selected by analyzing the hole depth, radial overcut, hole taper angle and the minimum time required to drill through holes in a 400μm thick sheet of titanium alloy. The electrolyte combination of 1M of NaNO3 and 1 M of NaCl was found suitable to machine Ti6Al4V using μECDM process, as it employed lower machining voltage with less machining time. The μECM process applied subsequent to μECDM process removed flaws such as the recast layer consisting of burrs, cracks, micro-pores in the heat affected zone and improved the surface quality of the hole. The μECDM process produces micro-holes rapidly but it consists of a recast layer, micro-cracks, and heat affected zone etc. The surface characteristics of a μECDMed hole were improved by applying μECM process subsequent to the μECDM process. The sequential combination of μECDM shaping and μECM finishing results in improved dimensional accuracy, machining depth, taper angle and surface quality of the hole produced by the sequential micro machining process.

Zao *et al*. [28] used a novel ECDM approach based on a non-Newtonian fluid electrolyte, i.e. the mixture of Polyacrylamide and KOH to improve the stability of the gas film. It was observed that compared to the traditional Newtonian fluid KOH electrolyte, the non-Newtonian fluid electrolyte significantly weakened the effect of the impact force on the gas film, and thus the gas film was more stable. It was also seen that stable electrochemical discharge and a lower critical voltage was achieved with a non-Newtonian fluid electrolyte and the condition for gas film was more thinner and stable than with the KOH electrolyte. With the non- Newtonian fluid electrolyte, the heat-affected zone and entrance overcut of the microchannel were both smaller than with the KOH electrolyte. It was concluded that using the non-Newtonian fluid electrolyte could be a simple and effective way to enhance the stability of gas film and thus, improve the micromachining performance of ECDM process.

Ho *et al*. [29] investigated the effect of addition of microbubbles with the use of hollow electrodes to absorb the processed slag and replenish the electrolyte during the processing. For glass processing, the processing time using micro-nano bubble electrolyte was 31% faster than the processing time using ordinary electrolyte. As for the current response for the first 20 s, the average current intensity increased by 26.7%. It was found that when using hollow electrodes, the time between the formation of a gas film and the generation of electric sparks in the way of replenishing the electrolyte is the shortest. The time of replenishing electrolyte was 34.5% faster than that of not replenishing. In addition, the thickness of the gas film was reduced by 54%.

Md. Rashdul *et al*. [30] investigated the influence of different electrode materials, namely titanium alloy (TC4), stainless steel (SS304), brass, and copper–tungsten (CuW) alloys (W70Cu30, W80Cu20, W90Cu10), on electrodes' electrical properties, and to select an appropriate electrode in the ECDM process. The material removal rate (MRR), electrode wear ratio (EWR), overcut (OC), and surface defects were considered as responses. Through the deep study and experiments it was noticed that electrical conductivity had the influence on MRR, whereas thermal conductivity had a greater impact on the EWR. As a result of higher conductivity, the discharge channel was formed as the electrical conductivity was increased and the discharge delay time was decreased, and the discharge energy emitted to the workpiece at the same time also increased, resulting in an increased MRR. The highest MRR of about 70 µg/s was obtained when the W70Cu30 electrode was used. Among all CuW electrodes W70Cu30 had lower EWR (8.1%) due to its very high thermal conductivity and so the heat produced during machining diffuses into the space, decomposing the electrolyte fluids' oxygen at a very high temperature, with some accumulating around the electrode, preventing further electrode erosion.

Paul *et al.* [31] observed that the MRR was increased gradually with an increase in electrolyte concentration due to chemical etching of the glass. With the increase of electrolyte concentration, the inter-electrode resistance between the tool and the auxiliary electrode decreased. This increased the chemical etching on the workpiece surface. The chemical etching rate increased with the concentration of the electrolyte. Higher concentration resulted in irregular shaped micro features due to lack of control of process. The experiment was conducted at a constant duty factor of 80% and a concentration of 25 wt.%. It was also observed that at lower applied voltage, the MRR was lower due to low spark intensity on the tool surface. When the voltage was increased, spark intensity was also increased. This would produce more heating effects on the tool-workpiece gap. Hence more material would get melted and vaporized which resulted in high MRR. It was noted that at lower voltage (below 30 V) no spark was produced instead only hydrogen bubbles were produced and MRR obtained for the discharge voltage below 30 V was insignificant. Also at higher voltage (above 45 V), sparks change to arc and only surface heating was produced without any material removal.

Rajput *et al*. [32] investigated the machining performance of the ECDM process during the machining of silica (Quartz) through establishing the optimum combination of the level of the parameters for multi-response parameters. MRR, HAZ, HT (high hole tapering), ROC (radial overcut), and CE (circularity error) were picked as response parameters. Results through Grey Relational Analysis (GRA) to identify the optimum levels of input process parameters for their combined fusion i.e. maximum MRR, minimum HAZ, minimum HT, minimum ROC, and minimum CE also analyzed. All responses increased with the increase in applied voltage and electrolyte concentration. Also it was concluded that electrolyte concentration (wt.%) was the utmost governing input parameter followed by applied voltage (V) and inter-electrode gap ((IEG), mm) for controlling the multi-response parameters simultaneously. Single response optimization suggested that applied voltage is the main dominating parameter for MRR and ROC while electrolyte concentration is the dominating parameter for HAZ, HT, and CE.

Kumar *et al.* [33] attempted to machine the hard-to-machine zirconia material on the developed ECDM set-up. The micro-holes were generated with varying the DC supply voltage, electrolyte concentration, and inter-electrode gap and analyzed the effect of ECDM parameters on machining performance, i.e. material removal rate, and overcut. The effects of machining parameters on machining responses were analyzed through different graphs. The experimental results revealed that the DC supply voltage and electrolyte concentration were the main governing factors in controlling the machining performance. The better material removal rate was identified at 65 V, 16 g/l electrolyte concentration, and 60-mm inter-electrode gap. The presence of iron (Fe) was identified from EDS (energy dispersive x-ray spectroscopy) analysis, and that could be due to the diffused part of the steel cathode adhering to the machined surface.

Bellubbi *et al.* [34] focused his study on the effect of mainly three parameters applied voltage, Electrolyte concentration and Machining time on the MRR. For the applied voltage it was noticed that with increase in applied voltage the intensity of sparking was increased causing high MRR. Similarly For the electrolyte it was observed that higher concentration of electrolyte caused increased chemical reactions and so increased gas bubbles in the sparking zone. It was further observed that with increased machining time MRR also increased but comparatively at a slower rate, this increase in MRR is due to increase in spark intensity and rate of chemical reaction with machining time.

Sadashiv *et al.* [35] worked on the machining of microchannel in silica glass. It was a successful attempt by considering Analysis of Means (ANOM) of ECDM process parameters. The experiments were planned using Taguchi's L9 orthogonal array with applied voltage, stand-off distance (SOD), electrolyte concentration (EC) and pulse on time (TON) as process parameters. The Material Removal Rate (MRR), Machining Depth (MD) and overcut (OC) were observed as output characteristics. Stand-off distance was found to be the most significant factor followed by pulse on time, applied voltage and electrolyte concentration from ANOVA. Confirmation test was performed by setting the optimum combination of process parameters and the predicted values from regression analysis exhibited a good agreement with experimental results.

Arab *et al*. [36] reported the effect of the gap between the tool and workpiece on depth of hole and electrode tool wear. It was observed that As the T-W gap was increased, the penetration in the workpiece due to the thermal energy of EC discharges was reduced. Ultimately, at a large T-W gap, no penetration was observed due to discharges, which led to negligible depths. The opening sizes of the micro hole were increased up to a critical TW gap and then reduced when the T-W gap was increased. It was also concluded that tool wear was reduced when the process was carried out at a higher T-W gap and with KOH electrolyte having lower concentration.

Harugade *et al*. [37] used ECDM to remove the delaminated fibers from carbon fiber reinforced epoxy composite. Two different approaches viz. top machining and inside machining were followed for this purpose. Process evaluation was done in terms of its ability to remove the delaminated fibers and the extent of thermal damage (heat affected zone and hole overcut) to the workpiece. It was reported that both approaches had considerable potential of removal of delaminated fibers precisely. In the process of removing laminates it was observed that the HAZ and HOC (hole overcut) increased with increased input voltage but there was an inverse relationship with the feed rate and tool rotation speed. With the combination of machining parameters as applied voltage 60 V, feed rate 1.5 mm/min, and tool rotation speed 1000 rpm minimum HAZ of 1.025 and 0.447 mm at the top and inside machining reported respectively.

Saini *et al.* [38] proposed some modification in the basic configuration of the ECDM process to increase the efficiency and developed basic understanding of the phenomenon of spark generation in ECDM process for the selection of a particular ECDM variant or triplex hybrid process for machining nonconductive materials. It was concluded that the hybridization triplex improved the productivity of the ECDM process. Ultrasonic vibration–assisted ECDM enhanced the flushing action at higher depth while machining and increased surface quality. The magnetic field–assisted ECDM process gave higher machinability due to uniform spark generation in the machining zone. Surface quality achieved up to nano level with the powder mixed ECDM process.

Mishra *et al.* [39] analyzed tool wear behavior of four different materials, i.e., brass, SS304, molybdenum, and tungsten, during fabrication of longer (>15 mm) and deeper (>200 μ m) array microchannels using multi-pass ECDM process. It was observed that the brass electrode's wear rate was relatively faster, and the line-array tool electrode became unusable for the ECDM process after 15 min of total machining time. The wear behavior of molybdenum and tungsten tool materials was similar and resulted in intermittent or no microchannels formation after 35 min of machining time. At the electrolyte-air interface, necking of the tips and subsequent breaking at different machining times was observed for the brass, molybdenum, and tungsten tool materials. Comparatively uniform tips height, microchannel depths, and negligible necking were observed for the SS304 tool electrode after 65 min of machining time. It was concluded that SS304 is a suitable tool material for fabricating longer and deeper array microchannels using the multi-pass ECDM process.

Charak *et al.* [40] reported the various methods using the same process i.e. electrode immersion depths but along with electrolytic stirring effects in ECDM are discussed. Keeping the voltage level beyond 53 V when the stirred the electrolyte the observed that there was increase in material removal. The surface finish improved with a stirring effect from 20 to 79%, mainly due to the flushing away of debris from the machining zone; which reduced the chances of re-cast layers being formed and helped to improve the process efficiency. The addition of stirring effect to the electrolyte along with proper immersion depths of the electrodes resulted in improvement of the process performance mainly the improvement in surface finish values up to around four times than the normal ECDM process. It was also observed that higher tool wear took place while using NaNO3 as compared to NaOH electrolytes.

Mallic *et al.* [41] analyzed the machining depth and surface roughness (Ra) using NaOH and KOH at the various ratio of concentration (wt.%) of these two electrolytes with varying voltage and frequency in forward as well as reverse polarity. Different shapes of micro-channel like Zig-Zag, 'Y' shaped were fabricated on silica glass by μ-ECDM process for utilization as a microfluidic device using automated spring feed and CAM-follower guided stainless steel (SS) micro-tool. The SEM analysis was performed to identify the micro-crack and uncut debris into the micro-channel. It was observed that Surface became rough due to the thermal effects in the machining zone when lower NaOH % was used at 55 V but as wt%. of NaOH increased it provided lower surface roughness and at NaOH : KOH :: 1 : 3 gave continuous surface finish when electrolyte concentration increased up to 25 wt%. It was observed that machining depth as well as surface roughness increased by increasing voltage, duty ratio and electrolyte concentration but after 55 V and 60% of duty ratio machining depth decreases. It was also observed that pulse frequency was inversely proportional to machining depth and achieved better machining depth at 600 Hz but it had less effect on surface roughness.

Paul *et al.* [42] performed the experiment to modify the micro features produced in ECDM machining with a sensor mechanism. The micro holes machined with a sensor mechanism had shown improvement in terms of circularity. Sensor devices provided higher MRR with reduction in ROC compared to without sensor setup. Working of the sensing device was based on tool electrodes, conducting material and LED. It was concluded that overheating on the side surface and re-solidification is reduced with sensor mechanism as machining is stopped once through hole is made in the specimen. And the most important conclusion was the voltage found to be the most influential factor in obtaining higher MRR with lower ROC.

Arya *et al*. [43] investigated the influence of deposition of the machined by-products on outcomes of the ECDM process at different parametric conditions. It was observed that continuous machining with ECDM formed the machining by products (i.e., sludge, debris, and salt), which critically lowered down the performance of the ECDM process after 8 min of machining owing to excessive deposition over the tool electrode. In case these by-products were deposited on the electrode tool that could alter the properties like the tool geometry, surface texture, and electrical properties, which overall reduced the process performance. It was also observed that higher applied voltage and electrolyte concentration caused more deposition during the processes. The EI-ECDM (injection ECDM) with controlled fresh electrolyte injection to the tooltip significantly reduced deposition rate.

Islam *et al*. [44] observed that there was a scope for study of Material removal rate of tool wear that means he studied about the various factors causing the tool wear as till now there were a few experiments and studies were done which was not enough for understanding of tool wear mechanism. It was observed that the mechanism by which the TWR became higher than the MRR was investigated from three important aspects: (i) type and concentration of the salt solution, (ii) pulse interval, and (iii) energy. Moreover, three processes were observed in the machining area when electrical discharge machining and electrochemical machining occur together: (i) spark discharge, (ii) ionic bombardment, and (iii) expansion of the plasma channel. These processes were investigated using experimental data and images. It was observed that the expansion of the plasma channel in the machining area was the key to the switch in the wear mechanism where the ratio of the TWR and MRR is higher than 1. The wear mechanism changed mainly because of the rapid expansion of the plasma channel. If the plasma did not expand, the TWR could still increase because of electron bombardment, but that would be momentary. During the bombardment, the TWR was higher than the MRR. When the plasma channel expanded, the TWR became very high and the MRR fell. However, the plasma channel produced a wide heat-affected area. Thus, a thick re-solidified layer formed around the hole drilled in the workpiece.

Ranganayakulu *et al*. [45] focused his study to overcome the problem of large radial overcut and insufficient electrolyte at depth as it was observed that material removal rate (MRR) decreased with the machining depth due to insufficient electrolyte at the tool tip. The radial over cut (ROC) was found at the entrance due to accumulation of electrolyte. A hybrid electrolyte (HE) of NaOH + 5% KOH was used and it was noticed that HE had low viscosity and high electrical conductivity compared to individual conventional electrolyte (CE). It was observed to increase in MRR and decrease in ROC (radial cut) and taper was also resulted with hybrid electrolyte due to its low viscosity and high electrical conductivity. It was also noticed to have a smooth machined surface texture with NaoH electrolyte and a feathery-like machined surface texture with Hybrid Electrolyte. Experiments were conducted with an in-house developed ECDM set-up integrated with a metal oxide semiconductor field effect transistor (MOSFET) assisted power module. A Simultaneous multi-response optimization technique using GTA and

DFA was implemented in ECDM. An increase in MRR and decrease in ROC and taper was obtained with hybrid electrolyte due to its low viscosity and high electrical conductivity.

