# EXPERIMENTAL INVESTIGATION ON SURFACE FINISH DURING ELECTROCHEMICAL MILLING OF Ti6Al4V

By

**PRITAM BISWAS**

B.Tech in Mechanical Engineering,2014-18
Netaji Subhash Engineering College
Maulana Abul Kalam Azad University of Technology

Examination Roll No.: M4PRD22005

Registration No.: 154473

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF MASTER OF PRODUCTION ENGINEERING IN THE FACULTY OF ENGINEERING AND TECHNOLOGY,
JADAVPUR UNIVERSITY

DEPARTMENT OF PRODUCTION ENGINEERING
JADAVPUR UNIVERSITY
KOLKATA-700032

JADAVPUR UNIVERSITY FACULTY OF ENGINEERING AND TECHNOLOGY

CERTIFICATE OF RECOMMEDATION

I HEREBY RECOMMEND THAT THE THESIS ENTITLED **"EXPERIMENTAL INVESTIGATION ON SURFACE FINISH DURING ELECTROCHEMICAL MILLING OF TI6AL4V**" CARRIED OUT UNDER MY/OUR GUIDANCE BY **MR. PRITAM BISWAS** MAY BE ACCEPTED IN THE PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF "MASTER OF PRODUCTION ENGINEERING".

______________________________________

(Dr.Bijoy Bhattacharyaa)
Thesis Advisor
Dept. of Production Engineering
Jadavpur University
Kolkata-700032

______________________________________

HEAD, Dept. of Production Engineering
Jadavpur University
Kolkata-700032

______________________________________

DEAN, Faculty of Engineering and Technology
Jadavpur University
Kolkata-700032

JADAVPUR UNIVERSITY
FACULTY OF ENGINEERING AND TECHNOLOGY

## CERTIFICATE OF APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner of satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but thesis only for the purpose for which it has been submitted.

COMMITTEE ON
FINAL EXAMINATION
FOR EVALUATION OF
THE THESIS

______________________________
(External Examiner)

______________________________
(Internal Examiner)

# ACKNOWLEDGEMENT

While bringing out this thesis to its final form, I came across a number of people whose contributions in various ways helped my field of project work and they deserve special thanks. It is a delight to convey my gratefulness to all of them. First and foremost, I would like to express my deep sense of gratitude and indebtedness to my supervisor Prof. Bijoy Bhattacharyya, Head of the Production Engineering Departmentat Jadavpur University for his priceless and meticulous supervision at each and every phase of my work inspired me in innumerable ways.

I would like to express my warmest gratitude to all respected teachers in this department for helping me with variable suggestions.

I also want to express my heartiest thanks to Dr. Koushik Mishra, Assistant Professor, Mechanical Engineering Department, Swami Vivekananda Institute of Science and Technology and to all the research scholars for their cordial assistance throughout my thesis work.

Finally, I am deeply indebted to my mother, Mrs. Jhuma Biswas, and my father, Mr. Shyamal Biswas, for their moral support and continuous encouragement while carrying out this study.

Any omission in this brief acknowledgment does not mean a lack of gratitude.

Pritam Biswas
Class Roll No: 002011702006

# Table of Content


TITLE SHEET i

CERTIFICATE OF RECOMMENDATION ii

CERTIFICATE OF APPROVAL iii

ACKNOWLEDGEMENT iv

TABLE OF CONTENT v

LIST OF FIGURES viii

**CHAPTER 1**

1. INTRODUCTION 10
   - 1.1 Overview of the Electrochemical Machining Process 11
   - 1.2 Various Advanced Electrochemical Machining Processes 13
   - 1.3 Principle of ECM 19
   - 1.4 Difference Between EC Milling and Conventional Milling and Conventional ECM Process 21
   - 1.5 EC Milling of Titanium-based Super Alloy (Ti6Al4V) 22
     - 1.5.1 Applications of titanium alloy 23
     - 1.5.2 Limitations of machining of titanium and its alloy 25
   - 1.6 Literature Review of Past Research Works 26
   - 1.7 Objectives of Present Research Work 38

**CHAPTER 2**

2. FUNDAMENTALS OF ELECTROCHEMICAL MILLING 39
   - 2.1 Process Parameters of EC Milling 41
   - 2.2 Performance Characteristics of EC Milling 41
   - 2.3 Advantages of EC Milling 46
   - 2.4 Various Challenges in EC Milling Process 47
   - 2.5 Different Applications of EC milling 48

## CHAPTER 3

3. MODIFICATION AND DESIGN OF EXPERIMENTAL SETUP OF ELECTROCHEMICAL MILLING 49

3.1 Detailed Description of the EC Milling Machine Setup 49

3.1.1 Machining chamber 50

3.1.2 Power supply unit 51

3.1.3 Motion control system 52

3.1.4 Monitoring system setup 52

3.1.5 Electrolyte flow system 53

3.1.6 Position control unit 53

3.1.7 Stepper motor controller 54

3.2 Modification of the Tool Holding Attachment Unit in EC Milling Setup 55

3.2.1 Various challenges faced on the tool-holding attachment 55

3.2.2 Electrolyte through system (ETS) holding unit 55

3.2.3 Stepper motor attachment unit 56

3.2.4 Tool and ETS holding unit 56

3.3 ETS System Modification 58

## CHAPTER 4

4. EXPERIMENTATION IN EC MILLING OF Ti6AL4V TO INVESTIGATE MACHINED SURFACE ROUGHNESS 60

4.1 Experimental planning 60

4.1.1 Selection of tool 60

4.1.2 Electrolyte for EC milling 61

4.1.3 Work piece property 63

4.1.4 Selection of electrochemical milling process parameters and responses 64

4.1.5 Tool path planning 65

4.1.6 Planning of Measurement 68

4.2 Results and Discussion 68

4.2.1 Influence of dwell time on surface roughness 68

4.2.2 Influence of dwell time on width overcut 71

**CHAPTER 5**

5. INFLUENCE OF ETHYLENE DIAMINE TETRA ACIDIC ACID (EDTA) FOR THE IMPROVEMENT OF SURFACE ROUGHNESS AND ACCURACY DURING EC MILLING DURING Ti6l4V 76

5.1 Anodic Dissolution of Ti6AL4V in EDTA 76

5.2 Experimental Planning 77

5.3 Results and Discussion 77

5.3.1 Effect of surface roughness and overcut with different concentrations of EDTA 78

5.3.2 Influence of duty cycle on surface roughness and accuracy 79

**CHAPTER 6**

CONCLUSIONS 83

**References** 86

| No.of Figures | Title of the Figures | Page no. |
|---|---|---|
| **1.1** | Schematic diagram of ECM | 12 |
| **1.2** | Schematic of EC turning | 14 |
| **1.3** | Schematic of EC grinding working principle | 15 |
| **1.4** | Schematic diagram of WECM process | 16 |
| **1.5** | Schematic showing EC deburring process | 17 |
| **1.6** | Schematic showing EC drilling process | 18 |
| **1.7** | Schematic Showing ELID grinding | 19 |
| **1.8** | Scanning layer-by-layer method | 20 |
| **2.1(a)** | Scanning layer-by-layer method | 39 |
| **2.1(b)** | Sinking and milling method respectively | 40 |
| **3.1** | Schematic diagram of the whole EC Milling setup | 50 |
| **3.2** | photographic view of the power supply machine | 52 |
| **3.3** | photographic view of control unit Mach 3 loader | 54 |
| **3.4** | Front view of the modified tool holding unit | 57 |
| **3.5** | Side view of the modified tool rotating unit | 58 |
| **3.6** | ETS system modification | 59 |
| **4.1** | Flow chart of tool path planning | 66 |
| **4.2** | Flow chart of the EC milling process | 67 |
| **4.3** | Variation of surface roughness with dwell time strategy (i) | 69 |
| **4.4** | Variation of surface roughness with dwell time with strategy (ii) | 70 |

| | | |
|---|---|---|
| **4.5** | Variation of overcutting with dwell time with strategy (i) | 72 |
| **4.6** | Variation of overcutting with dwell time with strategy (ii) | 73 |
| **4.7-4.10** | Photographic view of machined profile (different dwell time at last stage) | 74-75 |
| **5.1** | Variation of surface roughness with the molar concentration of EDTA | 78 |
| **5.2** | Variation of overcutting with the molar concentration of EDTA | 79 |
| **5.4** | Influence of surface roughness with the duty cycle | 80 |
| **5.5** | Influence of accuracy with the duty cycle | 81 |
| **5.6** | The photographic view of the machined surface using best parameter setting | 82 |

# CHAPTER 1

## 1. INTRODUCTION

Manufacturing is the procedure of converting raw materials or parts into finished goods with the help of tools, human labour, machinery, and chemical processing. Large-scale manufacturing allows for goods to be mass-produced using assembly line processes and advanced technologies. Efficient manufacturing techniques enable manufacturers to take advantage of economies of scale, producing more units at a lower cost. The Manufacturing process especially the machining process played an integral part in survival at the earlier phase of human civilization. With the help of appropriate tools starting from the rock marking, painting and products made of wood, iron, ceramic and different metals were manufactured. Casting and forging were the most popular manufacturing process in the initial phase of human lives. As time progresses steady growth rate of demand in the world accentuates the development of different manufacturing processes. The growth of new manufacturing processes leads to an increase the productivity and product variety. The invention of different kinds of materials i.e., different alloys, ceramics, composite, etc. fulfilled the specific demands in different sectors e.g., Aerospace Industry, space applications, defence, biomedical, etc. But it also brought huge challenges to the manufacturing industry.

High strength temperature resistant (HSTR) alloy is one of the most difficult to machine materials which includes Titanium and Nickel alloys. They have different applications for their outstanding material properties e.g., high strength to weight ratio, corrosion resistance, biocompatibility, etc. The conventional machining processes are completely based on machine tools however HSTR alloy is not really suitable for conventional machining processes because the cutting tool should have to be harder, more wear-resistant, stronger mechanical properties than the work piece itself. The difficulties of using a harder cutting tool can be overcome by using non-conventional machining processes very effectively and economically. Generally, there is no direct contact between tool and work piece (except tool base machining) and energy is used in its direct form, which is directed to process those difficult to machine materials in non-traditional processes. Having good accuracy, providing a good surface, making complex shapes, and helping the tool to have a longer life are the major advantages of the non-traditional machining process. Non-conventional machining processes can be classified into four groups based on the type of energy used e.g., thermo-electrical, chemical, mechanical, and electrochemical processes. Various non-conventional techniques are Electrochemical machining (ECM), Abrasive jet machining (AJM), Ultrasonic machining (USM), Abrasive water, Electrical discharge machining (EDM), Laser beam machining (LBM), Plasma arc machining (PAM), Chemical machining, etc. As EDM and LBM are thermal processes, therefore, heat-affected zone, surface cracks, and residual stresses are generated on the workpiece which directly affects the product quality and accuracy. In 1929, Gusseff first presented the most promising non-contact type non-conventional machining technique electrochemical machining (ECM). The material removal mechanism in the electrochemical process is selective ion dissolution i.e., machining takes place without applying any mechanical forces.