Jain *et al*. [46] analyzed the effect of adding the Ultrasonic vibrations to ECDM process performance. Machining performance in terms of material removal rate (MRR), tool wear rate (TWR) and aspect ratio was improved with the help of ultrasonic assistance. It was suggested that different methods and measures be applied to tool and electrolyte-based solutions to enhance the efficiency of ECDM. The change in the tool shape and size was used to concentrate the energy at the bottom of the tool electrode and reduce the distance between tool and the workpiece. The surfactant mixed electrolyte was used to decrease electrolyte conductivity. Thus, It was easier to obtain a surface with less thermal distortion. The combined effect of magnetic field assistance to the tool and ultrasonic assistance to electrolytes can be used to provide more concentrated spark around the work-piece. The effect of tool immersion depth on current density around the tool electrode was seen to be limited by providing ultrasonic assistance and side insulation around the tool electrode.

Zhao. *et al*. [47] showed the influence of Power, Voltage and Frequency on hole processing efficiency, hole entrance diameter and hole depth. Four factors such as Voltage, Frequency of pulse, Power, Tool feed rate and rotational Speed were considered. It was observed that spark discharge energy increased with increased power supply, but it also caused an increase in entrance diameter with deteriorated surface. And with lower power frequency short time required for gas thickness layer formation but it also deteriorated and increased entrance diameter. Further it was also observed that increased power supply had increased surface roughness but showed an inverse relationship of surface roughness with frequency of power supply. However any apparent relationship was not observed with electrode rotational speed.

Sandhu *et al*. [48] analyzed fabrication of novel hybrid Zn/(Ag + Fe)-MMC using stir casting method and microstructural and mechanical properties of fabricated MMC specimens. Electrochemical Discharge Machining (ECDM) was employed for the μ-drilling on the fabricated MMC. The effect of ECDM process variables like supply voltage, peak current, pulse-on-time, pulse-off-time, feed rate and electrolyte concentration on material removal rate (MRR), overcut (OC) and tool wear (TW) were identified during µ-drilling. Experiments were performed based on the one factor-at-a-time approach. It was found that MRR had increased as supply voltage, peak current, pulse-on-time, feed rate, electrolyte concentration increased and decreased as pulse-off-time increased. Overcut was found to be increased with supply voltage, peak current and pulse on-time whereas it decreased with increase in pulse-off-time and feed rate. Minimum OC was observed at 15 wt % electrolyte concentration. TW increased as supply voltage, peak current, feed rate and electrolyte concentration increased. For pulse-on-time, TW initially increased up-to 3 µs and then decreased as pulse-on-time further increased. Using Scanning electron microscopy (SEM) it was observed that at maximum MRR condition, rough surface finish and ovality in µ-drilled hole were present. Whereas high circularity and uniform drilling attributes were obtained along the whole depth at minimum OC condition.

Bhargav *et al.* [49] investigated in-depth experimentation to generate micro channels on PMMA using an in-house developed micro Electrochemical Discharge Machining (µ-ECDM) system. The µ-ECDM process parameters used for the experimentation include voltage (V), electrolyte concentration (wt%), and duty factor (DF) (%). Experiments were designed at three levels of process parameters for the parametric study. The micro channels were machined on a 2.5 mm thick PMMA workpiece using a titanium tool of 0.7 mm diameter. The optical microscope images, along with SEM images, were used to characterize the machined channels. The machining characteristics such as material removal rate (MRR), tool wear rate (TWR), channel width, surface roughness (SR), and depth of the channel were studied using the process parameters. Individual response optimization was carried out using S/N ratios, but confounding of factors at different factor level settings was observed for each response. Therefore, to overcome this problem, multi-response optimization using the JAYA algorithm coupled with the multi-attributed decision-making (MADM) R-method had been adopted for maximizing MRR and depth of the channel and minimizing TWR, channel width, and surface roughness at single factor level settings. The findings show that with increment in tool rotation rate improved the MRR, TWR, and depth of the channel decreased the channel width and surface roughness. For minimization of TWR, the optimized parameters were 50 V, 15 wt%, and 50%DF, resulting in 3 μg/min. For minimization of channel width, the optimized parameters were 50 V, 20 wt%, and 40%DF, resulting in 728.3 μm. For minimization of SR, the optimized parameters are 50 V, 25 wt%, and 50%DF, resulting in 5.008 μm. For maximization of the depth, the optimized parameters were 70 V, 25 wt%, and 60%DF, resulting in 534.55 μm. The R-method (MADM) was used to find the best compromise among the non-dominated Pareto optimal solution that was obtained by the MOJAYA algorithm. The optimal process parameters thus obtained were 50.5844 V, 24.2885 wt%, and 54.6066% DF.

Torabi e*t al.* [50] analyzed the electrochemical discharge machining (ECDM) process to fabricate a microchannel on polydimethylsiloxane (PDMS). The effect of electrolyte concentration, rotational speed, feed rate, and machining voltage on the surface quality and surface roughness was investigated in the PDMS micromachining. It was observed that with increased machining voltage and electrolyte concentration, the MRR increased and the possibility of mechanical contact between tool and workpiece decreases. It was observed that when the machining voltage was increased from 38 to 42 V the channel cross-section also increased by nearly 40% and the surface roughness increased by 36% with increasing the voltage from 38 to 42 V. It was observed that by changing the rotational speed from 0 to 10,000 rpm, due to the reduction in the thickness of gas film, there was reduction in the side sparks and concentration of the sparks on the bottom of the tool, which reduced the surface roughness.

1.7 OBJECTIVES OF THE PRESENT RESEARCH WORK

From the review of past research work it is seen that a lot of theoretical and experimental works have been carried out for proper understanding of the basic process of micro-electrochemical discharge machining (ECDM) and also reveals the basic mechanism of material removal. Due to the recent advancement of the technology, new types of CNC controlled micro-ECDM machines are available which are also used by some researchers. But these machines are not only very costly but also very difficult to maintain. And there is still not any working model for electrochemical discharge turning operation. So there is a need to explore and develop some new techniques through various experiments for low cost of production of micro-features and other manufactured products.

Hence, the objective of the present research work concentrate on

I. To develop a ECDT set-up for grooving and turning of cylindrical workpieces.
II. To study the feasibility of operation on glass with the help of a developed ECD T setup.
III. To investigate micro-grooving on Glass rod by ElectroChemical Discharge Turning process and select the ranges of process parameters..
IV. To study and analyze the process parameters mainly voltage, electrolyte concentration and rotational speed of the workpiece on responses such as MRR and width of groove while turning a glass rod using ECDT set up.
V. To find out the optimum conditions for maximum MRR and minimum width of groove with help of ECDT during micro-grooving on glass using ECDT process.

Chapter: 2

2. OVERVIEW OF ELECTROCHEMICAL DISCHARGE TURNING PROCESS

Electrochemical Discharge Turning (ECDT) is an advanced machining process that combines the principle of electrochemical machining (ECM) that is Faraday's law of electrolysis and the principle of electrical discharge machining (EDM) that is repeated electrical discharge in the form of sparks to perform material removal operations on conductive as well as non-conductive materials. It involves the controlled application of electrical energy and electrochemical reactions to remove material and shape the workpiece. Ongoing research and development in ECDT focus on optimizing process parameters, tooling designs, and control systems to enhance machining efficiency, surface finish, and dimensional accuracy. ECDT could evolve as a promising technology for advanced turning applications, offering unique capabilities for challenging machining requirements.

2.1 FUNDAMENTALS OF ELECTROCHEMICAL DISCHARGE TURNING (ECDT) PROCESS

Like Electrochemical Discharge Machining (ECDM) the fundamentals of the Electrochemical Discharge Turning (ECDT) process are the same. In ECDT, a conductive tool electrode and a workpiece are immersed in an electrolyte solution. A voltage is applied between the tool electrode and the workpiece, creating an electrochemical cell. The electrolyte acts as a medium for the ion exchange and facilitates the electrochemical reactions.. ECDT utilizes controlled electrochemical reactions and localized sparks to remove material from the workpiece, resulting in the desired shape and surface finish.

Here are the key fundamentals of the ECDT process:

Electrochemical Reactions: ECDT relies on electrochemical reactions to dissolve the workpiece material. A conductive tool electrode is brought into close proximity to the workpiece, and an electrolyte is used as the medium for the electrochemical reactions to occur. By applying a controlled voltage between the tool electrode and the workpiece, electrochemical reactions take place, resulting in the formation of gas bubbles surrounding the tool electrode.

Electrical Discharge: In addition to the electrochemical reactions, ECDT utilizes localized sparks or electrical discharges between the tool electrode and the workpiece. These discharges generate high-energy pulses that aid in the material removal process. The sparks create localized heat, melting the material at the discharge site and causing it to be eroded or vaporized. The combination of electrochemical dissolution and electrical discharges results in efficient material removal.

Tool Electrode and Workpiece Configuration: The ECDT process involves the use of a conductive tool electrode and an auxiliary electrode having larger surface area. The tool electrode could be designed to have the desired shape and contour of the component to be machined. The workpiece is positioned in the electrolyte bath and interacts with the tool electrode during the machining process.

Electrolyte: The electrolyte serves as a medium for the electrochemical reactions to occur and formation of an insulating gas bubble layer. It helps to maintain a stable machining environment, cools the machining zone, and facilitates the transport of ions and debris generated during the process. The selection of the appropriate electrolyte depends on factors such as the workpiece material, machining requirements, and desired surface finish.

Process Parameters: Various process parameters need to be controlled and optimized for effective ECDT. These include the current and voltage applied, the rotational speed of the tool electrode, the gap distance between the tool electrode and the workpiece, and the composition and temperature of the electrolyte. The selection and adjustment of these parameters are critical for achieving the desired machining results, including material removal rate, surface finish, and dimensional accuracy.

The evolution of micro-ECDT has been driven by the demand for higher precision, better surface quality, and the ability to machine complex geometries in the micro and nanometer range. Advances in microfabrication technology have led to the development of micro-ECM and micro-EDM processes, which have been combined to create micro-ECDM.

In recent years, research has focused on optimizing the process parameters to improve performance of any machining method. This includes the development of mathematical models, response surface methodology, and Taguchi method based optimization techniques to optimize the process parameters. Future research may focus on the development of new tool and electrolyte materials, as well as the use of ECDT for new applications.

2.2 WORKING PRINCIPLE OF ELECTROCHEMICAL DISCHARGE TURNING (ECDT) PROCESS

The mechanism of Electrochemical Discharge Turning (ECDT) is the same as that of Electrochemical Discharge Machining (ECDM) process; the difference is only in the setup and shape of the workpiece. ECDT is a hybrid machining process that combines Electrochemical Machining (ECM) and Electrical Discharge Machining (EDM) techniques to achieve precise and complex shapes on conductive as well as non-conductive materials. In the ECDT process, an electrolyte is used as the medium to remove material from the workpiece.

The process involves the generation of bubbles due to the electrolyte decomposition caused by the applied electric field, which creates pressure on the surrounding electrolyte, leading to material removal. The process also involves the formation of electrical sparks between the tool and workpiece due to the high electric field intensity that results in localized melting and vaporization of the workpiece material. The combination of these two processes leads to efficient material removal with high accuracy and surface quality.

2.2.1 Bubbles Generation Mechanism

When a high potential difference is applied between two electrodes, here the tool and the workpiece which are kept at a few microns apart, gas bubbles start forming continuously at both the electrodes as shown by the Fig.2.1, this is because of the chemical action. These bubbles on the smaller electrode, which is nothing, but the cathode, collided to form a thin gaseous film on the tool, similar to the ECM process. Due to electrolysis effect, bubbles are released which help in initiation of the sparking. The chemical reactions at the larger electrode and the electrolyte interface that is at anode, is that the electrolyte invariably water will be present, and this water will get dissociate like H2O will be broken down to oxygen and nascent hydrogen, with the release of electrons. If there are two molecules of water, then 4 electrons will be released then OH ions that are present in alkaline solutions, which is a characteristic of any alkaline solution.

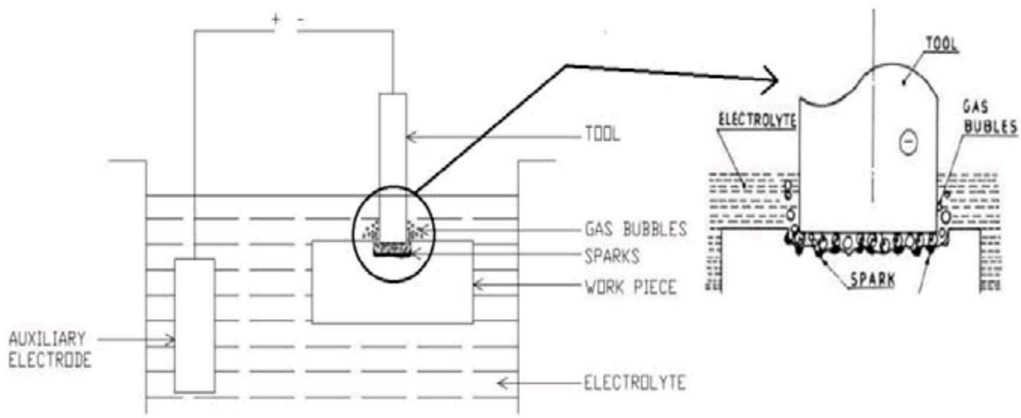


Figure.2.1. Bubble formation and sparking phenomena in ECDT

So, OH ions will be there, these OH ions will form continuously water, oxygen and it can release electrons again. Following chemical reaction is responsible for bubble generation when applied voltage reaches a certain point.

Reactions at anode (auxiliary electrode):

Dissolution of metal ions

$$M \text{ -------}\rightarrow M^{+} + e^{-}$$

Evolution of oxygen gas

$$2H_2O \text{ -------}\rightarrow O_2\uparrow + 4H^{+} + 4e^{-}$$

$$4(OH^{-}) \text{ -------}\rightarrow 2H_2O + O_2\uparrow + 4e^{-}$$

Reactions at Cathode (Tool):

$$M^{+} + e^{-} \text{------}\rightarrow M$$

Evolution of Hydrogen gas:

$$2H^{+} + 2e^{-} \text{------}\rightarrow H_2\uparrow$$

$$2H_2O + 2e^{-} \text{------}\rightarrow 2(OH^{-}) + \rightarrow H_2\uparrow$$

In the electrolyte solution the hydrogen will be there, and the electrons released from the electrolyte will combine with or will act on these water molecules, which will form the nascent hydrogen as well as the OH ions. These OH ions are responsible for forming the metallic hydroxides, this is the fall out of the reaction of or the action of the electrons available, in the electrolyte and with water they form these OH ions and hydrogen bubbles. And continuously this hydrogen ion and electron will continue to react together. This hydrogen bubble generation is basically responsible for the gas layer, or the bubble layer.

2.2.2 Spark Generation Mechanism

The gap voltage is applied across the tool electrode and workpiece; thus, the electric field is created in the gap between them. The electrode is then driven by a servo controller to reduce the gap distance leading to the increase of electric field.

As the voltage is increased, the bubbles grow in size and reach a critical size, which triggers the spark generation process as shown in Fig.2.2.

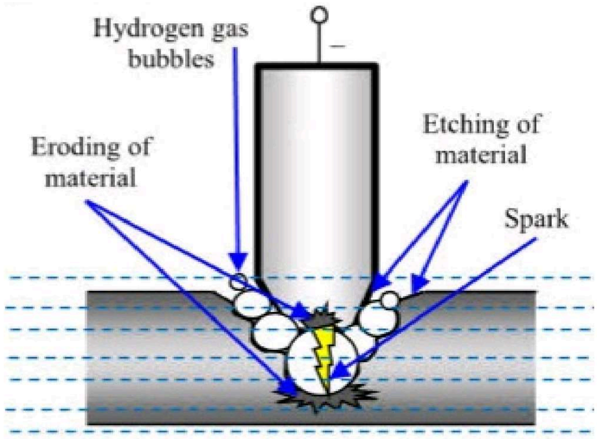


Fig.2.2 Bubble Generation and Sparking in ECDM Process

When the electric field is strong enough, the gas bubbles collapse, generating a high temperature and high-pressure plasma channel between the tool and the workpiece. This channel vaporizes the material from the workpiece surface and causes the material to be removed. The formation of these plasma channels and subsequent collapse of bubbles also causes the release of energy in the form of heat, light, and acoustic emissions. The process of spark generation, plasma channel formation, and material removal repeats itself several times per second, depending on the voltage, current, and other process parameters. As the gap meets the critical value, the electric field is stronger than the dielectric strength. There is then a breakdown of dielectric fluid and the spark occurs. The plasma column grows, within which the electrons move toward the anode and the positive ions move toward the cathode. When the electrons hit the anode and the positive ions reach the cathode, their kinetic energies are converted into heat. It is reported that extremely high temperature (8000–12 000 °C) is created in the plasma column [11]. The material is thus melted and vaporized. Besides, dielectric fluid is also evaporated forming dielectric gasses.

At the end of discharge, the plasma column disappears. The heated dielectric gas envelope collapses, ejecting material from the electrodes in the form of debris. A discharge the crater is thus formed on the machined surface. With the flushing of fresh dielectric fluid, the debris generated is carried away.

2.2.3 Material Removal Mechanism

The material removal mechanism in ECDT is complex and involves several physical and chemical phenomena. Since at a critical point, sparking occurs between the tool and the electrolyte. The material removal takes place when the workpiece is in the close vicinity of the sparks; this is due to the basic EDM phenomena, which is nothing but the sparking or the cavitation erosion and thermal removal of the material because of the EDM action. However, as soon as the sparking takes place and since this is not a continuous process, the gas layer will disappear momentarily and again the chemical action will take place and again the gas layer will be formed, and this will continue for further action. The tool is made of a conducting material and its cross section is smaller depending on the type of profile required. The other tool or the anode is usually larger in cross section and is dipped into electrolyte both the tools are connected to the complete circuit. Suitable fixtures are used for holding the work-piece in place. Once the parameters of current and voltage are set, and a suitable gap is established between the tool and the work-piece sparking begins.

The primary mechanism responsible for material removal in ECDM is electrochemical dissolution, which is similar to the mechanism in ECM. However, in ECDT, the electrochemical dissolution is enhanced by the application of electric discharge sparks. The sparks act as localized heat sources and cause localized melting of the material. This localized melting creates a thin and unstable surface layer on the workpiece, which is then removed by electrochemical dissolution. The material removal rate (MRR) in ECDM is influenced by several process parameters, such as applied voltage, electrolyte concentration, tool geometry, and spark frequency.

Thus, it is seen that both the chemical action due to ECM, as well as the thermal action due to the EDM are present in the ECDM mechanism. The MRR in ECDT is influenced by various process parameters, such as applied voltage, electrolyte concentration, tool geometry, and spark frequency. The mechanism is also affected by the tool wear, which is caused by the continuous erosion of the tool electrode.

2.2.4 Tool Wear Mechanism

During the process of ECDT, an electrically conductive or non-conductive workpiece is dissolved by the action of an electrolyte, and a spark is generated between the tool and the workpiece, which causes material to be removed from the workpiece. Tool wear in ECDT can occur due to several mechanisms which include:

Electrochemical wear: This occurs due to the dissolution of the tool material by the electrolyte. The extent of this wear depends on the tool material and the type of electrolyte used.

Thermal wear: The spark generated during ECDM can lead to high temperatures that can cause the tool material to soften, melt, and even evaporate. This can result in tool wear and degradation.

Mechanical wear: The repeated impact of the tool against the workpiece can cause mechanical wear, which can lead to chipping, cracking, and other forms of damage.

Chemical wear: The chemical reaction between the tool material and the electrolyte can cause chemical wear, leading to the formation of corrosion products and other compounds that can degrade the tool surface.

To minimize tool wear in ECDT, it is important to use a suitable tool material and geometry, optimize the machining parameters such as the electrolyte concentration, applied voltage, and pulse duration, and monitor the tool wear during the machining process. Additionally, the use of advanced tool coatings and lubrication can also help reduce tool wear and improve the overall performance of the process.

2.3 PROCESS VARIABLES IN ELECTROCHEMICAL DISCHARGE TURNING (ECDT) PROCESS

The selection of variables in the Electrochemical Discharge Turning (ECDT) process is crucial for achieving desired outcomes and optimizing the machining performance. There are several key variables that need to be considered and controlled during the ECDT process.

One of the primary variables is voltage, which determines the electric potential difference applied between the tool electrode and the workpiece. Voltage influences the discharge energy and material removal rate (MRR). The selection of voltage needs to strike a balance between achieving efficient material removal and avoiding excessive discharge energy that could lead to unwanted effects such as surface damage or tool wear.

Another critical variable is the current, which controls the intensity of the electrical current flowing through the ECDT setup. The current affects the discharge frequency and the heat generation within the machining zone. Adjusting the current can help regulate the material removal rate and control the temperature rise, as excessive heat can lead to thermal damage or even cracking of the glass rod.

Electrolyte composition is another variable to consider. The choice of electrolyte and its concentration influences the conductivity, chemical reactions, and dissolution characteristics during the ECDT process. Different electrolytes can have varying effects on the material removal rate, surface finish, and tool life. It is important to select an electrolyte that provides stable and controlled electrochemical reactions, while also considering its environmental impact and compatibility with the glass material.

The selection of these variables in ECDT is interconnected and must be carefully balanced to achieve the desired outcomes. Therefore, after a lot of trial experiments, discussions and based on previous research works the final variables for present research work are selected as applied voltage, electrolyte concentration and speed of rotation of the workpiece. Further, these parameters require a systematic experimental approach, to study the effects of varying these variables on the machining performance. Therefore, Optimization techniques are applied to identify the optimal range or combination of variables that result in better responses.

2.4 PERFORMANCE RESPONSES FOR ELECTROCHEMICAL DISCHARGE TURNING (ECDT) PROCESS

In electrochemical discharge turning (ECDT), several variable responses can be considered to evaluate and analyze the machining process. These variable responses provide valuable information about the performance and outcomes of the ECDT experiment. Here are some key variable responses that can be chosen:

Material removal rate (MRR): MRR represents the rate at which material is removed from the workpiece during the ECDT process. It is an important quality characteristic to assess the machining efficiency and productivity. Monitoring and analyzing MRR can help optimize the machining parameters and enhance material removal capabilities.

Surface roughness: Surface roughness is a crucial aspect of the machined surface and influences the functional and aesthetic quality of the workpiece. Evaluating the surface roughness parameter provides insights into the effectiveness of the ECDT process in achieving the desired surface finish.

Tool wear: Monitoring and quantifying tool wear is vital in assessing the tool life and performance during ECDT. Tool wear can affect the dimensional accuracy, surface finish, and overall machining quality. By examining tool wear, adjustments can be made to optimize tool life, reduce costs, and maintain consistent machining performance.

Material microstructure: ECDT can induce changes in the microstructure of the machined material due to the high-energy discharges involved. Analyzing the material microstructure, such as grain size, phase transformations, or recrystallization, provides valuable information on the effect of ECDT on the materials structure and properties.

Width of Groove: In modern time accuracy is the most demanding aspect to fulfill this objective there should not be any over cut during machining. For this during grooving the width of cut should be minimum or as exactly equal to the diameter of the tool for getting high accuracy.

The selection of variable responses in ECDT depends on the specific objectives of the experiment and the properties of the workpiece material. It is essential to choose appropriate measurement and analysis techniques to accurately quantify these variables and draw meaningful conclusions from the ECDT process.

2.5 RELATION BETWEEN PROCESS PARAMETERS & PERFORMANCE CRITERIA

The performance criteria in Electrochemical Discharge Turning (ECDT) are directly influenced by the process parameters. By adjusting and optimizing the process parameters, the performance criteria can be controlled and improved. Here are some of the key parameters and their relationship with performance criteria in ECDT:

Material Removal Rate (MRR): The material removal rate is a measure of the amount of material removed per unit of time. It is influenced by the applied current, voltage, and electrolyte conductivity. Higher current and voltage levels generally result in increased material removal rates. Additionally, a higher electrolyte conductivity can enhance the material removal rate by facilitating the electrochemical reactions. However, it is important to balance the material removal rate with other performance criteria to avoid excessive tool wear or surface damage.

Surface Finish: Surface finish is a critical performance criterion in ECDT, especially for applications where smooth and defect-free surfaces are required. The surface finish is influenced by parameters such as voltage, current, electrolyte composition, and tool electrode rotation speed. Lower voltage and current settings tend to produce finer surface finishes, while higher voltage and current can lead to rougher surfaces due to increased material removal.

Dimensional Accuracy: Dimensional accuracy refers to the ability to maintain precise dimensions and tolerances during the ECDT process. It is influenced by parameters such as voltage, current, gap distance, and tool electrode rotation speed. Controlling the voltage and current levels helps minimize thermal effects and ensure accurate material removal. Proper adjustment of the gap distance is crucial to maintain the desired tool-workpiece interaction and prevent excessive material removal. Additionally, optimizing the tool electrode rotation speed can contribute to better dimensional accuracy by promoting uniform material removal.

Tool Wear: Tool wear is an important consideration in ECDT as it can affect the process stability, surface finish, and dimensional accuracy. Tool wear is influenced by parameters such as current, voltage, electrolyte composition, and tool electrode rotation speed. Higher current and voltage levels can accelerate tool wear due to increased material removal rates and higher discharge energies. Using appropriate electrolyte compositions and concentrations, as well as optimizing the tool electrode rotation speed, can help mitigate tool wear and prolong tool life.

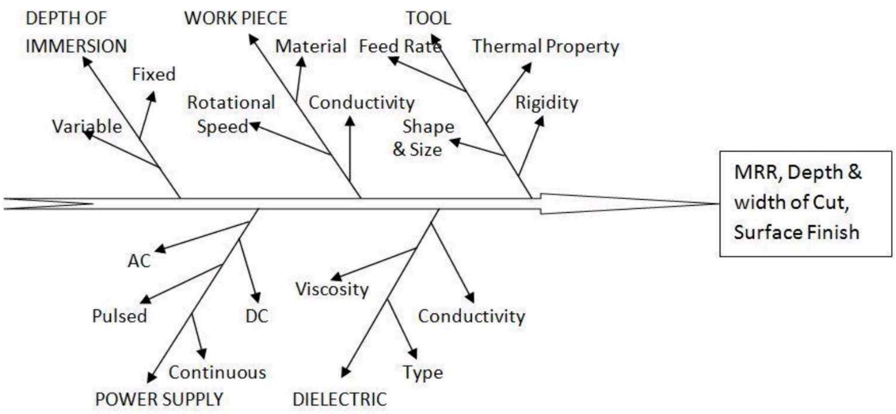


Fig:2.2. Cause And Effect diagram for ECDT Process

It is important to note that these relationships between process parameters and performance criteria may vary depending on the specific workpiece material, geometry, and machining conditions. Fig.2.2 shows the various process parameters and their possible effects. Optimization of the process parameters requires careful experimentation, analysis, and parameter tuning to achieve the desired performance criteria in ECDT.

Chapter: 3

3. EXPERIMENTAL SETUP DETAILS FOR ELECTROCHEMICAL DISCHARGE TURNING (ECDT) PROCESS

The experimental setup for ECDT involves several mechanical and electrical components, including a main machine chamber, a job holding and rotating unit, an auxiliary electrode unit, electrolyte supply system and a tool feeding arrangement.

To fulfill the objectives of present research work an indigenously designed set-up has been developed and the schematic diagram is shown by Fig.3.1 and photographic view is shown by Fig.3.2. The developed set-up consists of various sub-system discussed separately in later sections.

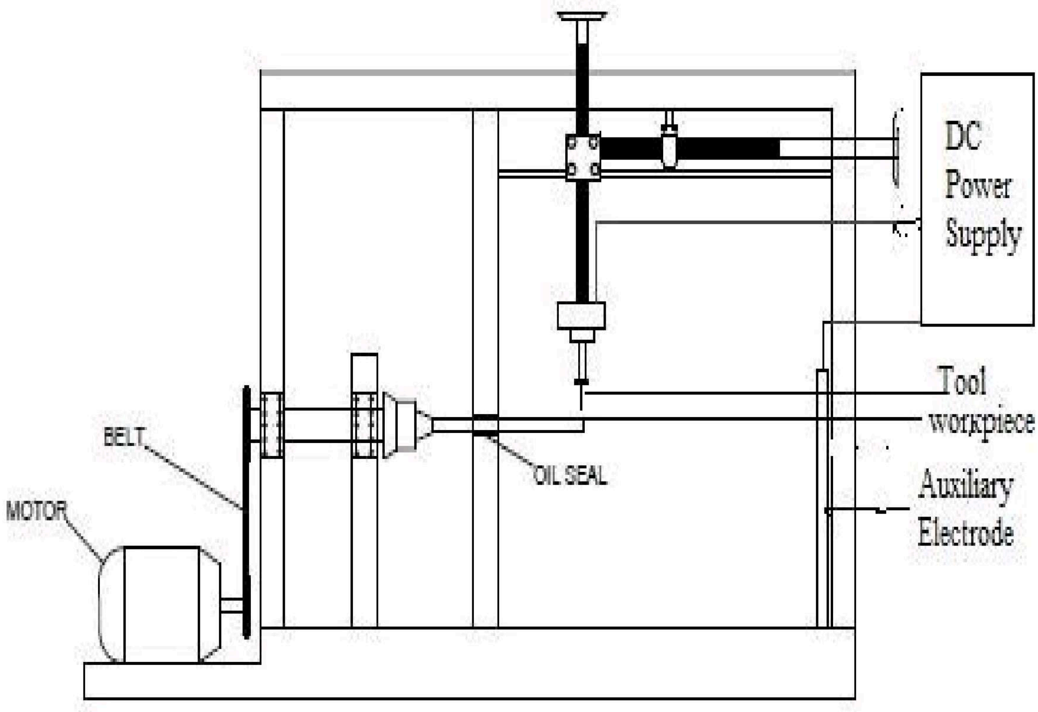


Fig.3.1. Schematic Diagram Of ECDT SETUP

The power supply and control unit may be provided the necessary electrical energy to generate the electrical discharges and control the process parameters such as voltage, current, pulse duration, and frequency. The ECDT setup could also include measuring instruments for getting the high efficiency and accuracy such as a digital multimeter, oscilloscope, and energy meter to monitor the process parameters and performance. The details of the ECDT setup vary depending on the specific experimental requirements. Proper safety precautions must be taken during the setup and operation of the ECDT machine due to the high voltage involved in the process.