Now modern days of manufacturing, improvement in non-conventional machining has occurred through evolution in already existing processes e.g., Electrochemical grinding, Electrochemical milling (EC milling), Wire ECM, Vibration assisted EDM, Wire EDM and also by combining two or more processes to take advantages of the process simultaneously by hybrid machining e.g., abrasive water jet machining (AWJM), electrochemical discharge machining process (ECDM), etc. EC milling is an improved form of the traditional ECM process which can produce three-dimensional surface profiles with the help of simple shaped tools. In comparison with the conventional ECM process, EC milling eradicates the complexity of tool design to achieve complex three-dimensional profiles. In this method, a simple geometrical tool follows a predefined path in a layer-by-layer fashion with multiple downward steps. With the help of EC milling, any kind of 3D feature, contour profile with great precision can be attained by a simple geometrical tool.

## 1.1 Overview of the Electrochemical Machining Process

Electrochemical machining (ECM) is a non-contact type machining process based on Faraday's electrolysis principle; thus, both the tool and workpiece have to be electrically conductive. In this process, the tool is connected with the negative terminal and acts as a cathode and the workpiece is connected with the positive terminal and does the role of an anode in the electrolysis process. The difference with basic electrolysis is no removal of cathode material and movement of the cathode. No removal from the tool i.e., no tool wear is the main advantage of the ECM process. When a certain voltage difference is applied across the tool and workpiece interface with the presence of an electrolyte, material removal is occurred by means of anodic dissolution. From the anode, metal is dissolute into the electrolytic solution in the form of an atom. As the tool approaches the workpiece it erodes its negative shape. Thus, the machined profile gets the negative shape of the tool. The material removal happens with the help of electrolyte dissolution therefore no mechanical forces are needed with any physical contact during machining.

Figure 1.1 shows the schematic diagram of the ECM process. The electrolyte is pumped from the electrolyte chamber and pumped into the tool-workpiece through the tool of the process. Then a certain voltage is applied between the tool and workpiece which enables to start of the process of electrochemical machining. In the ECM process, the initial inter-electrode gap (IEG) is one of the major contributing factors to the machine. While starting from the initial IEG with a constant feed of tools ultimately results in a constant gap. Without a proper initial inter-electrode gap, the tool tends to touch the workpiece and suddenly spark happens, this may harm the workpiece as well as the tool also. The sludge produced during the machining process is flashed away by the electrolyte filtration. After the filtration, the clean electrolyte is made ready to reuse again.

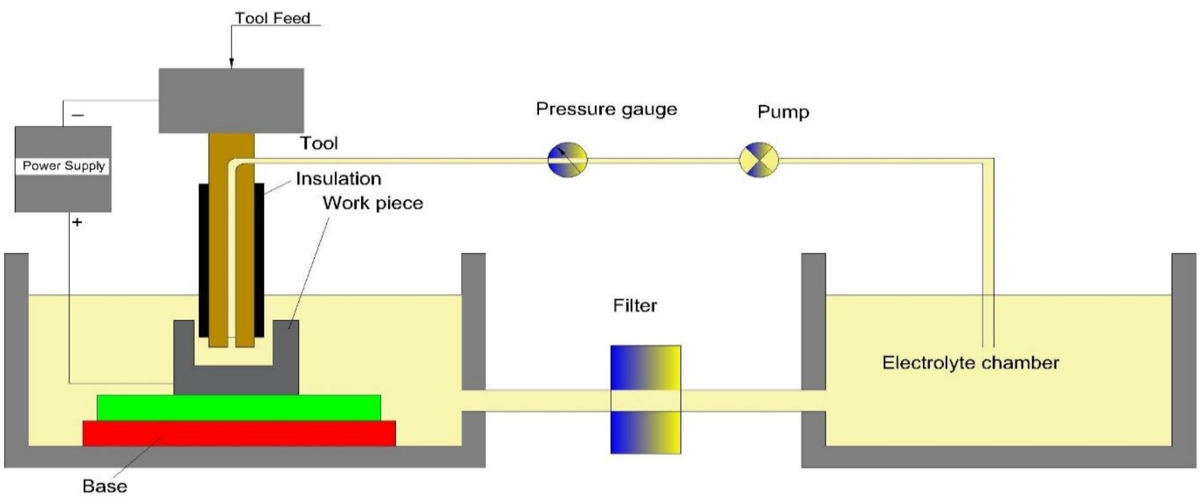


Fig. 1.1 Schematic diagram of ECM

### 1.2.1 Various advanced electrochemical machining processes on the basis of the dimension of the final machining zone and tool used

ECM can be classified into three categories as far as the dimension of the final machined zone is concerned – Macro ECM, Micro ECM, Nano ECM

#### *(i) Macro electrochemical machining*

The compulsory voltage and current for ECM in the macro range are in the order of 10-30 V and 150-1000 A respectively. The current density range is 20-200 A/cm$^2$ and the machining rate is generally 0.2-10 mm/min. If the dimension of the features produced by the electrochemical process on the workpiece is more than 1mm, then the process is termed as macro electrochemical machining. Turbine and compressor blades can be produced with the help of macro-ECM. To accomplish the specified range of tolerance sometimes a roughly cut part is again processed by ECM. To polish and harden the surface Electrochemical polishing is done in a water-based solution. Sophisticated servo systems and feedback controller has developed and the accuracy of the macro-ECM processes have enhanced nowadays.

#### *(ii) Electrochemical micromachining*

The recommended voltage for electrochemical micromachining (EMM) is less than 10V. Though the current density in EMM is 75-100A/cm$^2$, the required current is less than 1A because the surface area of the tool is very minor. The machining rate that can be attained in EMM is about 5µm/min. The term electrochemical micro machining (EMM) denotes material removal by electrochemical dissolution of very small dimensions ranging from 1µm to 999 µm. EMM requires an advanced high-frequency pulsed power supply for giving pulse DC power input and X-Y-Z stage controllers for precise movement of the micro tool relative to the work. EMM has various applications in aerospace, automobile, and electronic industries along with sensor, micro electro mechanical system (MEMS) and biomedical applications.

#### *(iii) Nano Electrochemical machining*

Design and fabrication of features on small objects or products by electrochemical means in the dimension range of 100 nm to 0.1 nm are labelled as electrochemical machining in the Nano range. Nano products are fabricated by deposition, dissolution and modification of electrochemical reactions by combining ion transfer reactions and electron transfer reactions. Due to the molecular dimension, the molecular motion and the quantum effect present in the process are significant in the nano range. Instead of using mechanical-driven systems like the X-Y-Z stage, piezo-driven systems are used in electrochemical machining in the Nano range to achieve nanoscale motions.

### 1.2.2 Various advanced electrochemical machining processes

Due to various advancements in the conventional ECM process, on the basis of machining type, ECM can also be classified as discussed below.

***(i) Electrochemical Turning***

In the case of electrochemical turning (EC Turning), an electrochemical machining technique has been employed for turning operations. The workpiece is rotated and connected with the positive terminal while the tool is connected with the negative terminal and attached with tool feed motion. Tool and job are submerged in an electrolyte solution. The moment after potential difference is applied between tool and workpiece removal of material starts from the workpiece. As the job is rotated homogeneous dissolution is expected from all sides of the job. As shown in Fig.1.2, the schematic diagram of the working principle of the EC turning process. The thickness of the workpiece is attained by controlling the movement of the tool. The workpiece is insulated except in the machining zone to confine the material removal from a portion of the job other than the chosen area.

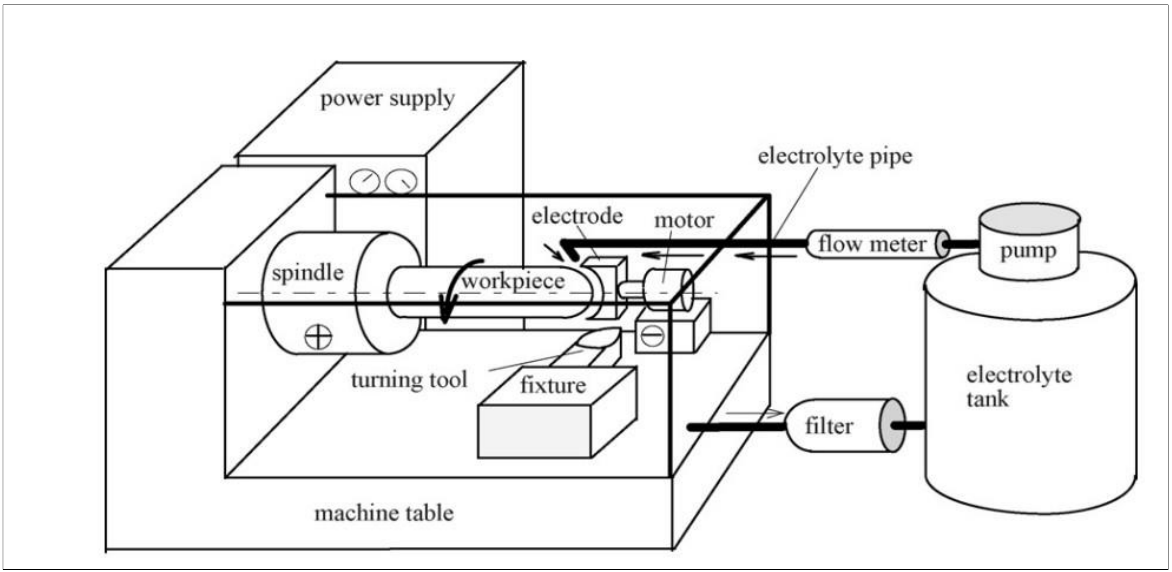


Fig. 1.2 Schematic of EC turning [4]

*(ii) Electrochemical Grinding*

In the case of electrochemical grinding (ECG), the grinding of the workpiece is carried out with the help of the ECM principle. Similar to the basic ECM process negative potential is given to the grinding wheel whereas positive potential is given to the workpiece. In the case of ECG, the flow rate of the supplied electrolyte should be very high. The grinding wheel where abrasives are bonded by the metallic bond is rotated with high velocity and the workpiece travels towards the wheel. A good surface finish was obtained as the material removal occurred from the uneven surface. In the case of ECM, the obtained surface finish is far better than any other process therefore it is possible to attain very good surface quality by grinding with the help of the ECM principle. In Fig. 1.3, the schematic diagram of the working principle of the ECG has been shown.

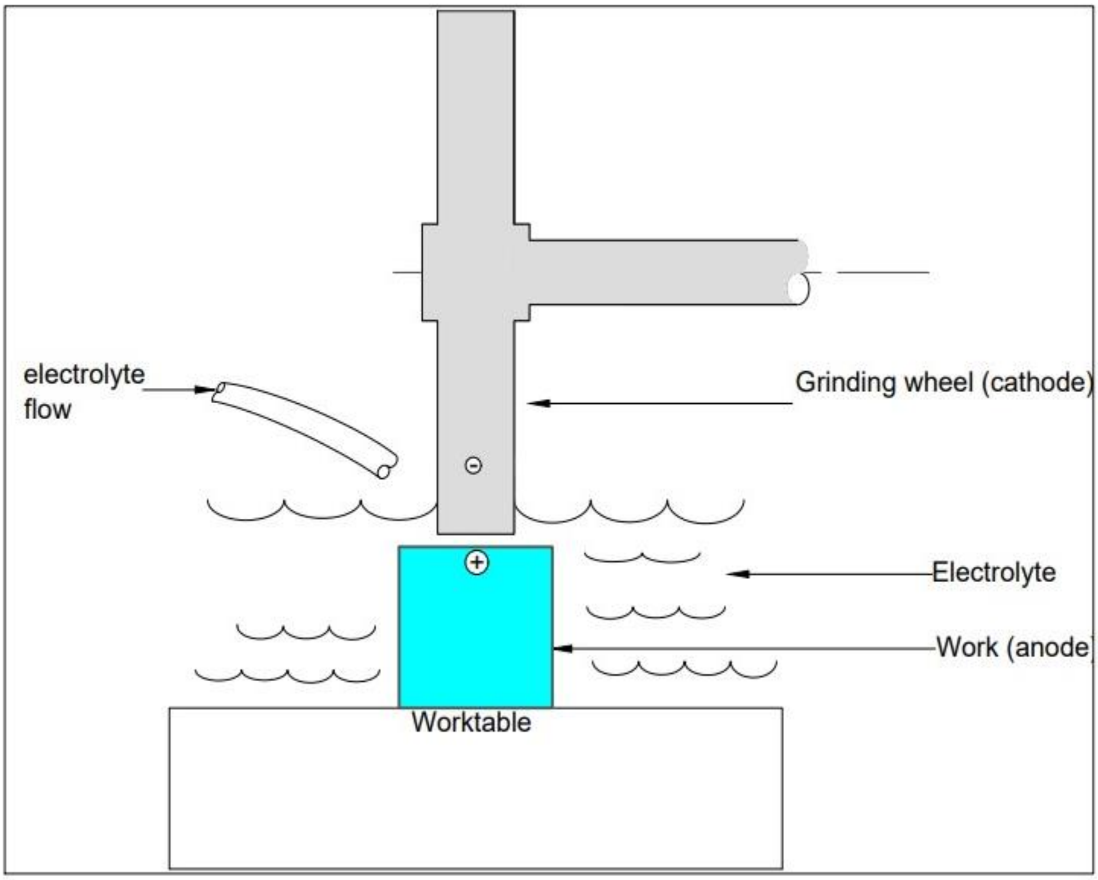


Fig. 1.3 Schematic of EC grinding working principle

***(iii) Wire Electrochemical Machining***

Wire electrochemical machining (WECM) is an advancement of the basic ECM process. In the case of WECM, a micro wire is used as a tool that is connected to the negative terminal. WECM process is mainly used for higher aspect ratio machining profiles. Similar to ECM no tool wear leads to more use of a single wire. Wire tension is an important factor in the case of WECM. The workpiece remains stationary and the wire travels in one direction with the flow of electrolyte through the machining zone. The electrolyte is supplied by a nozzle with a high flow velocity. Due to electrochemical dissolution, material from the workpiece in front of the tool is worn out, thus the metal is cut along the wire travel path. In Fig.1.4, a schematic diagram of wire ECDM has been given.

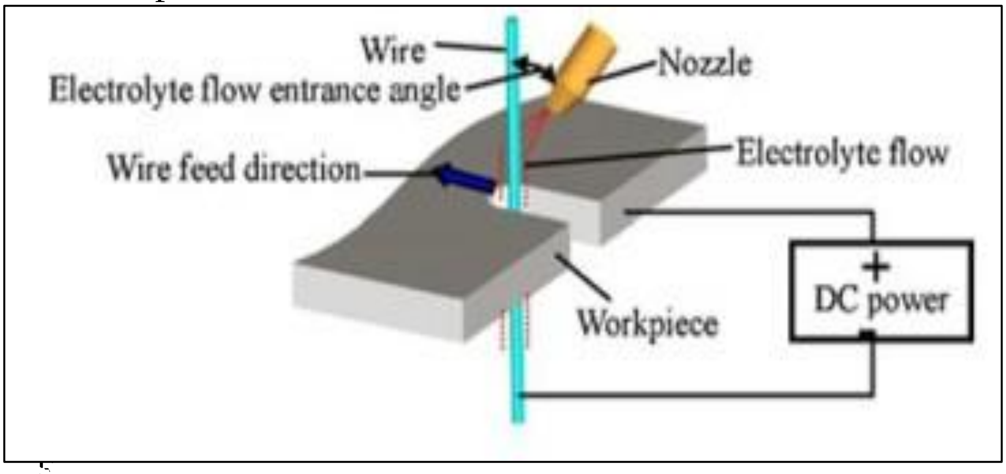


Fig. 1.4 schematic diagram of the WECM process [12]

***(iv) Electrochemical Deburring***

Electrochemical deburring (ECD) is an advanced process of electrochemical machining(ECM) a process designed to remove burrs or to round sharp corners on metal workpieces by the anodic dissolution method. One possible setup for ECD is shown in Fig. 1.5; the hole in the workpiece has a sharp burr of the type that is formed in a conventional through-hole drilling operation. The tool is designed better to emphasize the metal removal action on the burr. The tool associated with the negative terminal of a DC power source act as a cathode. Surface portions of the tool not being used for machining are insulated. The electrolyte flows through the hole to carry away the burr particles. The same ECM principles of operation also apply to Electrochemical deburring (ECD). Less material is removed in the Electrochemical deburring (ECD) machining process; cycle times are much shorter. A typical machining time in ECD is less than a minute.

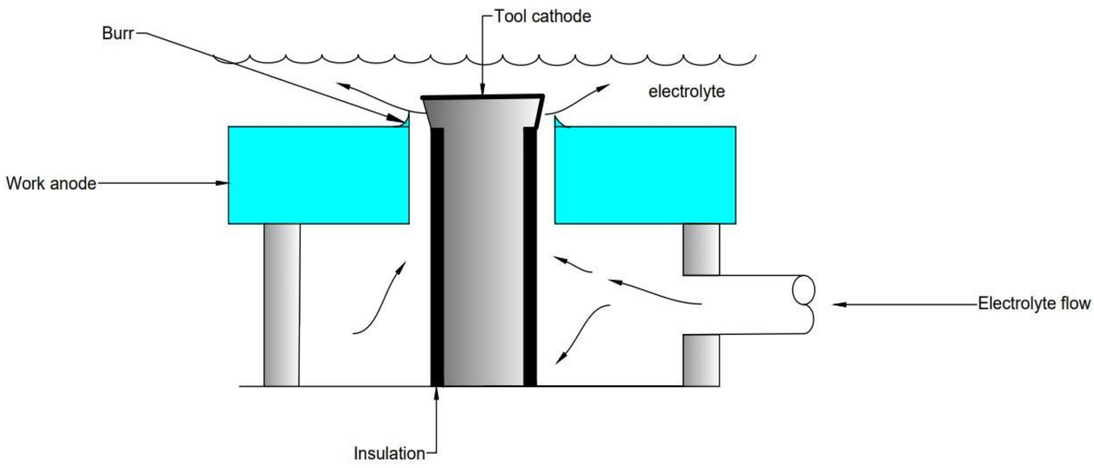


Fig. 1.5 Schematic showing EC deburring process

### (v) Electrochemical Drilling

Electrochemical machining technique has been employed for drilling operation in the case of electrochemical drilling (EC Drilling). In this process, drilling operation can be done by the electrolytic dissolution principle. The cathode is used as a drilling tool and rotated along the Z-axis in the case of EC drilling. The workpiece is connected with a positive terminal and acts as an anode. When a potential difference is applied across the tool and workpiece, the material is detached from the workpiece through dissolution as the rotating tool approaches the workpiece. Several multiple downward movements are given for higher aspect ratio drilling. A For higher aspect ratio the drilling tool is retracted from the machining zone after every downward movement to replace the sludge and electrolyte with fresh electrolyte. The sidewall of the tool is insulated to minimize the taper formation of higher aspect ratio drilling and diametric overcut. The schematic diagram of EC drilling has been shown in Fig. 1.6.

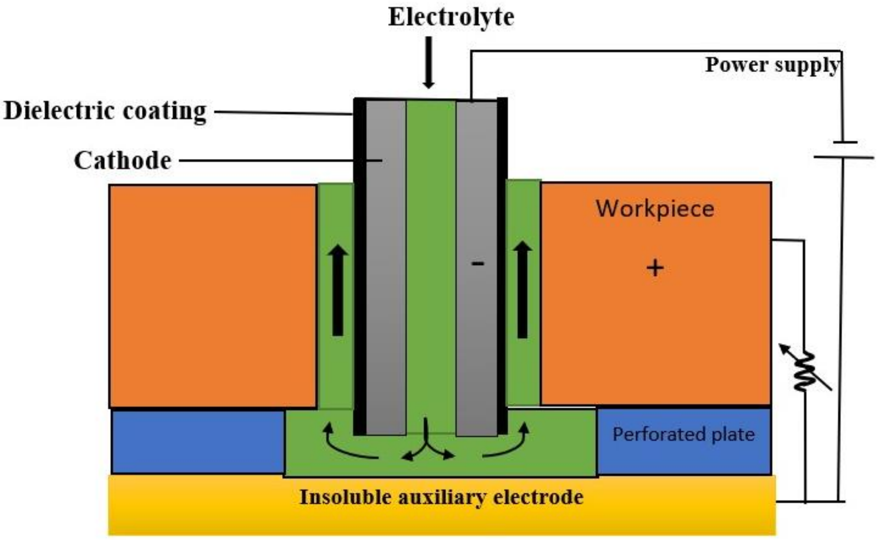


Fig. 1.6 Schematic showing EC drilling process

***(vi) Electrolytic in-process dressing (ELID) grinding***

This process is based on a metallic grinding wheel used as an anode while a copper or graphite electrode is used as a cathode. This electrolytic cell is placed on the grinding wheel diametrical to the point of chip formation during the grinding process. The lubricant used for the grinding process also helps as an electrolyte for the electrolysis. Electrochemical reactions will happen, depending on the boundary conditions. The metal bond in the grinding wheel undergoes dissolution according to the ECM principle in a specific passive area, i.e., the section where oxide layers cover the anode. During ELID grinding, usually, a pulsed voltage generator is used in order to produce the necessary electrolysis current. During the pulse duration (on-time) the nominal voltage is applied. The schematic diagram of the ELID grinding process is shown in Fig. 1.7.