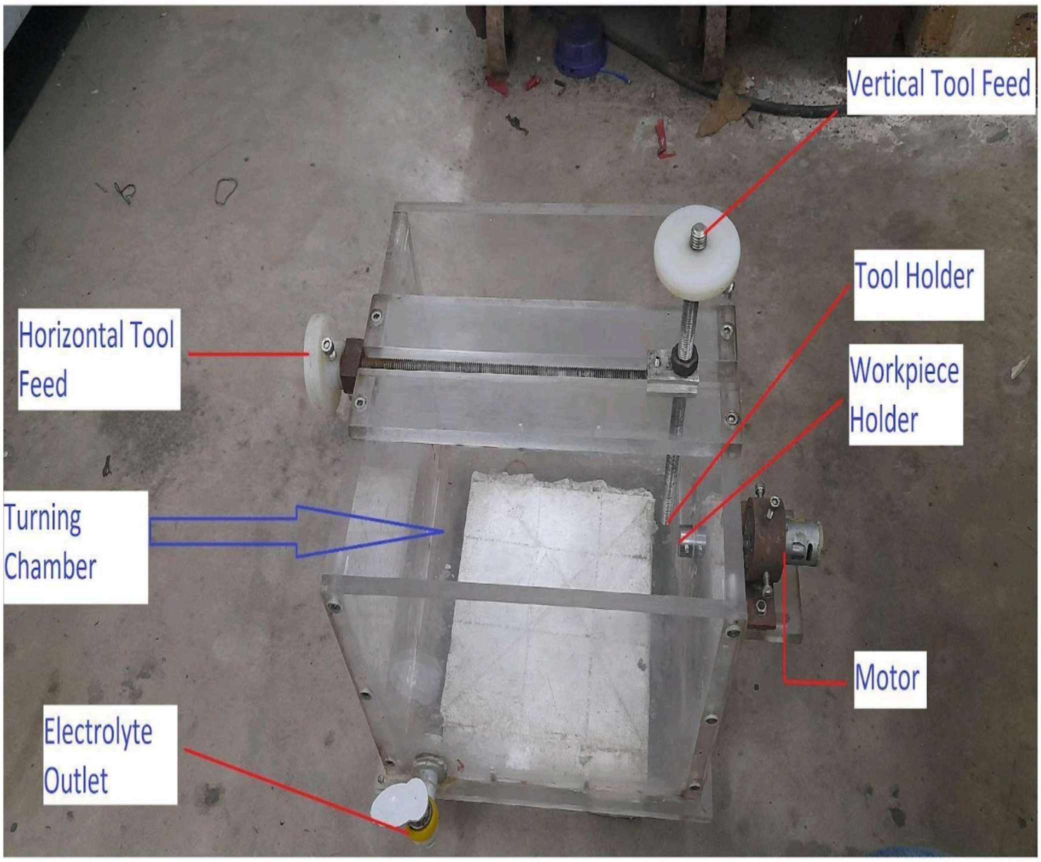


Fig.3.2 Photographic View of ECDT setup

The main machine chamber is made up of a non-conductive material such as acrylic or plastic photographic view is shown in Fig.3.2. The job holding and rotating unit holds the job securely in place and rotates it during the machining process.

The tool holding unit consists of the tool electrode, which is made up of a conductive material such as copper, brass, or tungsten, and is shaped according to the desired shape of the workpiece. The auxiliary electrode unit consists of a large area electrode mainly of graphite plate that is used to complete the circuit so that electric discharge and flow of ions can occur easily. The tool feeding arrangement is used to feed the job into the machining area at a controlled rate. The electrolyte solution is directly fed into the turning chamber. The electrolyte solution is a conductive solution that provides a path for the electrical current to flow between the electrodes. The power supply provides the electrical voltage necessary for the turning process.

The entire setup should be designed to operate under a controlled environment to ensure the accuracy and consistency of the machining process. Overall, the ECDM setup is a complex and sophisticated system that requires careful design and construction to achieve the desired machining results.

3.1 MECHANICAL HARDWARE SYSTEM

The mechanical hardware system for ECDT is an essential part of the process, and it comprises several components, including the main machine chamber, job holding and rotating unit, tool feeding unit, auxiliary electrode unit and electrolyte supply system.

3.1.1 Main Machine Chamber

The main machine chamber of an ECDT setup houses the main components of the machining system. The chamber is made of a non-conducting material Perspex which is resistant to corrosion and compatible with the electrolyte used in the machining process. The chamber is designed to accommodate the rotating workpiece, the tool, and the auxiliary electrode. The workpiece rotates in a horizontal axis and the tool lies in the vertical axis. Auxiliary electrode is kept at some distance from the workpiece within the chamber. The chamber is made in such a way to prevent the leakage of electrolyte during the turning process. The top side of the chamber is open by which electrolyte could be directly fed into the chamber and in the bottom side there is a valve to drain out the electrolyte after the turning process is completed. The size and shape of the chamber depend on the size and shape of the workpiece and the tool used in the machining process. The developed machining chamber have the dimension as 25*25*20 Cubic Centimeters. And the thickness of the side walls of the chamber is 1 CM. The total electrolyte requirement for carrying out the turning operation must be at least 5 liters.

3.1.2 Job Holding and Rotating Unit

The job holding and rotating unit is an important component of the ECDT setup that holds and rotates the workpiece during the machining process. The unit is designed to accommodate the workpiece securely and provide controlled rotational movement during the machining process. The unit can be driven by a motor or manually rotated. For rotation of the workpiece in the developed setup a motor is used having input voltage of 12 V to operate. The rotating speed and direction can be adjusted according to the machining requirements.

The material and design of the unit should be selected to ensure compatibility with the electrolyte used in the machining process and prevent any unwanted reactions between the workpiece and the unit.

Fig:3.3 Photographic view of workpiece holding device.

The loading and unloading of the workpiece could be done by the help of a Torx screwdriver used for tightening and loosing star shaped head screws as shown by the Fig.3.3. The design of the unit should also allow easy loading and unloading of the workpiece and facilitate quick changeovers between different machining setups.

3.1.3 Auxiliary Electrode Unit

The auxiliary electrode unit is an essential component of the ECDT setup. It consists of a graphite plate, which is mounted parallel to the machining electrode. The graphite plate of large surface area is used to increase the efficiency of the machining process as shown in Fig.3.4. The graphite plate, being an excellent conductor of electricity, provides a low resistance path for the hydrogen ions, thereby preventing the accumulation of hydrogen bubbles in the machining gap.

Moreover, the graphite plate also helps in reducing the electrical discharge gap between the machining electrode and the workpiece, which leads to a reduction in the machining time and improved surface finish.

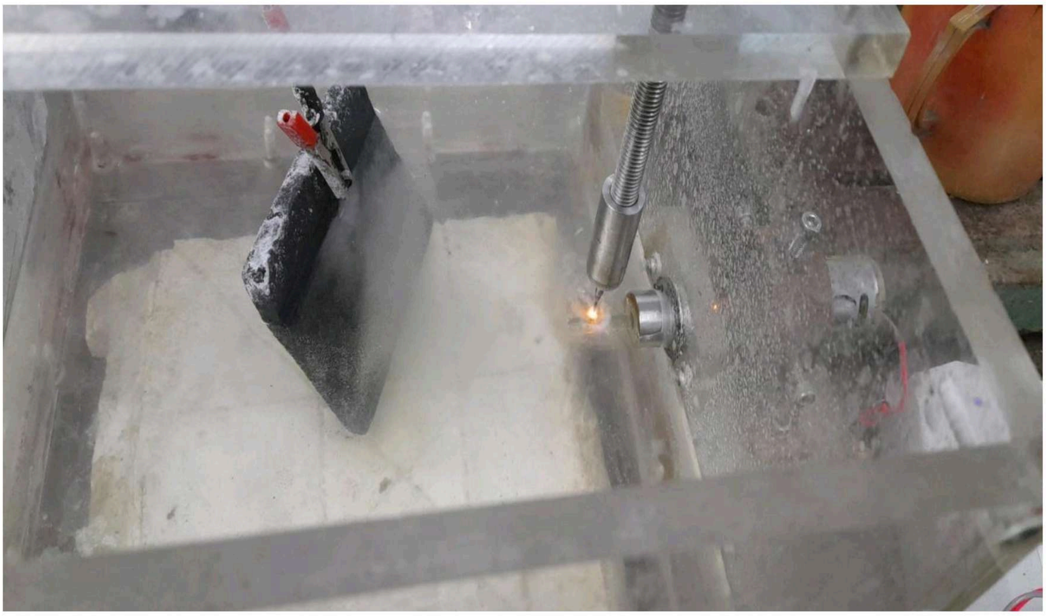


Fig:3.4 Photographic view of auxiliary electrode during turning

Overall, the auxiliary electrode unit plays a vital role in enhancing the machining performance and productivity of the ECDM setup.

3.1.4 Tool Feeding Arrangement

The tool feed arrangement in Electrochemical Discharge Turning (ECDT) is an important aspect of the machining process. It involves the controlled movement of the tool electrode relative to the workpiece to achieve desired material removal and shape generation. The tool feed arrangement in ECDT can vary depending on the specific setup and requirements of the machining operation. Here are some considerations for the tool feed arrangement in ECDT:

Axial Feed: In ECDT, the axial feed refers to the movement of the tool electrode along the axial direction of the workpiece. It determines the depth of cut and the amount of material removed during each pass. The axial feed can be achieved using various mechanisms such as manual adjustment, mechanical drives, or automated systems. The axial feed should be precisely controlled to ensure consistent and accurate material removal while avoiding excessive forces or vibrations.

Radial Feed: The radial feed in ECDT involves the movement of the tool electrode radially towards or away from the center of the workpiece. This feed is typically used to adjust the radial position of the tool electrode and control the cutting diameter. The radial feed can be achieved through mechanisms like slide adjustments, tool holders, or automated radial feed systems. Precise control of the radial feed helps achieve the desired dimensional accuracy and contour control during the turning process.

Feed Rate: The feed rate in ECDT refers to the speed at which the tool electrode moves relative to the workpiece. It determines the material removal rate and influences the surface finish and machining forces. The feed rate can be controlled manually or through automated systems. It is important to select an appropriate feed rate that balances the desired material removal rate with the limitations of the machining setup and the workpiece material.

The tool feed arrangement in ECDT should be carefully designed and controlled to achieve the desired machining objectives. It should consider factors such as dimensional accuracy, surface finish requirements, material removal rate, and the specific characteristics of the workpiece material. Optimal tool feed arrangements, along with appropriate feed rates and control mechanisms, contribute to efficient and precise turning operations in ECDT.

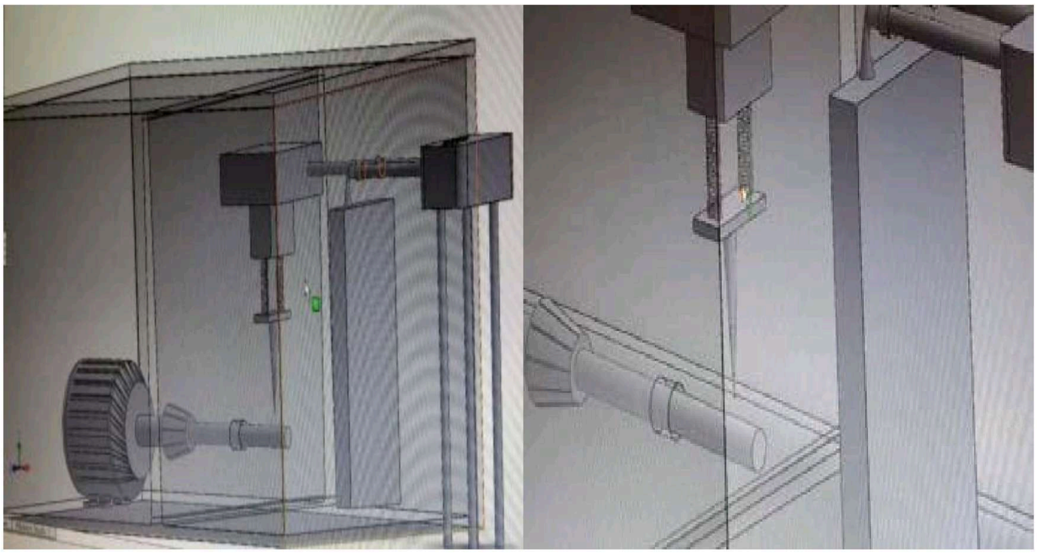


Fig:3.5. Isometric view of Tool And Workpiece holding devices

Therefore tool feeding arrangement for the developed setup has been done very carefully. The tool feed in the developed setup can be given in horizontal as well as vertical direction as shown by Fig.3.5. However the remaining axis of the tool should be adjusted by observation and kept fixed throughout the turning operation. For better control the feed should be automated but in the proposed set up we have used manual feeding.

3.2 ELECTROLYTE SUPPLY SYSTEM

The electrolyte supply system is a critical component of the Electrochemical Discharge Turning (ECDT) setup. The electrolyte is either circulated through the workpiece and the tool during the machining process or the workpiece and tool are submerged within the electrolyte depending upon the situations. The selection of the electrolyte is one of the important factors and hence while selecting the electrolyte the workpiece material and the desired quality after turning should be kept in mind. The electrolyte used in ECDM is typically a solution of sodium chloride/hydroxide or potassium chloride/hydroxide. The concentration of the electrolyte is an important parameter that affects the machining performance. In the developed setup the electrolyte is supplied directly by pouring the electrolyte into the turning chamber from above as the chamber is opened from top. And after completion of turning operation the electrolyte could be drained out by the valve installed at the bottom corner.

3.3 POWER SUPPLY AND CONTROL UNIT

The power supply and control unit is a crucial component of the ECDM setup. It provides the electrical energy required for the process to take place and controls various parameters such as voltage, current, and frequency. The power supply unit typically consists of a DC power supply that is capable of delivering required voltage as shown by Fig.3.6.

Various types of power supply units are available for ECDT applications, including pulse power supplies, DC power supplies, and AC power supplies. The power supply and control unit could consist of a power supply, a pulse generator, and a control panel.

Following Specification are for the Power supply used for desired outcome during turning:

Voltage : 0-200 V

Current : 0-10 A

Frequency: 50 Hz

Duty Ratio: 0.5

Input Voltage: 0-415 V, 3 Phase AC

Fig:3.6 Photographic View of Power Supply Unit

The control unit is responsible for regulating the input voltage and current and controlling the pulse frequency and duration. It also monitors the system for any faults or errors and alerts the operator if necessary. The pulse generator generates a series of pulses that are used to control the rate of material removal. Pulse power supplies are commonly used for ECDM applications because they allow for precise control over the electrical discharge and can generate high peak currents for short duration. DC power supplies are suitable for low-current applications, whereas AC power supplies are used in applications that require high-frequency pulsing. The selection of the power supply and control unit should be made based on the specific application and the requirements of the ECDM setup. For our experimental purpose it is chosen based on the availability and feasibility and also the requirements for fulfilling the decided objectives.

In the Electrochemical Discharge Turning (ECDT) process, a rectifier transformer is often used to convert the input AC voltage to the required DC voltage for the electrochemical machining operation. The rectifier transformer plays a crucial role in providing the necessary power supply to the ECDT setup. Here are some key points regarding the rectifier transformer in ECDT:

Voltage Conversion: The rectifier transformer converts the standard alternating current (AC) voltage from the power source into direct current (DC) voltage. ECDT typically requires a low voltage and high current DC power supply for the electrochemical reactions and electrical discharges to occur effectively.

Rectification: The rectifier transformer includes a rectification circuit that rectifies the AC input voltage. The rectification process involves converting the sinusoidal AC waveform into a unidirectional current waveform, which is essential for the ECDT process. The rectification circuit can use diodes, thyristors, or other semiconductor devices to achieve the rectification.

Voltage Regulation: The rectifier transformer may include voltage regulation features to maintain a stable DC output voltage. Voltage regulation ensures that the DC voltage supplied to the ECDT setup remains within the desired range, even when there are variations in the input AC voltage or fluctuations in the load.

Current Capacity: The rectifier transformer is designed to handle the required current capacity of the ECDT process. The current capacity is determined by factors such as the material removal rate, electrode configuration, and the size of the workpiece. The rectifier transformer should be capable of delivering the necessary current without overheating or causing voltage drops.

Isolation and safety: The rectifier transformer provides electrical isolation between the power source and the ECDT setup, ensuring safety for the operators and preventing any electrical hazards. It isolates the DC output from the input AC voltage and provides protection against electrical shock and short circuits.

Transformer Cooling: Depending on the power rating and duty cycle of the ECDT process, the rectifier transformer may require cooling mechanisms such as oil or air cooling to dissipate the heat generated during operation. Proper cooling helps maintain the transformer's temperature within acceptable limits and ensures its reliability and longevity.

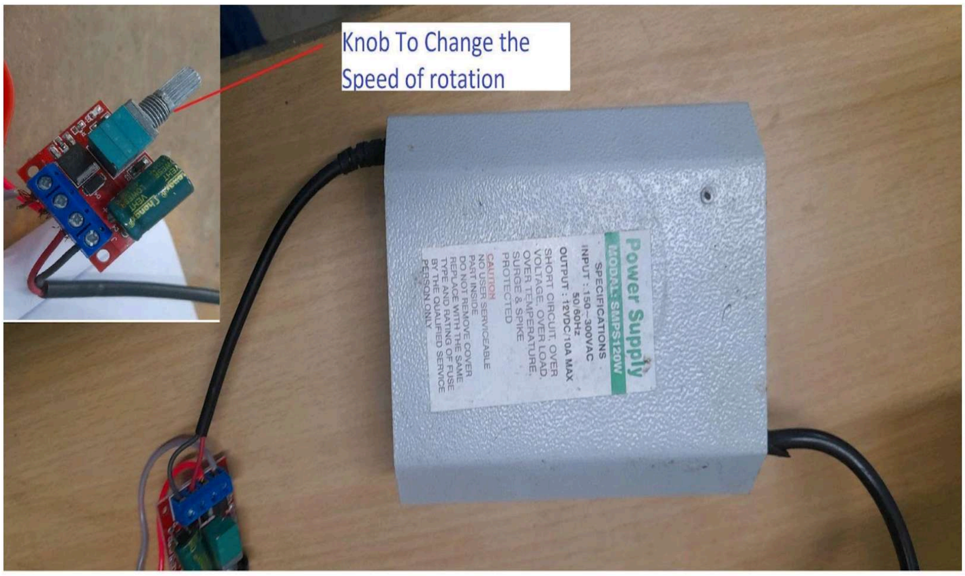


Fig.3.7 Rectifier Transformer and Speed of Rotation of Workpiece Controller

It is important to select a rectifier transformer that meets the specific voltage and current requirements of the ECDT process. The transformer should be designed to handle the expected load conditions, provide stable DC output voltage, and ensure electrical safety. Consulting with electrical engineers or specialists in power supply systems can help in selecting the appropriate rectifier transformer for ECDT applications. And the most important thing is that the power supply and control unit should be selected based on the requirements of the specific ECDM application and the capabilities of the machine. The Fig.3.7 shows the rectifier transformer used for the turning operation in the developed ECDT setup which has specifications as follows:

3.4 TOOL DEVELOPMENT

Tool development for ECDM involves designing and fabricating the tool electrode, which is the cathode in the process. The tool electrode is responsible for generating the electrical discharge without wearing out or with minimum wear. The electrode material must have high electrical conductivity, high thermal conductivity, and good wear resistance to withstand the high current density and high temperatures generated during the process.

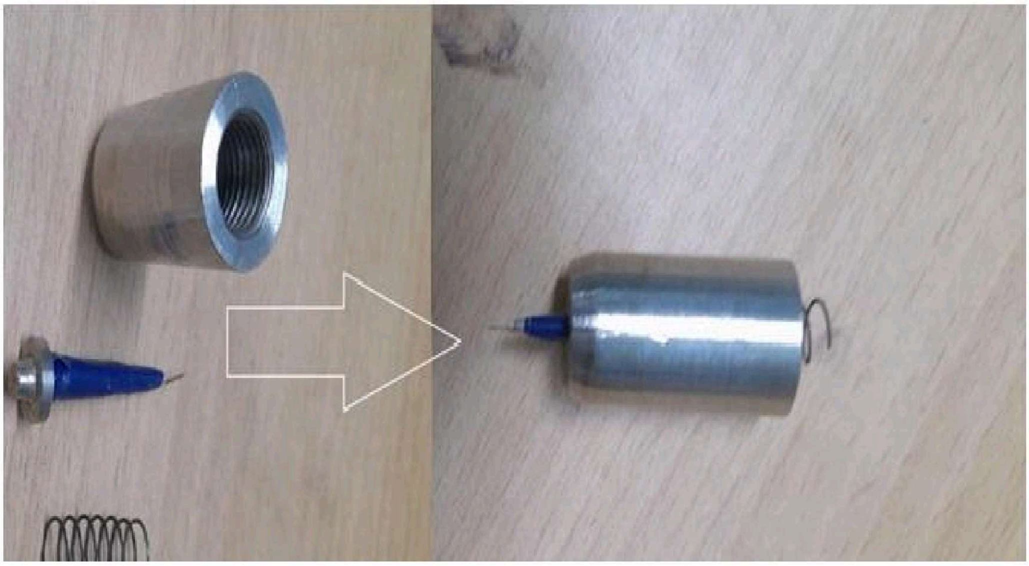


Fig.3.7 Tool and Its assembling

The commonly used tool electrode materials in ECDM are copper, brass, tungsten, and graphite. But for the present research work Copper Tool is used since in trial experiments copper and stainless steel tools were used and it was observed that copper tool wears less compared to Stainless steel tool, and also copper tool is easily available. Fig.3.7 shows the tool fixing arrangement by the help of spring. The tool electrode is shaped and dimensioned based on the specific machining requirements such as the desired shape, size, and surface finish of the workpiece. Based on the workpiece material and required level of accuracy and precision, geometry of the tool electrode is selected as of cylindrical shape of dia 270µm.

Chapter: 4

4. MATERIALS AND METHODS

Although, there are a number of methods for turning of conductive materials, but for the turning of nonconductive materials there are a limited number of methods and also they have some limitations. ECDT has a good scope for the turning of nonconductive, brittle material therefore present research work and its feasibility is investigated. Planning for a research work involves several key steps to ensure a systematic and successful execution of the project. Such steps are discussed in the upcoming sections.

4.1 SETTING OF PROCESS PARAMETERS

A series of experiments are conducted to arrive at an understanding. This is achieved by careful observation of the measurements after every experiment so that analysis of observed data will give the scope to evaluate what to do "which parameters should be varied and by how much" to achieve the desired results. Trial Experiments were conducted a number of times to observe all the variables, responses and their relationship for the turning process.

After careful observation of the results obtained in trial experiment following ranges of process variables as given in Table 4.1 is selected for conducting the experiments:

Table 4.1 Machining parameters and their Level

Factor	Level of Factors		
	1	2	3
1. Voltage (V)	35	40	45
2. Electrolyte Concentration (% by wt)	10	15	20
3. Speed of Rotation of workpiece (RPM)	20	30	40

4.2 PLANNING AND PROCEDURE FOR EXPERIMENT

After going through a lot of past research work it is revealed that the most influencing process parameters in ECDT are applied voltage, Electrolyte concentration and speed of rotation of the workpiece. The present research work attempts to make investigations of micro-ECDT characteristics such as material removal rate (MRR), width of cut of groove during turning of glass. During turning Applied voltage, Electrolyte concentration and speed of rotation of the workpiece will be considered as the process parameters during experimentation.

4.2.1 Selection of process Parameters

The selection of process Parameters in the ECDT (Electrochemical Discharge Turning) process is crucial for achieving desired outcomes and optimizing the machining performance. There are several key variables which we have seen in previous sections. After considering various factors applied voltage, electrolyte concentration and speed of rotation of the workpiece is considered as the process parameters for the proposed grooving operations.

The applied voltage which determines the electric potential difference applied between the tool electrode and the workpiece. Voltage influences the discharge energy and material removal rate (MRR) and width of groove. The selection of voltage needs to strike a balance between achieving efficient material removal and avoiding excessive discharge energy that could lead to unwanted effects such as surface damage or tool wear.

Electrolyte composition is another parameter considered for grooving. Electrolyte and its concentration influences the conductivity, chemical reactions, and dissolution characteristics during the ECDT process. Different electrolytes can have varying effects on the material removal rate, surface finish, and tool life. For the present research NaOH is selected as an electrolyte as it provides stable and controlled electrochemical reactions, while also considering its availability and compatibility with the glass material.

Speed of rotation by which the workpiece rotates during the grooving process is the third considered factor which could affect the material removal rate and width of groove. As fast as the workpiece will rotate the tool has less time of effective contact and hence less material will be removed and there will also be less width of groove as observed during the trial experiment.

4.2.2 Selection of Responses

In electrochemical discharge turning (ECDT), several variable responses can be considered to evaluate and analyze the machining process. These variable responses provide valuable information about the performance and outcomes of the ECDT experiment. Here are some key variable responses that can be chosen:

Material removal rate (MRR): MRR represents the rate at which material is removed from the workpiece during the ECDT process. It is an important parameter to assess the machining efficiency and productivity. Monitoring and analyzing MRR can help optimize the machining parameters and enhance material removal capabilities.

Width of groove during turning is another process parameter considered mainly during the grooving operation as if there is more overcut then accuracy could not be attained. It is desired that the width of the cut is equal to the diameter of the tool.

The selection of variable responses in ECDT depends on the specific objectives of the experiment and the properties of the workpiece material. It is essential to choose appropriate measurement and analysis techniques to accurately quantify these variables and draw meaningful conclusions from the ECDT process.

4.2.3 Selection of Workpiece Material

The selection of workpiece material for ECDT is dependent on various factors such as the application, required surface finish, material properties and the most important conclusion could be drawn from the research reviews as it was concluded that there are a lot of conventional and unconventional machining methods for conducting metals like aluminum, copper, titanium, and their alloys, as well as semiconductors such as silicon and germanium. But there are difficulties while machining nonconducting material as there are no completely developed methods which can be used for machining of such hard and brittle materials. The material's mechanical properties, such as hardness, toughness, and ductility, can also affect the process parameters and tool wear.

The selection of the workpiece material in machining processes, including Electro Chemical Discharge Machining (ECDM), is a critical factor that directly impacts the machining performance and outcome. For selection of material consider the intended application of the machined component. Thus, keeping in mind the difficulties arising during the machining of non-conducting materials and the applications of glass; the glass is selected as the workpiece for carrying out the experiments.

Properties of Soda Lime Glass:

Soda-lime glass is the most common commercial glass. It is comparatively inexpensive and amenable to recycling. A typical composition of this glass is 70–75 wt% SiO2, 12–16 wt% of NaNa_2O, and 10–15 wt% CaO . A small percentage of other reagents can be added for specific properties and application requirements. The principal addition in this type of glass, other than silica (SiO_2), is sodium oxide or soda (Na_2O). Even though sodium oxide contains oxygen atoms, it is held together by ionic rather than covalent bonds. The sodium atoms in the mixture donate electrons to the oxygen atom, producing a mixture of negatively charged oxygen ions and positively charged sodium ions. The oxygen atom with an extra electron binds to one silicon atom and does not form a bridge between pairs of silicon atoms. Therefore, the melting temperature of the mixture is considerably reduced (Bloomfield, 2001). Relatively high amount of alkali content in the glass also causes an increase of the thermal expansion coefficient by about 20 times (Pfaender, 1996). Since sodium ions are so soluble in aqueous solution, calcium oxide (CaO) is added to the mixture to improve its insolubility. Soda-lime glass is produced on a large scale and used for bottles, drinking glasses, and windows. Its light transmission properties, as well as low melting temperature, make it suitable for use as window glass. Its smooth and non-reactive surface makes it excellent as containers for food and drinks. Nowadays recycled glass, also known as cullet, is used to make green glass, which helps to save energy and reduce emissions.

4.2.4 Selection of Tool Electrode

The selection of a tool electrode for electrochemical discharge turning (ECDT) is an important aspect to ensure efficient and effective machining. Here are some considerations for selecting a tool electrode for ECDT:

Conductivity: Like the workpiece material, the tool electrode should also be conductive to enable the electrochemical discharge machining process. Common choices for tool electrode materials include copper, graphite, or tungsten.

Material compatibility: Consider the compatibility between the tool electrode material and the workpiece material. The tool electrode should be chemically stable and not react excessively with the workpiece material or the electrolyte used in the ECDT process. Compatibility can help prevent electrode wear or contamination of the workpiece.

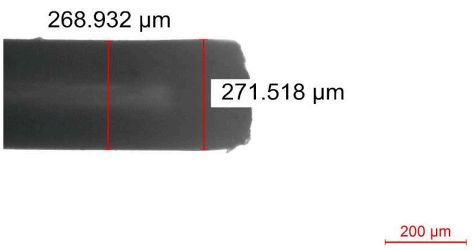
Machining objectives: Determine the specific objectives of your ECDT experiment. Different tool electrode materials can offer varying machining characteristics, such as material removal rate, surface finish, and tool life. Choose a tool electrode material that aligns with your desired machining objectives.

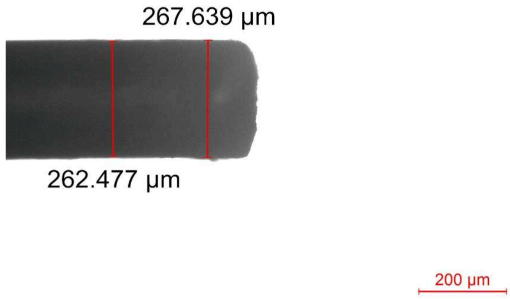
Wear resistance: Evaluate the wear resistance of the tool electrode material. ECDT involves high-energy discharges, which can subject the tool electrode to wear and degradation over time. Select a tool electrode material that exhibits good wear resistance to ensure longer tool life and consistent machining performance.

Thermal conductivity: Consider the thermal conductivity of the tool electrode material. Efficient heat dissipation is crucial during ECDT to control the temperature rise at the machining zone. Tool electrodes with higher thermal conductivity can help dissipate heat effectively, preventing thermal damage to the workpiece.

Cost and availability: Take into account the cost and availability of the tool electrode material. Some materials may be more expensive or less readily available, which can impact the feasibility of using them as tool electrodes for ECDT.

Based on relevant literature, research papers in the field of ECDT and on the basis of trial experiments it was concluded that copper has better performance and less tool wear when compared to Stainless steel as shown by Fig.4.1.





(a) (b)

Fig.4.1 Microscopic view of Tool: (a) Before Grooving (b) After Grooving

4.2.5 Selection of electrolyte

The selection of the electrolyte in ECDT is a crucial factor that can significantly affect the machining performance and results. The choice of electrolyte depends on several factors, including the type of material being machined, desired machining characteristics, and process parameters. Here are some considerations for the selection of an electrolyte.

Conductivity: The electrolyte should have good electrical conductivity to facilitate the flow of current between the workpiece and the tool electrode. High conductivity ensures efficient material removal and a stable machining process.

Chemical Compatibility: The electrolyte should be chemically compatible with both the workpiece material and the tool electrode. It should not react excessively with the workpiece, tool electrode, or other components of the machining setup, which could lead to unwanted side effects or deterioration of the tool.