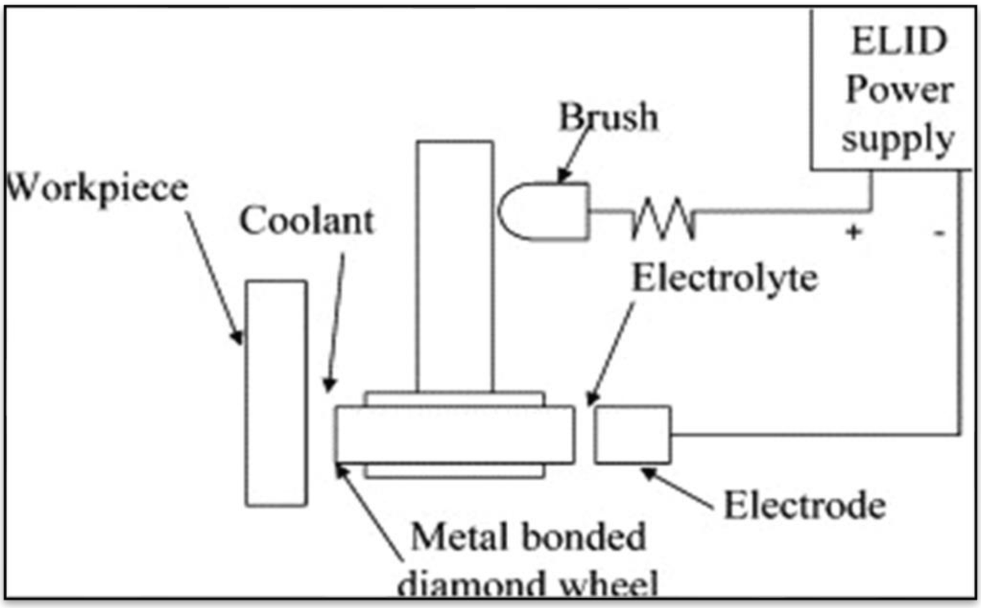


Fig.1.7 Schematic Showing ELID grinding

***(vii) Electrochemical Milling Process***

In this process, electrolytic dissolution is used for milling the workpiece. This process is usedfor the generation of complex features. As with conventional end milling, the tool also moves along a predetermined path in the case of EC milling. With the help of a simple geometrical tool, the material can be removed layer-by-layer. The electrochemical milling (EC milling) process has been elaborated further below.

**1.3 Principle of ECM Process**

In EC milling the material removal mechanism is identical to conventional ECM where electrochemical dissolution arises from the anode (workpiece). When a voltage difference is applied across a tool (cathode) and workpiece (anode) electrochemical reaction takes place and dissolves material from the workpiece as discussed in section 1.1. The tool shape complexity of the ECM process can be resolved in the EC milling process where a simple geometrical shape tool is used as a cathode. In this process, the job is connected to the positive terminal and the tool is connected to the negative terminal of a pulse or constant DC power source. In Fig. 1.8, the machining starting position and the instantaneous position of the tool during machining has been shown. The movement of the tool with the suitable speed in a predefined path is required to produce a desired geometry on the job. In EC milling tool moves in a predefined path and the whole machining depth is obtained through multiple downward steps. The number of layers depends on how much material is removed in a single layer. Similar to the conventional end milling processes, EC milling also removes material in the same layer-by-layer fashion. The geometry or the shape of the profile generated in the job can easily be altered by changing the tool movement path as of the need. The different profiles can be obtained by the same tool. The movement of the tool in the three axes system can easily be manipulated through the CNC X-Y-Z stage or control system. The electrolyte should be highly conductive inorganic salt solution e.g., sodium chloride (NaCl), sodium bromide (NaBr), sodium nitrate ($NaNO_3$), etc. Electrolyte pumped at the narrow gap with high-pressure value varies within 0.2 kgf/cm$^2$ to 5 kgf/cm$^2$and flow rate values are around 5 to 10 LPM. The generated sludge drives to the electrolyte in ultra-granular form. Their electrolyte should move through the filtration unit before it is pumped to the machining zone again.

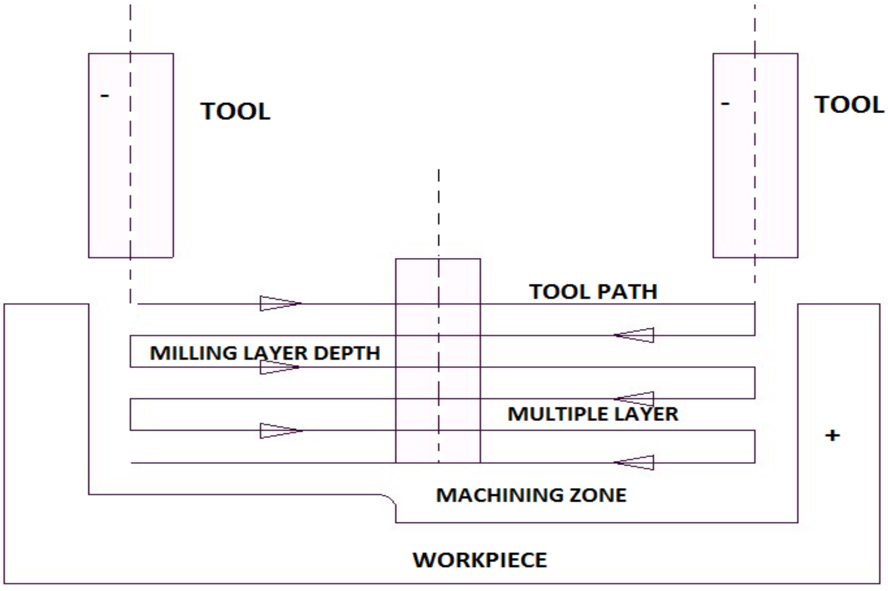


Fig. 1.8 Scanning Layer-by-layer method

## 1.4 Difference between EC Milling with Conventional Milling Process and Conventional ECM Process

EC milling process is the direct application of electrolysis with the technique of tool movement same as end milling. The material removal is completely due to electrochemical action. There are many striking similarities between these processes but both the processes can be distinguished easily with the help of the following discussions. A comparison between conventional ECM and EC milling and a comparison between EC milling and conventional end milling is shown in Table 1.1 and Table 1.2 respectively.

Table 1.1 Comparison between conventional ECM and EC milling

| **Characteristics** | **ECM** | **EC milling** |
|---|---|---|
| Energy type | Electrochemical | Electrochemical |
| Type of power | Constant DC | Constant/pulsed DC |
| Material removal technique | Ionic dissolution | Ionic dissolution |
| Tool design | Complex as the tool is replica of the desired machining zone. | Simple square or cylindrical shaped tool. |
| Shape of the machining profile | Completely depends on tool shape | Depends on the tool movement path. |
| Electrolyte flow system | Complex | Simple |
| No of passes required | Entire material removal in single run | Multiple pass |
| Magnitude of machining current | Moderate to high | Low to moderate |
| Pulsed DC | Difficult to achieve due to higher magnitude of current. | Can be possible due to lower magnitude of current. |

Table 1.2 Comparisons between EC milling and conventional end milling

| Characteristics | EC milling | Conventional end milling |
|---|---|---|
| Rotation | The tool has rotational motion. | The tool has rotational motion. |
| Passes | Multiple number of passes or a single pass. | Multiple number of passes. |
| Rotational axis | Perpendicular to the machine surface. | Perpendicular to the machine surface. |
| Energy type | Electrochemical | Mechanical |
| Electrolyte | Required | Not required |
| Heat generation | No | High amount of heat generation. |
| Tool | Only electrically conductive material | Should be harder than the workpiece. |
| Scrap | Sludge | Chip |
| Tool geometry | Simple shape | Complex geometry |
| Work piece mechanical property | Process independent of mechanical properties. | Completely depends on mechanical properties. |
| Work piece electrical property | Should be electrically conductive value desired. | No such requirement. |
| Material | Difficult to cut material can be easily machined. | Mostly Ductile material. |
| Stresses | No residual stresses | Residual stresses present at the machined surface. |

## 1.5 EC Milling of Titanium-Based Super Alloy (Ti6Al4V)

Titanium alloy is one of the most promising materials in the manufacturing industry. Today titanium and its alloys are widely used in the aerospace industry, chemical processing, medicine, power generation, marine and offshore, sports and leisure, and transportation industries. Titanium is the ninth most abundant element in the earth's crust and the fourth most abundant metallic element. Titanium and its alloys are promisingly used indifferent modern-day applications. The main benefit of titanium base super alloys is they can keep its major mechanical property at high temperatures. Therefore, it is called high strength temperature resistant (HSTR) alloy. It is one of the hardest materials at temperature more than 400°C majorly used in gas turbine blades. The density is roughly 4420 $kg/m^3$, with young'smodulus value of 120 GPa and tensile strength of 1000 MPa. Several non-conventional machining approaches has used as the major limitation related to tool material in case of conventional machining processes. The melting point temperature of titanium alloy is around 1700°C. High electrical conductivity value and electrochemical equivalence make ECM easier in case of titanium alloy than any other process. Control anodic dissolution is one of the major challenges in case of ECM of titanium alloy but mostly the sludge produced during the machining is electrochemically nonconductive which do not influence the dissolution process. In ECM process, material removal is directly proportional with the electrochemical equivalence, so titanium alloys can be machined by electrochemical dissolution. Therefore, 3D contour profile, complex shape in titanium alloy can be effectively generated by EC milling. Due to low modulus of elasticity this alloy gives excellent flexibility and it is also the most biocompatible material in comparison to other.

Due to some previously discussed properties of titanium alloys, it has been employed in many areas into versatile applications. As EC Milling can generate three-dimensional surface profile irrespective of mechanical property, this process is really suitable to machine titanium alloy. The working principle of EC Milling of titanium alloy is same as the working principle of general EC Milling. The process and hurdles of EC milling on titanium alloy are discussed in detail in the following sections.

### 1.5.1 Applications of Titanium alloy

Titanium can sustain environmental attacks regardless of pollutants. It can withstand urban pollution, marine environments, high temperature environments, sulphur compounds of industrial areas and even more aggressive environments. Because of these reasons, it is widely used in different areas as follows:

***(i) Aerospace Industry***

Titanium alloys have been used in different area of aerospace industry for its high temperature performance, creep resistance, strength, and metallurgical structure. Titanium is used for components of jet engine rotating applications. In the newest technology jet engines, wide titanium fan blades enhance efficiency of engine. Titanium alloys are used in airframe because of its high strength to density ratio.

***(ii) Power Generation***

In power generating plants, where saline, brackish or polluted waters are used as the cooling medium, titanium thin wall condenser tube can endure that and eliminates the need for a corrosion allowance. In, thermal power plant high temperature vapour strikes on the blade, thus HSTR materials like titanium alloys are use as titanium blades.