Material Specificity: Different electrolytes may be more suitable for specific materials. Consider the compatibility of the electrolyte with the workpiece material in terms of its ability to effectively dissolve or react with the material. For example, for machining steel, an acidic electrolyte like sulfuric acid or sodium chloride solution may be appropriate.

Machining Characteristics: The electrolyte choice can influence the machining characteristics, such as material removal rate, surface finish, and dimensional accuracy. Some electrolytes may offer faster material removal rates but produce rougher surface finishes, while others may provide finer finishes but at slower rates. Consider the desired machining outcomes and select an electrolyte that aligns with those requirements.

Environmental and Safety Considerations: Take into account the environmental and safety aspects of the electrolyte. Some electrolytes may contain toxic or hazardous components that require proper handling, disposal, or regulatory compliance. Consider the impact on operator safety, waste management, and environmental regulations when selecting an electrolyte.

Availability and Cost: Consider the availability and cost of the electrolyte. Ensure that the selected electrolyte is readily available in the required quantity and at a reasonable cost, considering the scale and duration of your machining operations.

On the basis of preliminary testing and review of past research performance of using different electrolytes for the machining process were analyzed. During the trial experiment KOH and NaOH electrolyte were used but any significant differences could not be established by observation after turning operation. However ,it was observed that NaOH gave the satisfactory result and was also easily available, therefore considered as electrolyte for the present research work.

4.3 DESIGN OF EXPERIMENT

In order to assess the effect of each machining parameter on the process, the Taguchi approach was used. This method is a type of statistical technique called Design of Experiments (DOE) that makes it possible to analyze the effect of more than one factor at the same time while reducing the number of experiments. Thus, using the Taguchi approach, the design of experiments and analysis of results can be done with less effort and expenses. However, since the method considerably reduces the number of experiments, quality loss of results could appear. Design of Experiments (DOE) is a statistical methodology that plays a crucial role in optimizing process parameters and understanding the relationship between variables in the ElectroChemical Discharge Turning (ECDT) process. DOE allows researchers to efficiently explore the parameter space, identify significant factors, and determine optimal parameter settings for achieving desired machining objectives.

In the context of ECDT, DOE helps in investigating the effects of various process parameters, such as voltage, electrolyte concentration, and workpiece rotational speed on output variables like material removal rate (MRR), and dimensional accuracy. By using DOE, researchers can systematically vary and control these parameters to understand their individual and combined effects on the performance measures.

The application of DOE in ECDT offers several advantages. It enables researchers to identify the key process parameters affecting the machining performance and understand their individual and combined effects. By optimizing these parameters, researchers can improve the efficiency, quality, and precision of the ECDT process. Furthermore, the structured approach of DOE minimizes the number of experiments required, reducing the time and cost associated with the experimental study.

In summary, DOE is a valuable tool in the design and optimization of the ECDT process. By using factorial designs, response surface methodology, and statistical analysis techniques like ANOVA, we can efficiently explore the parameter space, identify significant factors, and determine optimal parameter settings for achieving desired machining objectives. Also DOE enables us to gain insights into the ECDT process, improve performance, and enhance the overall efficiency of the machining operation.

4.3.1 Taguchi Method for S/N ratio analysis

The Taguchi method is a powerful statistical technique used in experimental design and optimization. It was developed by Genichi Taguchi in the 1950s and has been widely applied in various fields, including manufacturing, engineering, and quality control. The method aims to improve the quality and performance of products or processes by systematically optimizing the design parameters while considering the effects of noise factors.

Taguchi method has widely been used for experimentation analysis and development of product or process. In robust design, Taguchi philosophy of orthogonal erase determines the effects of various process parameters efficiently. The treatment of the experimental results has been carried out based on the analysis of signal to noise ratio (S/N). The orthogonal array of Taguchi method is adopted to reduce the number of experiments in order to save time and cost.

Table 4.2 Variable machining parameters and their Levels

Machining Parameters	Level 1	Level 2	Level 3
Voltage	1	2	3
Electrolyte Concentration	1	2	3
Speed of Rotation	1	2	3

In the present study the interaction between the machining parameters is not considered. It is concluded that at least 9 experiments are to be conducted to estimate the effects of each machining parameter. The chosen standard orthogonal array was the L_9 that has nine rows corresponding to nine experiments. It has three factors at three levels. On the basis of input factors and mixed levels nine experiments have been conducted. Table 4.2 and 4.3 show the level of various process parameters and the total experimental layout according to orthogonal arrays (L_9) of Taguchi method respectively.

For precision manufacturing, the objective is to minimize the actual value of performance characteristics which smaller value indicates the better machining performance and it Is addressed as “smaller the better” type problem. Similarly the actual value of performance characteristics, which higher value indicates the better turning performance and it is addressed as “higher the better” type problem. This minimization of quality losses is equivalent to maximization of signal to noise ratio (S/N ratio).

Table 4.3 The experimental layout of orthogonal arrays (L_9) by Taguchi Method

Exp. No	Voltage	Electrolyte Concentration	Speed of Rotation
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

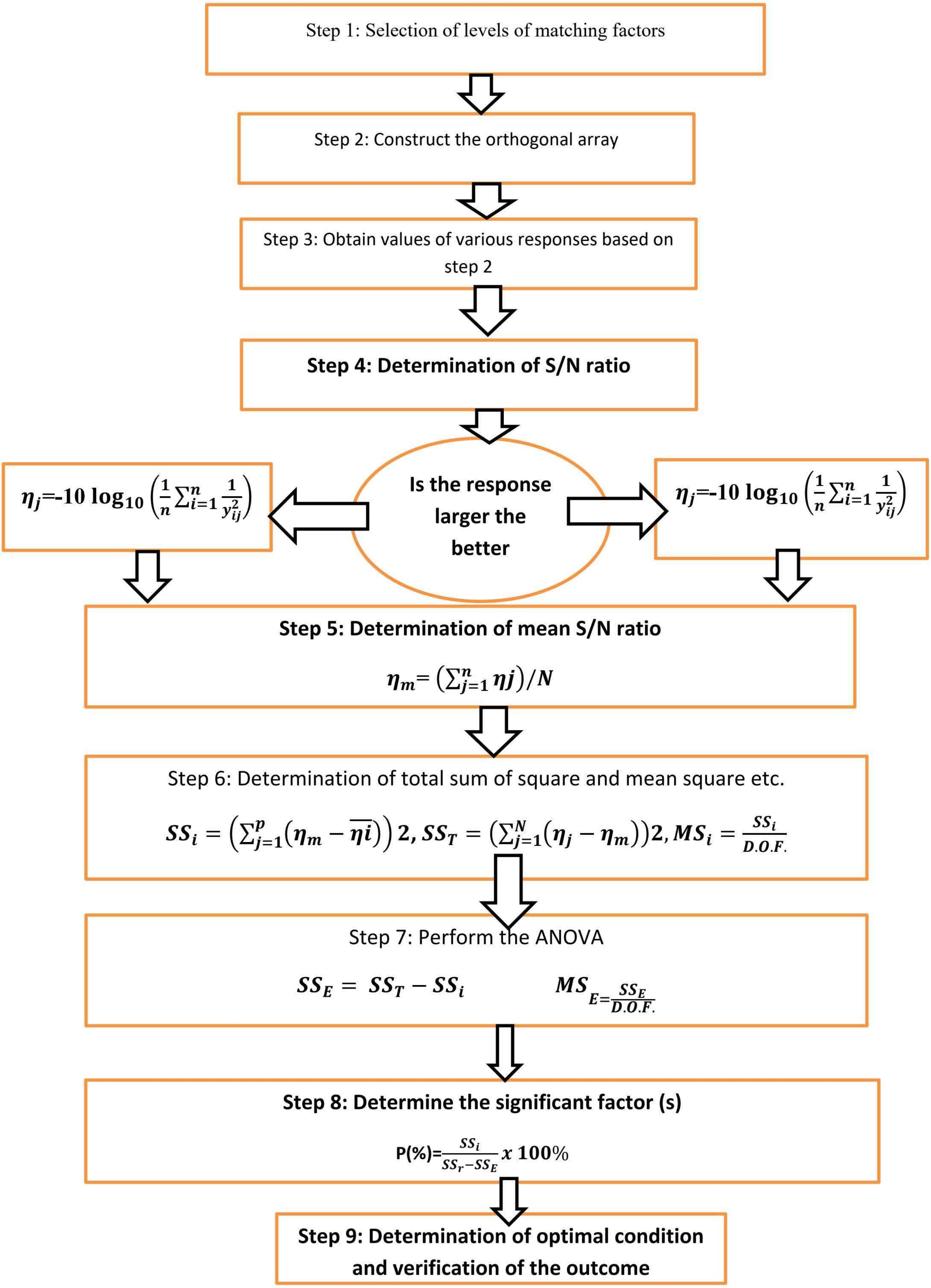
In order to obtain optimal machining performance the "larger-the-better" quality characteristics, the S/N ratio for responses for jth experiment is defined as

$$\eta_j = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^2}\right) \qquad \text{Eq.4.1}$$

Similarly, in order to obtain optimal machining performance the "smaller-the-better" quality characteristic, the S/N ratio for responses for the jth experiment is defined as

$$\eta_j = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_{ij}^2\right) \qquad \text{Eq.4.2}$$

Where n is the number of replications and yij is the value of responses of earth replication test for jth experimental condition.



Step 1: Selection of levels of matching factors
Step 2: Construct the orthogonal array
Step 3: Obtain values of various responses based on step 2
Step 4: Determination of S/N ratio
Is the response larger the better
η_j=-10 $\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^2}\right)$
η_j=-10 $\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^2}\right)$
Step 5: Determination of mean S/N ratio
$\eta_m = \left(\sum_{j=1}^{n}\eta j\right)/N$
Step 6: Determination of total sum of square and mean square etc.
$SS_i = \left(\sum_{j=1}^{p}(\eta_m - \overline{\eta i})\right)2, SS_T = \left(\sum_{j=1}^{N}(\eta_j - \eta_m)\right)2, MS_i = \frac{SS_i}{D.O.F.}$
Step 7: Perform the ANOVA
$SS_E = SS_T - SS_i$
$MS_{E=\frac{SS_E}{D.O.F.}}$
Step 8: Determine the significant factor (s)
P(%)=$\frac{SS_i}{SS_r - SS_E}x\ 100\%$
Step 9: Determination of optimal condition and verification of the outcome

4.3.2 Grey Relational Analysis (GRA)

Grey relational analysis is an impacting measurement method in grey system theory that analyzes uncertain relations between one main factor and all the other factors in a given system. In the case when experiments are ambiguous or when the experimental method cannot be carried out exactly, grey analysis helps to compensate for shortcomings in statistical regression. Grey relational analysis is actually a measurement of the absolute value of data difference between sequences and it could be used to measure the approximate correlation between sequences.

In the grey relational analysis. data preprocessing is the first performed in order to normalize the raw data for analysis. The linear normalization of the experimental results is performed in the range between zero and unity, which is also called the grey relational generating.. Usually, there are three categories of performance characteristics in the analysis of normalized values that is the “higher-the-better”, the “lower-the-better" and the “nominal-the-best”. Then the normalized results can be expressed as

For “higher-the-better” type response,

$$X_i(k) = \frac{\eta_i(k) - min\eta_i(k)}{max\eta_i(k) - min\eta_i(k)} \quad \text{Eq.4.3}$$

For “lower-the-better” type response,

$$X_i(k) = \frac{max\eta_i(k) - \eta_i(k)}{max\eta_i(k) - min\eta_i(k)} \quad \text{Eq.4.4}$$

Where is $X_i(k)$ is the normalized value of the kth performance characteristic in the experiment is the ith experiment, $\eta_i(k)$ is the kth experimental result in the ith experiment, and Max $\eta_i(k)$ and min $\eta_i(k)$ are the maximum and minimum values of $\eta_i(k)$ respectively. The larger normalized results crosspond to better performance and the best normalized results should be equal to one. Then, the grey relational coefficients are calculated to express the relationship between the ideal best and the actual experimental results. The grey relational coefficient can be expressed as:

$$\xi_i = \frac{\Delta min + \zeta \Delta max}{\Delta_{oi}(k) + \zeta \Delta max} \qquad \text{Eq.4.5}$$

Where, Δoi is the deviation sequence of the reference sequence X_0 and the comparability sequence (X_i), i.e. $\Delta_{ok} = \left\| X_0(k) - X_i(k) \right\|$ and ξ is the distinguishing coefficient set between zero and unity; in this study, it was set to ξ=.5.

Next, the grey relational grade $\xi(X0, Xi)$ is computed by averaging the grey relational coefficient corresponding to each performance characteristic and it is identified as

$$\xi\left(X_{0,} X_i\right) = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \qquad \text{Eq.4.6}$$

Where n is the number of performance characteristics. The grey relational grade shows the correlation between the reference sequence and the comparability sequence the evaluated grey relational grade fluctuates from zero to one and equals one if these two sequences are identically coincident.

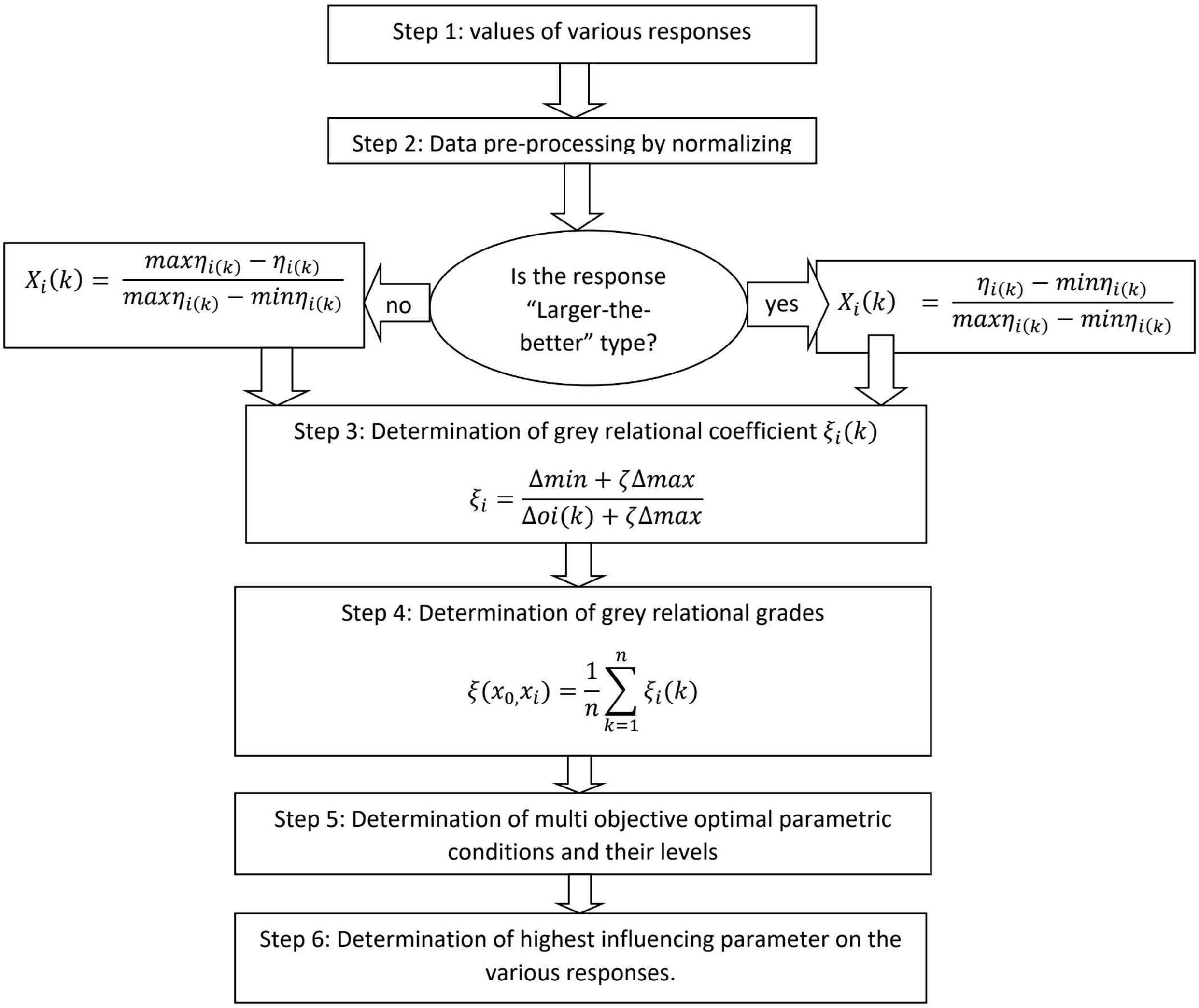


Fig. 4.3 Flow diagram of various steps of GRA

4.4 Measurement of Different Performance Characteristics

The two main process responses considered in this research work are MRR and width of cut, in the next section we will see the methods followed for calculation of these two responses. But, In micro-ECDT, the material is not only removed from the tool but also from the tool and size and shape of the groove is dependent on the shape and size of the tool. Therefore, in this research work a qualitative analysis is also done for tool wear, tool material.