***(iii) Petroleum Industry***

In petroleum exploration and production, due to light weight of titanium, it used for making pipe line and it is an excellent material for deep sea production risers. In addition, titanium's ability to endure corrosion by sea water makes it the preferred material for top side water management systems.

***(iv) Automotive Industry***

In the automotive industry, uses are being developed for titanium in the automotive/motorcycle after markets and racing market. Engine parts such as connecting rods, wrist pins, valves, valve retainers and springs, rocker arms and camshafts are made of titanium alloy, because of its durability, strength, lightweight and resistance on heat and corrosion.

***(v) Computer Industry***

In the computer industry, titanium is a promising substrate for hard disk drives. Compared to aluminium, which is the primary material currently used, titanium provides significant advantages. Its non-magnetic properties prevent interference with the data storage process; its ability to withstand heat allows higher temperatures during the coating process, which improves manufacturing rates; and the purity of titanium permits closer read/write head tolerances, increasing disk capacity.

***(vi) Human Implants***

Titanium is completely inert to human body fluids, making it ideal for medical replacement structures such as hip and knee implants. Titanium actually allows bone growth to adhere to the implants, so they last longer than those made of other materials. Reconstructive titanium plates and mesh that support broken bones are also commonly used today.

***(vii) Armour Applications***

The high strength-to-weight ratio makes titanium well suited for armour applications. Used as protective armour personnel carriers and tanks, it makes the vehicles much lighter, increasing the mobility of the force. Personal armour vests and helmets for police made from titanium are far lighter and more comfortable than those made from competing materials.

### 1.5.2 Limitationsof machining of Titanium and its alloy

Titanium and its alloy have several applications in different fields but the conventional machining process cannot be performed in case of these materials. High strength temperature resistant alloy requires harder machine tool than alloy itself which is the main obstacle in conventional machining method. Conventional machining removes material in the form of chip but the generated chip is serrated in nature which renders the machining process. Therefore, non-conventional machining processes are suitable in case of titanium and its alloy. Conventional electrochemical machining, Electrical discharge machining, Wire EDM etc. have already been used very successfully to generate different kind of surface profile or complex feature in titanium and its alloy. Thermal energy base non-conventional process face problem during machining of titanium as the melting point temperature is very high. Mechanical energy base non-conventional process is ineffective as the hardness value of the material exceeds a certain range. So, with the help of high electrical conductivity and electrochemical equivalence value electrochemical energy base machining process can be conducted. Machining of titanium alloy is relatively different from electrochemical machining of commonly used material because titanium has a huge tendency of forming passive oxide layer. The tenacious passive oxide layer film which makes titanium very useful as a corrosion resistant material renders the electrochemical machining of this material. The choice of electrolyte e.g., type of electrolyte, concentration etc play vital role in ECM of titanium alloy.

### 1.6 Literature Review of Past Research Work

Michael Faraday established the laws of electrolysis at the beginning of 19$^{th}$ century. These laws are fundamentals behind the principle of electrochemical dissolution. In 1929 researcher W. Gusseff first developed the process to machine material through an electrolytic process. Since the time ECM had been developed and still advancement of the process is going on. ECM has received industrial importance due to its various advantages. As well as ECM also has various challenges those have been addressed by researchers to make the process more effective. Researchers are trying very hard to overcome these problems and investigations from different research work have been documented in this section.

Sarkar et al. [1] experimented on electrochemical deburring operation to remove burrs from the workpiece. In industry, burr removal had done manually but the removal of internal burrs of various size and shape sometimes become very difficult task. Researchers have removed burr by electrochemical dissolution and developed a mathematical model to analyse the characteristics of ECD. From experiments, they have found out the most influencing factors like time, initial burr height, inter-electrode gap, voltage and base material removal. The developed mathematical model is quite powerful to analyse and determine the deburring time as well as base material removal for a given parametric combination. From the experimentation, it was observed that initially deburring is high and higher voltage reduces the deburring time. Also, it was figured out that higher initial burr height requires more time and leads to more base material loss. Loss of base material is independent of electrolyte type, concentration, voltage and workpiece material. It is only function of inter-electrode gap setting, initial burr height and final desired burr height.

Vanderauwera et al. [2] focused on the electrochemical milling process by which the material is removed by a tubular tool following a predefined path in a layer-by-layer fashion. In this initial study, the influence of different process parameters, electrode geometry and electrode rotation on the process performance is investigated by the author. Experiments showed that the best performance in terms of removal rate, surface quality and accuracy can be obtained when using a pulsed voltage input. Moreover, inaccuracies due to the tubular electrode shape can be avoided by using alternative electrodes which distribute the flushing holes over the entire cross-section of the electrode or by decreasing the inner diameter of the tubular electrodes. Finally, specific milling aspects like performing multiple passes and step-over were investigated.

Rajurkar et al. [3] experimented with the new developments in electrochemical machining. Electrochemical machining (ECM) has traditionally been used in highly specialized fields such as those of the aerospace and defence industries. It is now increasingly being applied in other industries where parts with difficult-to-cut materials and complex geometry are required. In this paper, the author discussed the latest advances, and the principal issues in ECM 7 development and related research are raised. The author also covered Developments in tool design, pulse current, micro-shaping, finishing, numerically controlled, environmental concerns, hybrid processes, and recent industrial applications.

S. Pa et al. [4] performed an electrochemical turning operation to obtain a better surface finish for the work piece. In this experiment, various geometric tools have been developed to study the effect of the geometry of the tool on the finish of the machined surface. It has been found that a suitable rotational speed of the part associated with a higher rotation of the electrode can produce better polishing. It has been observed that the electrode of effective design with a small wedge angle and a small edge rounding radius has generated a smoother surface. The partial curve electrode with a small line diameter performed best for electrochemical polishing. It has been observed that electrochemical smoothing completely eliminates the need for precise turning, making total processing time less than electro-brightening. It was also observed that the requirement of high current can be reduced by effective tool design. It was understood that the electrochemical smoothing for the cutting operation was possible by attaching some simple equipment to a simple turning machine.

Bhattacharyya et al. [5] focused on the new possibilities for micromachining. A better understanding of high-rate anodic dissolution processes is urgently required for electrochemical micromachining (EMM) to become a widely employed manufacturing process in the electronic and precision manufacturing industries particularly in the micromanufacturing domain. The author has developed an EMM setup for carrying out in-depth independent research for achieving satisfactory control of electrochemical machining process parameters to meet the micromachining requirements. The developed EMM setup mainly consists of various sub-components and systems, e.g., mechanical machining unit, micro tooling system, electrical power and controlling system and controlled electrolyte flow system, etc. All these system components are integrated in such a way that the developed EMM system setup will be capable of performing basic and fundamental research in the area of EMM fulfilling the requirements of micromachining objectives.

Bhattacharyya et al. [6] emphasised the experimental investigation into the electrochemical micromachining process. A suitable EMM setup mainly consists of various components and sub-systems, e.g., mechanical machining unit, micro tooling system, electrical power, controlling system and controlled electrolyte flow system etc. have been developed successfully to control several electrochemical machining (ECM) parameters to meet the micromachining requirements. Investigation indicates the most effective zone of predominant process parameters such as machining voltage and electrolyte concentration, which give the appreciable amount of material removal rate (MRR) with less overcut.

Rathod et al. [7] experimented with the process parameters on EMM set up development. Product miniaturization is the principal driving force for 21$^{st}$ century's industries because of the escalating demands for compact, intelligent, robust, multi-functional, and low-cost products in all fields. As the demand of miniaturized products is exponentially increasing, the need to manufacture such products from advanced engineering materials becomes more apparent. Design of microtools, tool wear, surface quality, burr and heat removal are the main challenges in various micromachining methods. Electrochemical micromachining is one of the important techniques because of its special material removal mechanism, better precision and control, environmentally acceptable, and mainly it permits machining of any metallic materials irrespective of its hardness. For better understanding of EMM process, the author discussed the basic concepts such as electrochemistry, Faraday's laws of electrolysis, electrical double layer, equivalent electrical circuit, and material removal mechanism. Significant process parameters which affect the process performance, need of EMM setup development, various subsystems, along with the challenges in setup developments, and important techniques for improving the machining accuracy have been highlighted. The author also discussed Machining, finishing, and surface engineering applications of EMM, as well as recent advancement in EMM for micro and nanofabrication in this paper.

Nguyen *et al.* [8] studied of transitions of micro-EDM/SEDCM/micro-ECM milling in low-resistivity deionised water on same machine set up. For having slight conductivity, deionised water was used as a bi-characteristic fluid to combine micro-EDM and micro-ECM milling in a unique machining process which had been termed as SEDCM milling. In this experimentation, the criteria for three distinct machining modes micro-EDM/SEDCM/micro-ECM milling were determined based on the thickness of material layer that electrochemical reaction could dissolve when the electrode scan over the surface. The critical feed rate for transitions of material removal mechanisms were predicted using double layer theory, Butler–Volmer equation and Faraday's law of electrolysis. It was figured out that the SEDCM milling was only possible at moderate feed rate. It was postulated from the experimentation that for high feed rate, machining mode was changed to micro-EDM milling alone as the thickness of material layer that electrochemical reaction could dissolve was smaller than the roughness of micro-EDM surface.At the end, it was found that lower feed rate was used for SEDCM milling when higher layer depth was used because more material needs to be removed by the sparks in every feed.

Mishra et al. [9] gave us the idea on the mathematical modelling of the volumetric material removal for various complex shapes generation on Ti6A14V. Generation of accurate complex shaped products on various HSTR alloys is a key feature for many kinds of machine parts widely used in industries starting from biomedical to defence industries. However, producing these kinds of complex features using traditional processes face great challenges due to the thermo-mechanical effects. Being free of tool wear, thermal stresses and residual stresses, electrochemical machining (ECM) has the potential of machining of those materials. The electrochemical milling (EC milling) process is similar to conventional ECM in which metal is removed in a layer-by-layer fashion with simple geometric tool by moving a predefined path. Not only it is difficult to produce complex shaped products on various HSTR alloys but also it is almost impossible to predict the volumetric material removal prior to the production. In this paper author concluded that by using empirical formula, the volumetric material removal of EC milling process is mostly dependent on the process parameters like feed rate and milling layer thickness.

Zhang et al. [10] proposed on electrochemical milling of narrow groves with high aspect ratio using a tube electrode. This paper proposes a novel method of electrochemical milling using a tube electrode to fabricate a DNG by single-pass milling. A multi-physics coupling model, including a gas-liquid two-phase flow field and an electric field, was built to investigate the flow field distribution in the inter-electrode gap as well as the current density distribution at the DNG edge with different electrolyte pressures. The simulation and experimental results indicated that a higher pressure was associated with a high electrolyte velocity, and had a significant influence on the machining process.