(A) Material Removal Rate:

Material removal Rate in micro-ECDT is defined as the amount of the material removed from the workpiece per unit time and usually expressed in µg/min (microgram per minute) and µg/sec (microgram per second) here we would use the unit µg/sec (microgram per second). For the measurement purpose of the weight of workpiece; weight balance was used having following specifications:

Product name: Sartorius BSA **Modal:** 224S-CW

Capacity: 220g **Least Count:** 0.0001g

Repeatability: 0.0001g **Linearity:** 0.0002g

Stabilization Time: 2.5 Sec **Draftshield:** Yes

Construction: Draft Shield Chamber from pan to top of glass door

Calibration: Internal

Using the weight machine, the weight of the workpiece before turning is measured and in the same way after turning we again measure the weight of the workpiece. Now the difference between these two gives the total material removed. When material removed is divided by the total time taken for removing that specified material we get the material removal rate (MRR) for the turning process. The time of tuning is noted by using a stopwatch Following formula gives the value of MRR:.

$$MRR = (W_i - W_f) / t, \mu g/sec$$

Where,

Wi = Weight of the workpiece before machining, in µg

Wf = Weight of the workpiece after machining, in µg

t = Total time taken for the grooving, in sec

(B) Width of Cut of Groove

It is the width of the groove created on the rotating workpiece against the tool electrode. And for the measurement of it first LEICA microscope was used but since the workpiece is glass rod and is transparent therefore desired results were not obtained therefore DINO-microscope was used for better accuracy.

Chapter: 5

5. RESULTS AND DISCUSSION

On the basis of experiments which have been performed after setting all the process parameters at different combinations, various data were obtained from various measurements such as reduction in the weight of the workpiece, width of cut of grooves. A total of 9 (3*3) experiments have been carried out but before this a number of trial experiments were performed and on the basis of those observations the final experiments were performed. The results and the discussion section of the thesis presents the findings of the experimental study conducted on the turning of glass rod using Electrochemical Discharge Turning (ECDT). This section aims to analyze and interpret the data collected during the experiments and provide a comprehensive discussion of the outcomes. It allows for a deeper understanding of the effects of various parameters and their impact on the machining performance and quality of the groove generated on glass rods. Through a detailed examination of the results, the section provides insights into the effectiveness and limitations of the ECDT process, as well as potential areas for improvement. The discussion part of this section further explores the implications of the findings, compares them with existing literature, and offers explanations for observed trends of data representation.

5.1 EXPERIMENTAL RESULTS BASED ON TAGUCHI METHOD

The main objective of this experiment is to get the maximum value of material removal rate with the minimum width of cut of groove and this MRR is addressed as “larger is better” quality. And “smaller is better” quality type problem is also considered for minimizing the width of the groove. In this experiment Eq.4.1 and Eq.4.2 have been utilized to get signal to noise (S/N ratio) for “larger the better” type and “smaller the better” type responses respectively. The average values of experimental results and corresponding S/N ratios of various performance characteristics have been listed in Table 5.1 and Table 5.2 respectively as below.

Table 5.1 Average values of experimental results of various performance characteristics

Exp. No.	MRR (μg/sec)	Width of Groove (μm)
1	8.33	335
2	9.14	328
3	8.80	302
4	19.35	338
5	21.07	309
6	31.11	380
7	65.95	651
8	75.26	858
9	74.54	819

Table 5.2 The S/N ratios of various performance characteristics

Exp. No.	MRR (dB)	Width of Groove (dB)
1	18.4129	-50.5009
2	19.2189	-50.3175
3	18.8897	-49.6001
4	25.7336	-50.5783
5	26.4733	-49.7992
6	29.8580	-51.5957
7	36.3843	-56.2716
8	37.5313	-58.6697
9	37.4478	-58.2657

5.2 ANALYSIS BASED ON S/N RATIO FOR DIFFERENT PERFORMANCE CHARACTERISTICS

In robust design, Taguchi philosophy of orthogonal arrays determines the effects of various process parameters efficiently. The analyses of the experimental results have been carried out based on the values of signal to noise (S/N) ratios.

5.2.1 Effect of different process parameters on Material Removal Rate (MRR)

The S/N ratio of graphs as shown in Fig.5.1 represents the variation of average S/N ratio at different levels of turning parameters. According to the “larger is better” principle the maximum value of S/N ratio refers to the maximum MRR.

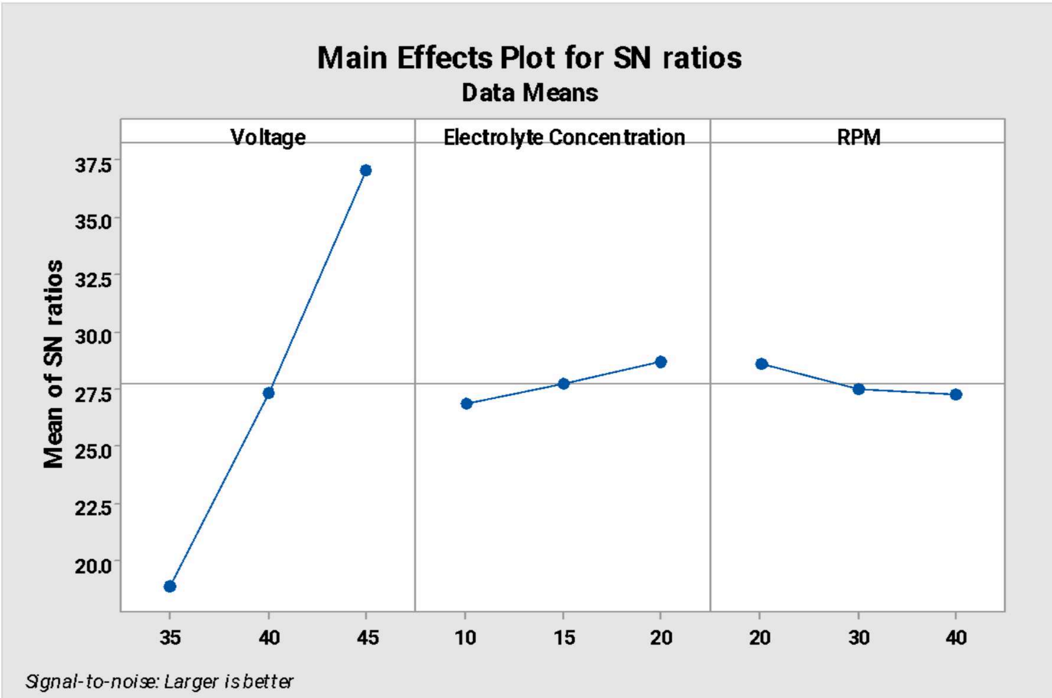


Fig.5.1 Effects of process parameters on MRR

From the Table.5.3 as given below that is the response table for average signal to noise ratio it can be observed that the most influential parameter for the MRR is the applied voltage and the electrolyte concentration and speed of rotation of the workpiece respectively.

Table.5.3 Response Table for average Signal to Noise Ratios dB for MRR

Level	Voltage	Electrolyte Concentrati on	Speed of Rotation
1	18.84	26.84	28.60
2	27.35	27.74	27.47
3	37.12	28.73	27.25
Delta	18.28	01.89	01.35
Rank	1	2	3

From the S/N ratio graph Fig.5.1, it is concluded that for achieving maximum MRR the optimal parametric condition for turning of glass is obtained as applied voltage of 45 V, electrolyte concentration of 20% by wt. and speed of rotation of workpiece of 20 rpm. From the nature of variation of S/N ratio it is observed that during turning of glass the intensity of electric discharge phenomenon increases which causes increase in material removal rate. Also from the graph it is evident that the MRR increases within the range 35 V to 45 V.

With increase in electrolyte concentration more chemical reactions can occur which may lead to higher MRR as it is also shown by the graph Fig.5.1 and when the workpiece rotates at a higher speed there is less time for the tool to interact with the workpiece so less MRR at higher speed is observed.

5.2.2 Effect of different process parameters on Width of Cut

The S/N ratio graph for width of groove is depicted in Fig.5.2 and is according to "smaller–the-better" principle. From the nature of variation of S/N ratio it is observed that width of groove increases as the applied voltage increases from 35 V to 45 V, however the increase in width of groove is less from 35 V to 40 V but it increases suddenly from 40 V to 45 V during the grooving of the glass.

From the graph it is clear that width of groove decreases with decrease in electrolyte concentration, with increase in electrolyte concentration more chemical reactions occur and also if speed of rotation of workpiece is increased then also it is observed that the width of cut decreases.

Table.5.4 Response Table for average Signal to Noise Ratio dB for width of cut

Level	Voltage	Electrolyte Concentration	Speed of Rotation
1	-50.14	-52.45	-53.59
2	-50.66	-52.93	-53.05
3	-57.74	-53.15	-51.89
Delta	7.60	0.70	1.70
Rank	1	3	2

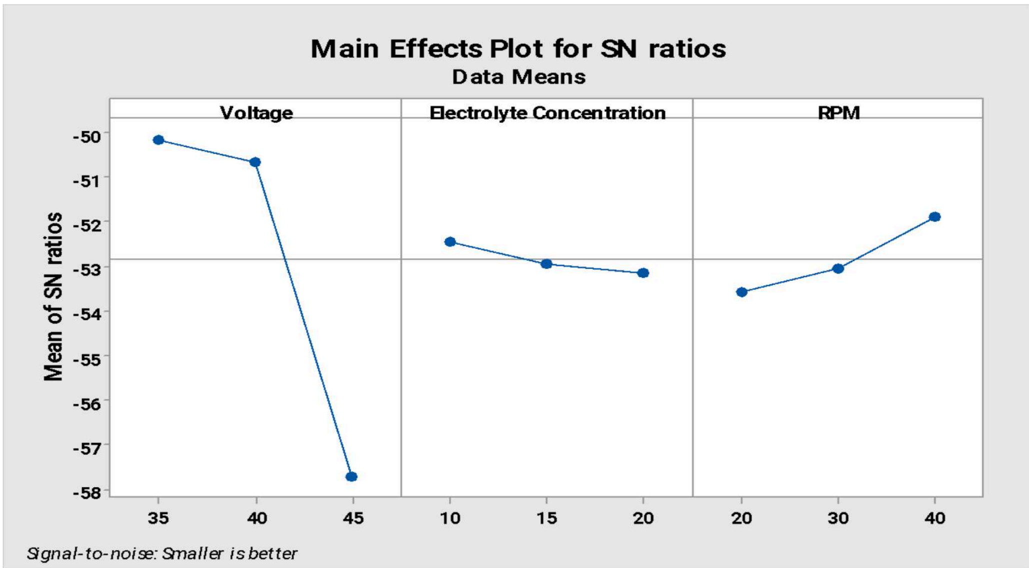


Fig.5.2 Effects of process parameters on Width of Groove

The average values of S/N ratio for width of cut at different level of process parameters are given in Table.5.4 and the effect of voltage on width of cut is highest other two factors such as speed of rotation of workpiece and electrolyte concentration has comparatively less effect on width of groove during turning. From the S/N ratio graph, it is concluded that for achieving minimum width of groove applied voltage should be minimum that is 35 V, electrolyte concentration as 10 % by Wt. and speed of rotation of workpiece should be 40 rpm.

5.3 DETERMINATION OF OPTIMAL PARAMETRIC CONDITION BASED ON S/N RATIO

The effects of different process parameters on turning performance have been analyzed and discussed based on S/N ratio curves previously and these will help the manufacturing engineers or researchers. At the same time there is a requirement of determining the optimal parametric conditions, which can reduce the time as well as cost of turning. From the analyses of the S/N ratio curves the best combinations for the turning for different optimal requirements have been obtained.

5.3.1 Single-optimized conditions based on S/N ratio

During turning for achieving maximum values of MRR and minimum value of width of groove, the parametric combinations are determined based on S/N ratio values of Taguchi method and shown in Table 5.5 below.

Table 5.5 Parametric combinations for optimal results by S/N ratio

Parameters	Parametric Combination	
	Maximized MRR	Minimized Width of Groove
Applied Voltage (Volt)	45	35
Electrolyte Concentration (% by Weight)	20	10
Speed of Rotation of Workpiece (rpm)	20	40

After the selection of the optimal level of design parameters, the final step is to predict and verify the improvement of the quality of the ECDT process. The predicted S/N ratio using the optimal machining parameter for various turning performance characteristics can then be obtained and corresponding performance characteristics can also be calculated using Eq. 4.1 and Eq.4.2.