Mishra et al. [11] presented on electrochemical milling using different electrolytes on the material like Ti6A14V which is extensively used in different field starting from defence to bio-medical industry. Study of comparative effects of different electrolytes on various performance characteristics on titanium alloy, is the soul of this paper. Commencement of making simple shape grooves to complex shape i.e., ‘L’ shaped feature was machined by means of electrochemical milling process with layer-by-layer fashion. In each layer, the tool was controlled to move along a predefined path with a multi downward step. ‘L’ shaped features were machined on Ti6Al4V using three different electrolytes by varying feed rates and frequency followed by the corresponding effects on various performance characteristics were studied. It was observed that NaCl (0.5 M) + $NaNO_3$ (0.5 M) mixed electrolyte gave better result compare to the other two electrolyte as far as accuracy and surface finish of the features were concerned. It was also observed that performance characteristics other than depth and surface finish was improved with increasing feed rate and frequency up to a certain limit and after that short circuit was occurred. After analysing all the graphs and figures, the author concluded that to achieve better accuracy and surface finish, type of electrolytes, feed rate and frequency are the major important factors of EC milling.

Minglu Wang and Ningsong Qu [12] focused on the investigation on material removal mechanism in mechano-electrochemical milling of TC4 titanium alloy. With the advantages of electrochemical milling (ECM) and conventional milling (CM), mechano-electrochemical milling (MECM) is effective for shaping titanium alloys. Author focused on in depth investigation of the material removal mechanism in the MECM of TC4 titanium alloy. There are three material removal processes in MECM, and a model for each is established. To generalize the MECM material removal mechanism, the first ($v_{ff}$) and second ($v_{sf}$) critical feed speeds are defined: when the feed speed is less than $v_{ff}$, the MECM material removal process is that of ECM; when the feed speed is between $v_f$ and $v_{sf}$, the process is that of ECM→CM→ECM; when the feed speed exceeds $v_{sf}$, the process is that of CM→ECM. When the MECM material removal process is ECM→CM→ECM, the difference in material removal rate between MECM and pure ECM is the largest, showing the higher machining efficiency of MECM. Also established is a mathematical model for calculating the relative contributions of ECM and CM during MECM.

Wang et al. [13] focused on the experimental studies on micro electrochemical slab milling using disc tool electrode. In this study the author proposed a method of micro-electro chemical slab milling with disc electrode for fabricating microgroove structures on the surface of the workpiece. The disc electrode is prepared by micro-WEDM and subsequently used for micro-electrochemical slab milling process. The effects of the main electrochemical parameters, such as electrode feed rate of disc electrode and pulse width of power generator, on the width of the micro groves and surface quality on 304 stainless steels were discussed by the author.

Hinduja et al. [14] performed an electrochemical milling operation. A mathematical model has been proposed and simulated. The experiment was conducted for study of electrochemical through some simple features such as slots and pockets generation. Preliminary experimentation was done by machining a simple slot feature. The researcher has found out suitable process parameters through machining a simple square pocket and slot. The tools used for machining were circular cross section tool and square cross section tool. It was found that a larger machining profile was generated using a square shaped tool instead of a circular tool. At the end of the preliminary experiment, human being shaped protrusion has been machined. The pocket feature has been machined by tool travel in zigzag and parallel-contour tool paths. It has been found that accuracy of machined profile is independent of tool path but completely depends on tool geometry and other process parameter. It has been discovered that surface finish and precision are similar in both zigzag and contour movement o tool. Shape prediction of the machined profile has been done by a boundary element which is almost alike desired profile.

C. Chen et al. [15] experimented micro-groove machining by micro-ECM process. In the study, the influential process parameter parameters such as the voltage, time and frequency of the pulse generator, the flow of the electrolyte on the machining performance such as the rate of removal of material and the accuracy of the micro-groove machining were studied. Micro-ECM equipment has developed and total 19 grooves were machined with a pulse generator of the order of nanosecond. It has been found that the radius of the curvature, the taperness of the side wall and the bottom surface of a groove vary with the voltage, pulse on time, the frequency of the pulse, the electrolyte system without affecting MRR and surface roughness. Both the radius of curvature and the taperness of the sidewall have been increased due to the increase of the magnitude of the pulse voltage as well as the pulse on time. The double nozzle electrolyte system was used to shorten the geometric deviation such as the wedge and taper of the right and left side walls of a groove. The symmetrical distribution of the electrolyte flow using a double nozzle jet system led to the uniform removal of the material on both sidewalls. As a result, the machining accuracy has been significantly improved over the use of a single jet nozzle system to provide the electrolyte.

Ghosal et al. [16] investigated electrochemical micromachining by generating micro channels. Researchers have used various shapes of a tool like the straight tool, conical tool and reverse taper and simulated models of voltage distribution. It was obtained from the simulation model that the less taper angle could be achieved for reverse taper tool and experimentally validated. The micro channel was generated following two types of tool paths; one was scanning method another was sinking and milling method. It was observed that higher side angle was generated for sinking and milling method but the surface roughness was less for scanning method compare to sinking and milling method tool path.

Liu et al. [17] used the in situ fabricated cylindrical electrode for electrochemical milling of the complex feature. During the experiments a mathematical model of electrochemical milling was established to get an idea for the shape of the tool. The mathematical model was entirely based on mono directional volumetric material removal with variable feed rate. At the end of the model, it has been proved that to obtain a good accuracy machining profile the thickness of the milling layer must be smaller than the diameter of the tool. First the in situ fabricated tool was manufactured by a reverse electrolysis process. The tungsten rod that was made was gradually dissolved and its diameter has decreased. The shape of the rod retained a uniform cylindrical shape throughout the etching process because the tungsten rod was positioned in the centre of the cylinder. To control the diameter of the electrode, a mathematical relationship has been developed over time. From the equation, it was determined that changes in tool diameter decreased with increasing machining time of reverse electrolysis. At the end of tool fabrication, experiments were conducted to investigate the effect of milling layer thickness on performance characteristics It was also determined that the machining side gap increased significantly with increasing electrolyte concentration, pulse time, machining voltage and tool diameter.

Xu et al. [18] performed Electrochemical machining of high-temperature titanium alloy Ti60 (Ti–5.6Al–4.8Sn–2Zr–1Mo–0.35Si–0.7Nd). This particular alloy has used for manufacturing critical component of aero engine. According to researcher ECM is the best process for machining high temperature difficult to machine material but the ECM for this alloy is quite different from other alloys. The anodic polarization curve, open circuit potential and actual volume electrochemical equivalent–current density curve of Ti60 is obtained and the electrochemical dissolution behaviour of Ti60 is analysed. Better electrochemical Mach inability is achieved using sodium chloride electrolyte. Dissolution experiments are performed at different current densities, and results show that the surface roughness of Ti60 undergoing ECM deteriorates when the current density is small. Finally, electrochemical parameters like composition concentration and temperature of the electrolyte used are optimized and a blink sector made of Ti60 is machined by ECM. The maximum machining rate of the channels was more than 1.2mm/min. Researchers were successful to achieve best surface roughness Ra 0.6 μm, and the machining accuracy of the blade profile 0.05–0.07mm.

S. D. Dhobe et al. [19] carried electrochemical machining process in a titanium alloy and studied the surface characteristics of titanium machining for biomedical application. An experimental ECM setup has been developed to allow the cross-flow electrolyte supply system. The developed cross-flow electrolyte supply system was used in electrochemical machining and studied the effects on surface characteristics on titanium samples. From the experimental result it was observed that the flow velocity of the electrolyte and the voltage between the electrodes were parameters strongly influence the surface characteristics. It was observed that the rate of material removal was increased to increase the working voltage as well as the flow rate of the electrolyte. Other responses, such as surface quality, current efficiency, have been improved for higher electrolyte flow. It has been observed that a titanium oxide layer is formed on the machined surface due to the electrochemical reaction during machining. The formation of the titanium oxide layer on the titanium was useful for improving the corrosion and chemical resistance of the titanium implant.

Grove et al. [20] observed an experiment on residual stresses in Annealed Ti6Al4V. Residual stresses can cause part distortion, especially in the case of large components such as structural parts in the aerospace industry. Therefore, this paper investigates machining-induced residual stresses for milling of a workpiece material with increasing usage in industry, the E-annealed titanium alloy Ti6Al4V. This thermal treatment results in a large-grained material structure. For this reason, X-ray diffraction, the standard residual stress measurement method, cannot be used for stress determination. In this paper an adopted indirect measurement method, the layer removal method is discussed. With respect to the material removal, two different methods are investigated, electrochemical material removal and laser ablation. Finally, the influence of the tool wear on the residual stress state after face milling is analysed.

Van Camp et al. [21] proposed a new hybrid process Mechano electrochemical milling for machining of high strength temperature resistant alloy in industry. Researchers have used combined effect of both conventional milling and electrochemical machining process. Principle of this process has depicted and to present the utility of this process experimental investigation carried out on Ti6Al4V. From the experiment a comparative study between ECM and MECM with respect to material removal rate and accuracy of the machined profile shape has also presented. During experiments some slot has been machined in Ti6Al4V with the help of a dedicated tool. From experimental results it has been observed that the material removal rate has increased up to 60 % by this hybrid machining process. Along with partial removal of oxide layers which renders the ECM of titanium some amount of base material has also been removed by conventional milling component due to hill effect. Finally, it has been concluded that the both the electrochemical and mechanical component of the MECM process has participated in the material removal process.

Zhang et al. [22] experimented on Electrochemical milling of narrow grooves with high aspect ratio using a tube electrode.Metallic narrow grooves with high aspect ratio, referred to here as deep narrow grooves (DNGs), are used widely in precision instruments, medical devices and other industries. Therefore, this paper proposes a novel method of electrochemical milling using a tube electrode to fabricate a DNG by single-pass milling. A multi-physics coupling model, including a gas-liquid two-phase flow field and an electric field, was built to investigate the flow field distribution in the inter-electrode gap as well as the current density distribution at the DNG edge with different electrolyte pressures. Then, systematic experiments were performed with different machining parameters (including electrolyte pressure, pulse parameters and feeding speed) to investigate their influence on the DNG dimensions; with the optimized parameters of an electrolyte pressure of 0.9 MPa, applied voltage of 12 V, pulse frequency of 9 kHz, pulse duty cycle of 40 % and feeding speed of 0.36 mm/min, a complex narrow groove of width 1.32 ± 0.02 mm (mean ± standard deviation) and depth 8.05 ± 0.01 mm was well fabricated with single pass milling, and the aspect ratio reached 6.1, showing a high precision and efficiency machining method.

Wang et al. [23] experimented on the effect of electrochemical polishing on surface quality of nickel-titanium shape memory alloy after milling. This paper proposed a sequential processing operation including milling, burnishing and electrochemical polishing. The effects of electrochemical parameters on surface quality, such as surface roughness, work hardening and surface grain size, are investigated in detail using orthogonal experiment. It is found that the electrochemical polishing parameters have the most significant effect on improving the surface roughness. With adjusting electrochemical polishing parameters, the surface roughness can be reduced to one tenth of the original value obtained by milling operations. Moreover, the current density in electrochemical polishing has more important influence on the surface quality than the distance and polishing time does, respectively. The conditions of 1.5 A/cm2 current density, 7 cm electrode distance and 20 s polishing time can obtain the lower surface roughness, hardening degree and the larger grain size. The effects of electrochemical parameters on surface roughness, work hardening and grain size are related to each other. The degree of work hardening can be qualitatively estimated by surface roughness and grain size to avoid damage to the machined surface.

Speidela et al. [24] did electrolyte jet machining on titanium alloys using novel electrolyte solutions. In the experimentation, material was removed through highly localised electrochemical dissolution by electrolyte jet. In this study, various electrolytes were investigated for the purpose of establishing more stable machining and controlled removal of the passivation layer. Surface finish, material removal rate and pit formations using solutions of sodium halides (bromide, chloride and fluoride respectively) were compared with using sodium nitrate solution. The concentration of each electrolyte was varied also to check the applicability of each solution. It was figured that removal rates increased by over 100% using Sodium chloride at concentrations less than 2.5M compared with using sodium nitrate electrolyte. It was shown from the experimentation that doping of sodium chloride electrolytes with sodium fluoride decreased the overcut effect in machined pits by half compared with the pits formed in chloride, bromide, and nitrate electrolytes.

Tak et al. [25] investigated about the pulsed electrochemical micro-drilling on titanium alloy in the presence of complexing agent in electrolyte. Titanium and its alloys have excellent mechanical and chemical properties; however, these properties make the processing of titanium alloys more challenging compared with other engineering materials. Electrochemical micromachining (ECMM) is a non-conventional machining process, which removes material through anodic dissolution regardless of the material's hardness. However, during the electrochemical machining of titanium, the formation of a passive oxide layer inhibits further material removal and deteriorates the machined surface quality. In addition, the accuracy of micromachining of titanium alloys is especially affected by the formation of electrolysis precipitates such as $TiO_2$ and stray current dissolution. In this study, the effect of the addition of the complexing agent to different electrolytic solutions on the radial overcut during micro-drilling of titanium alloy grade 5 (Ti6Al4V) has been experimentally studied using the in-house developed ECMM set-up. The influence of parameters such as applied voltage and different electrolytic concentration with and without the complexing agent on overcut during ECMM on Ti6Al4V of micro-holes has been studied. It has been safely concluded that the quality of micro-holes fabricated in the presence of EDTA in the electrolyte while machining is responsible for better dimensional characteristics.

He et al [26]. experimented on the influence of EDTA-2Na on the hydroxyapatite coating deposited by the hydrothermal-electrochemical method on Ti6AL4V.The influences of the Ethylenedi-amine Tetra-acetic Acid Disodium salt (EDTA-2Na) on the hydroxyapatite (HA) coating deposited by hydrothermal-electrochemical methods on the Ti6Al4V surface were investigated. The morphology of the HA crystals of the first layer changed from needle- or rod-like to flowerlike. The HA crystal became wider and the first layer became denser gradually, whereas the second layer became sparser. The thickness of the HA coating gradually decreased with the increase of EDTA-2Na concentration in the electrolyte. The bonding strength between coating and substrate reached the maximum of 16.8 MPa when the EDTA-2Na concentration was $7.5 \times 10^{-4}$ mol/L. The cell-culture test indicated that the HA coating with $7.5 \times 10^{-4}$ mol/L EDTA-2Na benefits the adhesion of cells onto the HA surface.

## 1.6 Objectives of the Present ResearchWork

From the literature review, it can be observed that several research works have already been done on ECM and EC milling. It can also be understood that the researcher may not be able to find out the most influential process parameter for EC milling. The complex profile with good surface finish onthe HSTR alloy especially titanium alloy is one of the biggest challenges for the EC Milling process. In this research work, attempts have been made to find out the most influential process parameters of EC milling and their effect on various performance characteristics mainly surface finish criteria. Hence, the main objectives of this research work are stated below:

(i) To design and modify the EC milling set up which may consist of different sub-units such as mechanical unit, electrolytic supply unit, power supply unit and control unit etc. The modified EC milling setup should be capable of performing EC Milling experimentation for investigating the surface finish of machined workpieces of titanium alloy e.g., Ti6Al4V.

(ii) To identify the different problems related to the existing Electrolyte Through System (ETS) and to overcome those issues by modifying the system.

(iii) To investigate the most influencing EC milling process parameters such as dwell time, duty cycle etc. and their influence on various major performance criteria e.g., surface finish and overcut through extensive experimentation during machining of Ti6Al4V.

(iv) To improve surface finish and accuracy of machined titanium alloy i.e., Ti6Al4V workpiece, attempt to be made by employing chelating agent such as Ethylene di-amine tetra acidic acid (EDTA) in the electrolyte during EC milling process.

# CHAPTER 2

## 2 FUNDAMENTALS OF EC MILLING

EC milling is an advancement of the conventional electrochemical machining process which is used to generate complex 3D and surface profiles with the help of a simple shape tool. The complexity in tool design of conventional ECM is completely removed by the EC milling process effectively. This method utilizes the ECM principle for material removal although the basic strategy of this process is different from the conventional ECM process. This process integrates flexibility and automation with the capability of ECM by consuming lower power. The basic strategy of this particular process is the same as End Milling where the tool rotation and the predefined tool travel path is the main criteria to attain the desired machining profile. EC Milling can be done by two methods as discussed below.

### *(i) Scanning layer-by-layer method*

Scanning method includes the milling process in layer-by-layer fashion alike to scanning of a feature through different layer. During machining the path of tool travel is important as it will decide the form and accuracy of the machined profile. The tool travel in case of scanning method has shown in Fig. 2.1(a) the obtained depth during machining has been achieved through a number of layers.

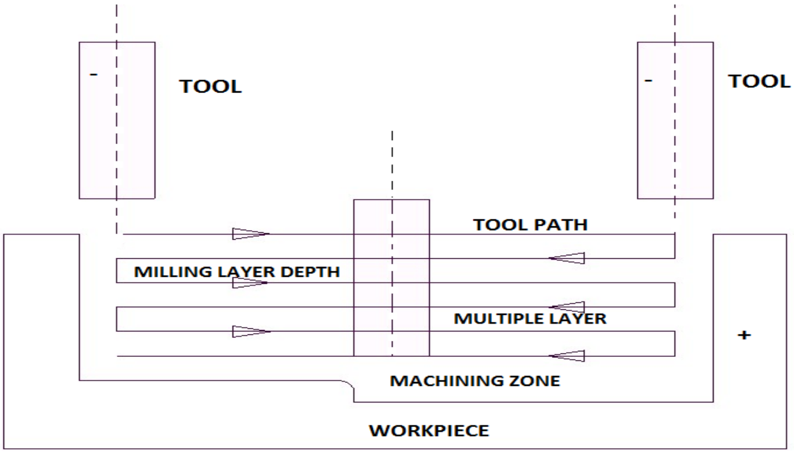


Fig. 2.1(a) Scanning layer-by-layer method

### *(ii) Sinking and milling method*

Sinking method resembles the meaning sinking as the tool achieved the whole depth in a single travel. As the machining started the tool at first sinks to the desired depth value then the tool travel starts to the XYZ direction. The generated profile has been obtained through a single pass only. The tool travel in case of sinking and milling method has shown in the Fig. 2.1 (b)

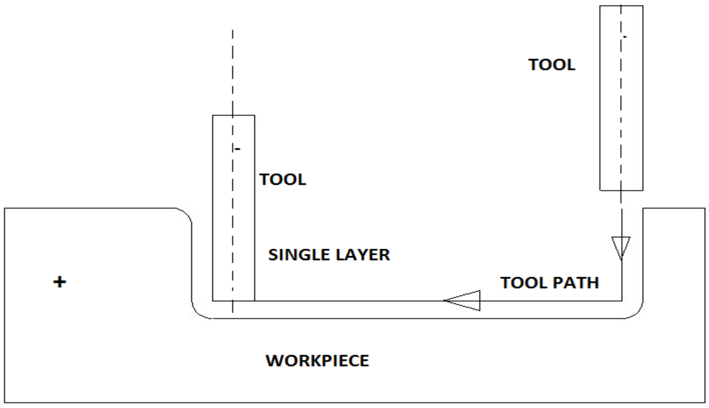


Fig. 2.1(b) Sinking and milling method respectively

The basic difference between these two processes is the milling layer depth to get the desired depth. In Fig. 2.1 (a) and (b) generation of blind channels through both the processes are shown. In case of sinking and milling method, one slot is produced in a single pass and there is a chance of end deviation at the initial point. At the tool sink point, there is a chance of getting larger width and depth than the desired. But in the scanning method same slot can be produced by a number of passes. With a single milling layer depth, another problem that arises in sinking method, especially in macro domain, is ineffective sludge removal at higher depth. A large volume of sludge is produced during the sinking and milling method in comparison of scanning. The accumulation of sludge at the instantaneous machining zone directly leads the tool to touch the workpiece which causes spark, which leads to tool damage.

## 2.1 Process Parameters of EC Milling

Though EC Milling is a modification of ECM, there have some distinguishable features which differfrom the process with ECM process. To perform EC milling, the understandingof the basics of the process is required. The various process parameters determine the EC milling process and the output of the process is checked by its performance characteristics.The major process parameters of EC milling are as follows

### *(i) power supply unit*

Nature of power supply means whether the power supply is constant DC type or pulse type. For a constant DC power source, continuous dissolution occurs, thus average machining current and material removal rate are high. On the other hand, as continuous material removal has occurred, the fresh electrolyte does not get adequate time to replace the sludge and hampers the dissolution process and it can also lead to short circuit. In case of pulse type power supply, voltage has given periodically in any form. When dissolution is occurred during pulse on time and no machining is done during pulse off time. Hence fresh electrolyte supplied and replace the sludge during pulse off time, thus machining quality is enhanced.

### *(ii) Applied voltage*

The applied voltage is one of the most influential process parameters in EC Milling. As Applied voltage is one of the most influential process parameters in EC Milling. As voltage is applied to overcome the resistance of the electrolyte and another element also helps to conduct the electrolysis process. Sufficient voltage differences should be given to overcome the double layer formation. Pre-set voltage determines the electrochemical dissolution ratethus, it also determines the time required to complete the machining operation.

### *(iii) Machining Current and Current density*

The flow of current from the anode to the cathode through the electrolyte is the main cause behind electrolysis. The electrochemical dissolution rate is directly proportional to the machining current. Another term current density which is the ratio of machining current and tool surface area also has a great impact on the process. Higher the machining current density indicates the higher dissolution of atoms from anode material. Therefore, higher machining current density leads to higher electrochemical dissolution as well as a higher amount of material removal. Uncontrolled material removal rate due to high machining current density also leads to overcut and deterioration of other performance characteristics. So,themachining current should be controlled carefully.