5.3.2 Multi-objective optimized condition based on Grey Relational Analysis (GRA)

In the present study, maximum material removal rate (MRR) and minimum width of groove are indications to have better machining performance. For data pre-processing in the grey relational analysis process, MRR is taken as “higher is better”. However, the width of the groove is taken as “lower is better”. Let the result of nine experiments be a comparability sequence. All the sequences after the data pre processing using equation 4.3 and 4.4 are listed in Table 5.6. denoted as reference sequence and comparability sequence respectively. The grey relational coefficients and grade values for each experiment orthogonal array are calculated by applying equation 4.5. The deviation sequences that are different between reference sequence and comparability sequences are shown in Table 5.7 and the grey relational grade is shown in Table 5.8. According to performed experiment design it is clearly observed from Table 5.8 that the micro grooving parameters setting up experiment no. 3 has the highest grey relational grade. Therefore experiment no. 3 is the optimal machining parameters setting for maximum material removal rate and minimum width of cut of groove among the 9 experiments based on multi performance characteristics. In addition to the determination of optimum grooving parameters the response table for the Taguchi method is used to calculate the average grey relational grade for each level of the grooving parameters. The procedure is (i) group the relational grades by factor level for each column in the orthogonal array; (ii) take the average of them. The average grey relational grade values are shown in Table 5.9. Since the grey relational grade represents the level of correlation between the reference sequence and the comparability sequence, the greater value of the reay relational grade means that the comparability sequence has a stronger correlation to the reference sequence at this level of factor. In other words, regardless of the category of the performance characteristics, a greater grey relational grade value corresponds to better performance. Therefore, the optimal level of the process parameters is the level with the greatest grey relational grade value. An asterisk (*) indicates that the level value results in better performance. Based on the grey relational grade values shown in Fig.5.3 and given in Table 5.9, the optimal multiple responses for micro-turning operation is for applied voltage (level 1), electrolyte concentration (level 1) and speed of rotation of workpiece (level 3) combination. As listed in Table 5.9, the difference between the maximum and minimum value of the grey relational grade of the grooving parameters indicates the significance of the role that every controllable factor plays over the multi-performance characteristics. It is shown that the performance characteristics are mainly affected by applied voltage**.**

Table 5.6. The sequences after Data pre-processing

Exp. No.	MRR	Width of Groove
Reference Sequences		
	0.000	1.000
Comparability Sequences		
1	0.000	0.940
2	0.012	0.953
3	0.007	1.000
4	0.165	0.935
5	0.190	0.987
6	0.340	0.859
7	0.860	0.372
8	1.000	0.000
9	0.990	0.070

Table 5.7. Deviation sequences

Exp. No.	MRR	Width of Groove
1	0.000	0.060
2	0.012	0.047
3	0.007	0.000
4	0.165	0.065
5	0.190	0.013
6	0.340	0.141
7	0.860	0.628
8	1.000	1.000
9	0.990	0.930

Table 5.8 Grey Relational coefficients with grades and their order

Exp. No.	Grey Relational Coefficients		Grade	Order
	MRR	Width of Groove		
1	1.000	0.892	0.946	2
2	0.023	0.914	0.568	6
3	0.986	1.000	0.993	1
4	0.752	0.885	0.818	4
5	0.725	0.975	0.850	3
6	0.595	0.780	0.687	5
7	0.368	0.443	0.405	7
8	0.333	0.333	0.333	9
9	0.335	0.350	0.342	8

Table 5.9 Response table for grey relational grades

Process parameters	Average grey relational grade by factor level			Max. - Min.
	Level 1	Level 2	Level 3	
Voltage	0.836*	0.785	0.360	0.476
Electrolyte Concentration	0.723*	0.583	0.674	0.140
Speed of rotation	0.655	0.576	0.749 *	0.173

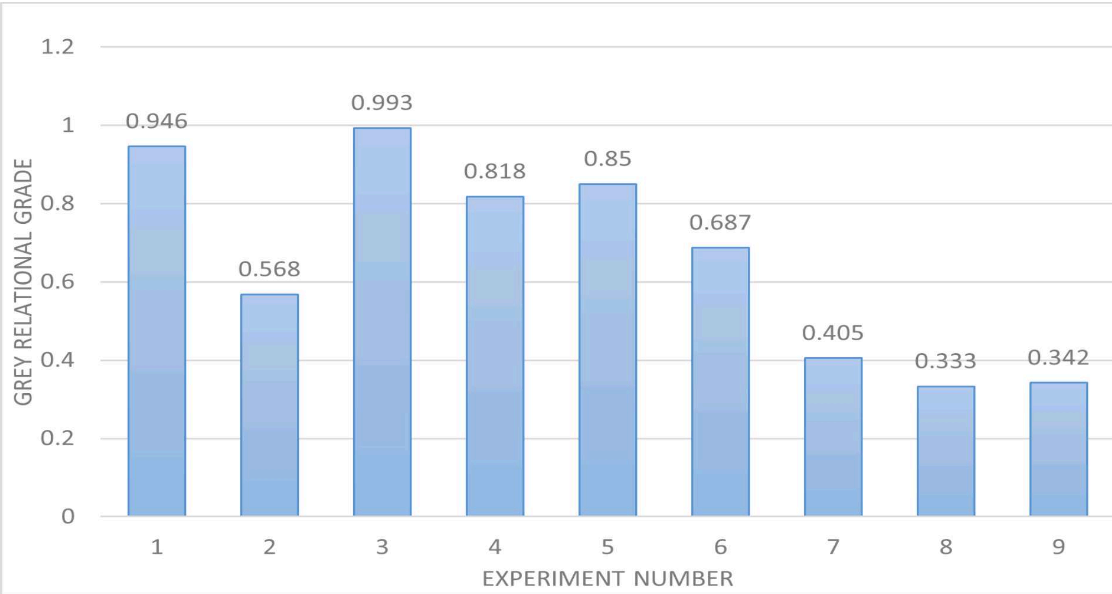


Fig.5.3 Bar graph of the grey relational grades

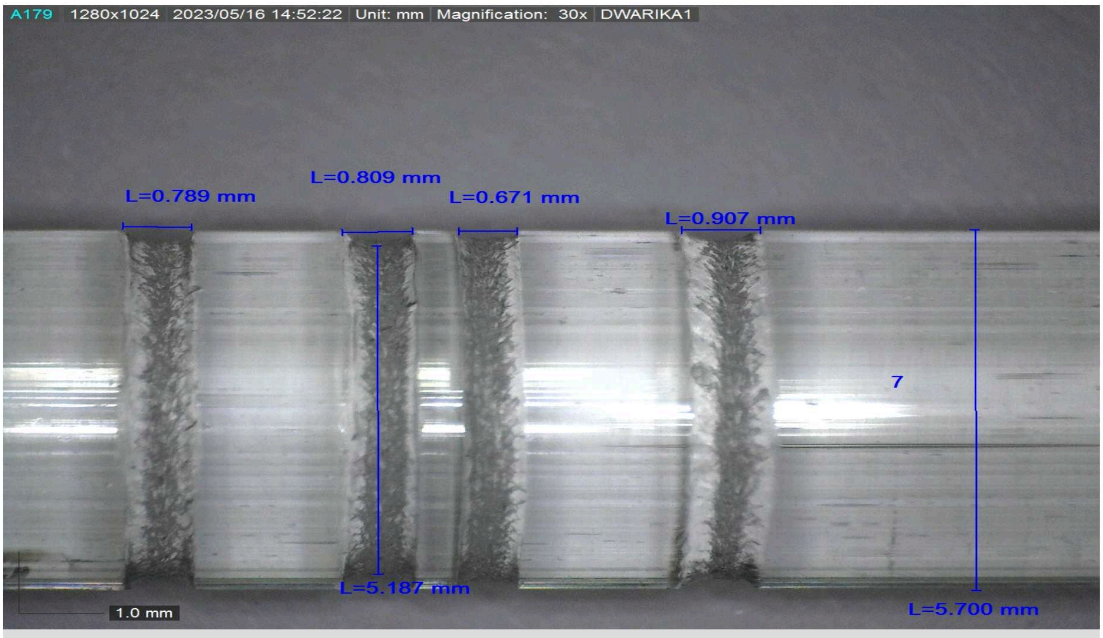


Fig.5.4 Microscopic view of Grooves created at V=45V, EC=10 % by wt and at 40 rpm

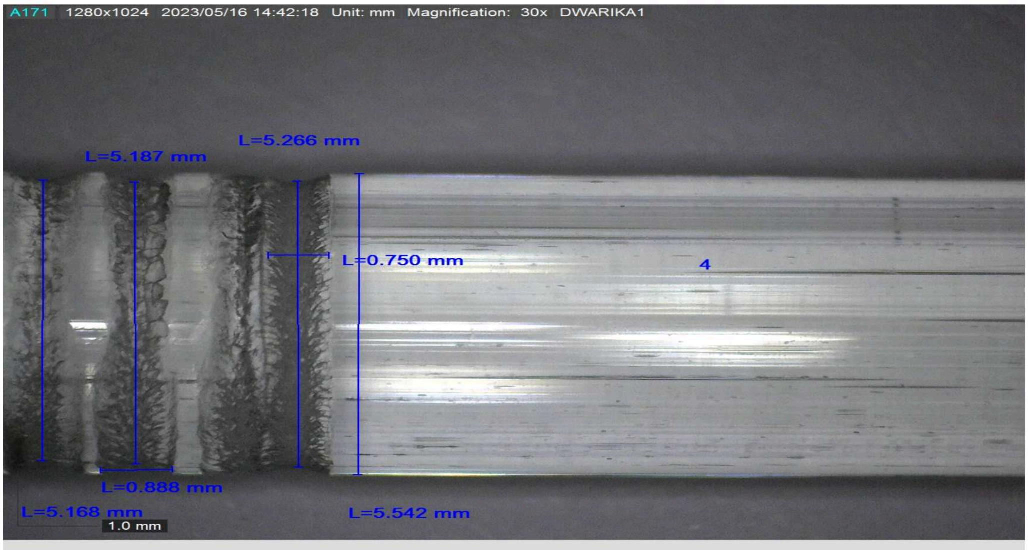


Fig.5.4 Microscopic view of Grooves created at V=40V, EC=10 % by wt and at 30 rpm

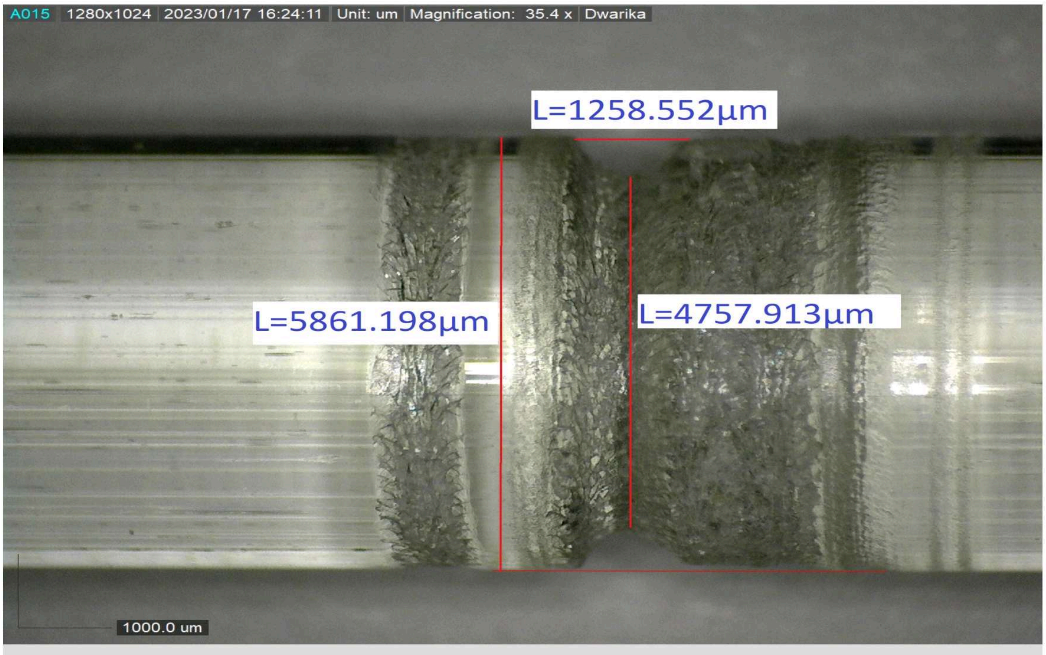


Fig.5.4 Microscopic view of turning at condition V=45V, EC=20 % by wt and at 20 rpm

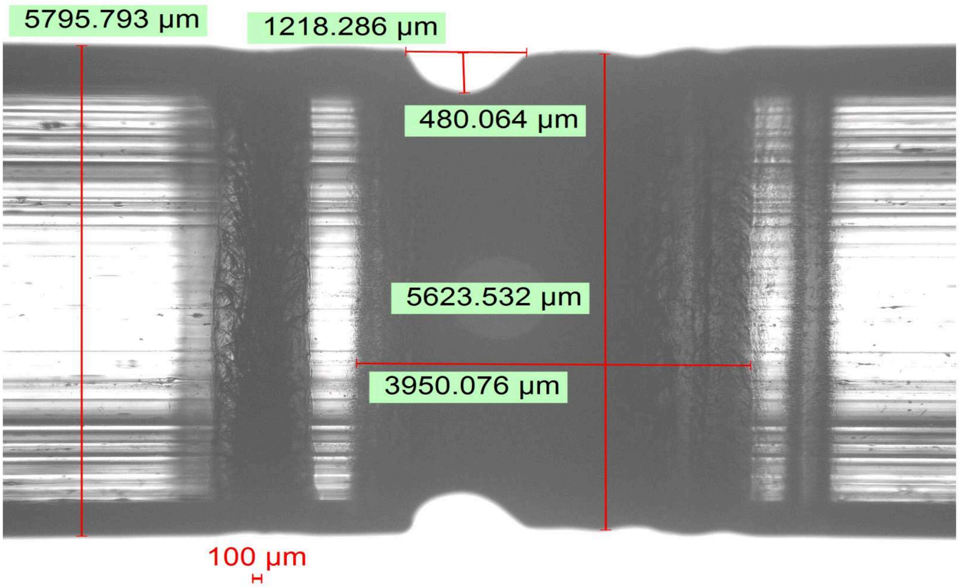


Fig.5.5 Microscopic view of turning at V=40V, EC=20 % by wt and at 30 rpm

Chapter: 6

6. GENERAL CONCLUSIONS & FUTURE SCOPE

An ElectroChemical Discharge Turning setup has been developed successfully and on that developed setup grooving operation is also performed and analyzed successfully. It was realized that ECDT has great potential for grooving as well as turning of non-conductive materials. Taguchi method based experimental investigations for single-objective optimized conditions and GRA based investigation for multi-objective optimized conditions of ECDT have been performed to develop empirical models on various responses. Optimization has been performed to determine the parametric combinations of ECDT by S/N ratio analysis. Within the constraints of the experimental set up of ECDT and based on experimental investigations and analysis, the following conclusions can be drawn:

I. The ECDT set-up for carrying out grooving operations has been successfully developed.

II. Using the developed ECDT setup the grooving and turning operations performed successfully.

III. It was observed that the working range for applied voltage 35 V to 45 V gives good results. The concentration of electrolyte could be varied between 10 % to 20 % by weight. The speed of rotation of the workpiece could range between 20 rpm to 40 rpm.

IV. From the S/N ratio graph it has been concluded that MRR has been increased at higher applied voltage within the range 35 V to 45 V, higher electrolyte concentration and low speed of rotation of the workpiece. However, the width of the groove decreases with decrease in voltage, increase in electrolyte concentration and also increase in rpm.

V. For single objective optimization, the optimal parametric combinations for maximum MRR are at applied voltage of 45 V, electrolyte concentration of 20% by weight, speed of rotation of workpiece of 20 rpm and for minimum width of groove 35 V applied voltage, 10% electrolyte concentration and 40 rpm as speed of rotation of workpiece.

VI. In multi objective optimization, using the GRA the optimized result is obtained when the applied voltage is as 35 V, and Electrolyte concentration 20 % by weight and the speed of rotation workpiece is as 40 rpm.

Thus, the present research work will help in manufacturing scientists as well as engineers for grooving of glass using ECDT process. From the experimental results, the influence of applied voltage on performance characteristics such as MRR and width of groove has been analyzed. However, this area of research still required further investigation and improvement of performance characteristics like surface roughness, depth of cut, tool wear and over cut.

The following future scope of this research includes:

I. To perform various grooving operations on other non-conducting engineering materials using developed ECDT set-up.

II. To perform turning operation using the developed ECDT set-up then analyze the surface roughness, reduction in diameter and over cut.

III. To develop the CNC control system integrating with ECDT system for turning, grooving and generating other surface profiles.

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