***(iv) Frequency of Pulse DC power***

When pulse DC voltage is used, frequency is one of the major important parameters. The Time period of the pulse cycle is inversely proportional to the frequency. Thus, higher frequency leads to a lower machining time in a single period. As the double layer charging time is constant for a set of process parameters, thus machining on time should be higher than the double layer charging time.

***(v) Duty ratio of Pulse DC power***

The duty ratio is defined as the ratio of machining on time to the total time period of a single pulse cycle. Thus, a higher duty ratio meanshigher machining on time which leads to higher overcut. On contrary, a lower duty ratio leads to lower overcut as machining on time reduces.

***(vi) Initial inter -gap (IEG)***

Initial IEG is the distance between the tool and workpiece before the start of machining. The electrochemical reaction starts when the tool is at the IEG position. Resistance in electrolyte increases with the increment of the distance between tool and workpiece. Thus, higher initial IEG may lead to discontinuous dissolution or much higher initial IEG may restrict dissolution to occur. Again, electrolyte cannot reach between tool workpiece interfaces for very low initial IEG, thus short circuit will occur. So, initial IEG is major important parameter and should be selected carefully.

**(viii)** ***Tool Feed rate***

The speed at which the tool is travelling over workpiece is called tool feed rate. It is the relativespeed between tool and the workpiece. Feed rate is one the most influential parameters on ECMilling. Higher the feed rate means lower the tool workpiece interaction time, thuslower the dissolution rate. On the other hand, lower feed rate directly leads to deterioration of machining accuracy with the higher overcut value. So, higher the feed rate means reducing material removal, a much higher feed rate may cause a short circuit phenomenon as the tool touches the workpiece in the subsequent passes. Very low feed rate causes larger overcut leading to dimensional inaccuracy and taking higher machining time.

### (ix) *Milling Layer Depth (MLD)*

The importance of MLD is higher is a case of the scanning method as the scanning method requires a greater number of passes. As the MLD in case of single pass has to be selected very carefully otherwise the disturbance in inter electrode gap may cause short circuit or deterioration of machining performances. Similar to conventional milling, in case of EC Milling operation also, material is removed layer-by-layer fashion. The thickness of layer to be removed in each milling pass is called milling layer thickness. This thickness determines the performance characteristics greatly. If the thickness of layer is higher than the dissolution in vertical direction for every pass then short circuit may occur. On the other hand, if layer thickness is very low, no of milling pass will be more. Thus, tool will react with workpiece for longer period which will make machining time longer as well as larger overcut.

### (x) *Type and concentration of electrolyte*

Selection of appropriate electrolyte is very important task. As material removal mechanism is based on electrochemistry, thus electrochemical property of electrolyte is one of the most influential parameters. Electrolyte is chosen depending on the type of workpiece as the reaction will be occurred between the electrolyte solution and workpiece. Higher the concentration of electrolyte means the more availability of ion in the solution which accelerates the dissolution and lower concentration means depletion of ion and lower material removal. So, concentration of electrolyte also should be selected carefully.

### *(xi) Electrolyte pressure and flow rate*

Electrolyte should reach in between tool and workpiece to carry out the dissolution of the anode material. When complex job or higher aspect ratio job is machined electrolyte flow should be high to reach the intricate zone. Otherwise, the sludge present at that zone hampers the dissolution process. Ineffective removal of sludge also leads to short circuit. In EC milling the use of rotating tool enhance the flow of electrolyte and help it to reach the intricate zone.

***(xii) Tool rotational Speed***

In EC milling tool rotation has a great impact on the performance of the process. Tool rotational speed is as important as electrolyte flow pattern is directly influenced.

**2.2 Performance Characteristics of EC Milling**

The performance of EC milling is dependent on the various process parameters that have been discussed in the earlier section. To generate a complex 3D or surface profile through EC milling the measured or obtained values of performance characteristics decide the quality or accuracy of the machining. Various important-performance characteristics are illustrated below

***(i) Surface Quality***

Surface quality indicates the condition of the surface produced by EC milling process. Generally, ECM has better surface quality than any other non-conventional machining process. In comparison to ECM EC milling has more improved surface finish. Surface finish of the machined profile mainly depends on the rate of anodic dissolution and the quality of sludge produced during machining. Property of sludge has great impact on anodic dissolution hence affecting the surface finish of the machined zone. Surface finish quantified by surface roughness value e.g., Ra, RMS, Rp, Rz values etc. Generally surface roughness value of EC milling is near 1 micron for Ti6Al4V but for nimonic 263 alloy it can be within the range of 0.07 to 0.08 micron.

***(ii) Geometrical Feature***

The Geometrical feature is quantified by the various dimensional variation of the machining zone in comparison to the desired. Various geometrical performance characteristics are listed below.

*(a)* ***Overcut***

Overcut of the machined profile is the most important performance criterion which decides the dimensional accuracy. Overcut is the difference of dimension of obtained machined profile and desired machined profile. There are various overcut in EC milling process, such as length overcut, with overcut, depth overcut etc. Generally, it is measured in terms of mm.

*(b)* ***Perpendicularity of sidewall***

Generation of a contour or complex 3D structure is very tough through ECM. As the generated 3D profile does not have perpendicular wall with the base. In conventional ECM taper wall formation or round edge between base and side wall is undesired and should be minimized. The roundness can be quantified by measuring radius of curvature. In EC milling the divergence of wall is far less than conventional ECM process.

*(c)* ***Corner radius***

While machining with simple shape tool when the tool changes its direction from X to Y directione.g., 'L' shape generation the edge between two directions should be perpendicular. Stray current plays a vital role in ECM as well as in EC milling, the junction in between them possesses a roundness. It is called corner radius. It is an undesirable property deteriorates the dimensional accuracy. Generally, it is measured in terms of mm.

*(d)* ***Flatness***

Flatness accounts for the base profile of the surface obtained after machining through EC milling. Inhomogeneous dissolution is one of the main purposes behind the deterioration of the surface flatness.

***(iii) Material removal rate (MRR)***

MRR is one of the most important performance characteristics in any machining process.The material removal rate is the material removed during EC milling by unit time. As discussed earlier, higher current density, higher machining voltage, higher duty ratio higher feed rate and lower frequency enhance material removal rate in EC milling process. Generally material removal rate is calculated by the difference of weight of the workpiece before and after machining divided by the machining time and it is expressed as gm/min. Sometimes material removal rate is also expressed in terms of volume, in that case it is called as volumetric material removal rate and it is expressed as cubic $cm^3$/min.

## 2.3 Advantages of EC Milling Process

As discussed in chapter1 EC milling is a very advantageous in comparison to the other nonconventional as well as other electrochemical processes. For its various advantages, it is a unique process. Material removal with the help of electrochemical dissolution and strategy of the end milling process makes it unique. The major advantages of EC milling processes are as follows:

(i) The major advantage is the less complexity in tool design in comparison to the conventional/die sinking ECM process. In the conventional ECM process tool should be the mirror image of the obtained profile. But in the case of EC milling simple shaped tool is used for generating any shape of the profile.

(ii) This process can machine material irrespective of their mechanical property so; any kind of conductive HSTR material can be machined by EC milling process.

(iii) EC milling does not employ any mechanical force to remove material, so no residual stress is developed on the workpiece. In fact, the mechanical property of the workpiece remains unaltered after the machining.

(iv) No heat-affected zone or thermal cracks are produced on the workpiece surface because no thermal energy is utilized for machining.

(v) No special electrical arrangement or power supply is required as the small simple shape can machine small as well as for large machining profile.

(vi) Sometime oxide layers are formed during the machining by EC milling which acts corrosion-resistant to the environment and protects the material. In the case of ECM oxide layer renders the further dissolution of some materialbut in the case of EC milling removal of the oxide layer is possible in low voltage.

(vii) Both Pulsed, as well as constant DC power supply is effective as the removal ofsludge from the machining zone is very easy in case of EC milling.

## 2.4 Various Challenges on EC milling Process

EC milling process can easily generate complex profile; but there have been various difficulties to perform the process. To find out the solution of difficulties, implementation of that particular process is very necessary. The challenges of EC milling process have been stated below:

(i) In EC milling generation of complex profile is possible through a simple shape electrode. The main criterion behind this is the predefined path for the tool movement. The tool motion should be controlled in precise manner to get accurate profile. Highly accurate position controller or motion controller required for tool movement, which leads to high setup cost.

(ii) Design of Electrolyte flow system is one of the most remarkable challenges of EC milling. It can be overcome by two ways. One is to supply the electrolyte through the tool and another way is to supply the electrolyte concentrically with the tool. In EC milling, tool is continuously moved along the required path, thus electrolyte jet should follow the tool to reach the electrolyte between tool and workpiece always. Thus, electrolyte flow system should be developed in such a way that it can reach all the time in the intricate machining zone properly. The most effective solution is flow of electrolyte through the tool i.e., internal flushing.

(iii)Rotating tool is required for improvement in the performance characteristics. So, internal flushing with tool rotation makes the design of the setup more complex.

(iv) In EC milling, relative movement in between tool and the workpiece is necessary, so it is very difficult to control the anodic dissolution in dynamic condition of tool.

### 2.5 Different Applications of the EC Milling Process

The global requirement in various field of manufacturing is increasing day by day, thus requirements of the advance manufacturing process is also increasing. With the variety and complexity of product manufacturing processes also to be developed to meet the challenges. In this scenario, EC milling has various significant applications starting from the aeronautical industry to the medical industry. Some specific applications are discussed below:

(i) During bio-medical implantation the artificial components have complex shape to match with the biological shaped of that part. This type of profile can be generated by EC milling process. Mainly bio medical implants consist of titanium and its alloys which can be effectively machined by EC milling very effectively.

(ii) The turbine blade of the power plant has complex surface profile (aero dynamic design), which can be fabricated by EC milling process. Micro holes, channels, arrays etc can be produced by EC milling. Turbine blade use high strength temperature resistant alloy in modern days and any HSTR alloys fabrication is possible with EC milling process.

(iii) Various components like gas turbine engine, rotating parts of the jet engine, body of the aerospace are generally made of HSTR materials and have complex shape. It is easy to generate these shapes by EC milling process.

# Chapter 3

## 3 DESIGN AND MODIFICATION OF EXPERIMENTAL SETUP OF ELECTROCHEMICAL MILLING

To identify the different problems related to the existing ETS unit and to overcome the issue some modifications have been indigenously designed in the laboratory. As the tool requires an intended motion to generate a predefined profile or contour in the workpiece, the setup requires some special attachments and components in comparison to the basic electrochemical machining setup. The setup consists of various subcomponents e.g., mechanical unit, power supply unit, electrolyte supply unit, control unit, etc.  A schematic diagram of the developed EC milling setup has been depicted in Fig. 3.1. In this figure, a schematic diagram is drawn to describe the whole setup. It consists of an x-y-z system, a power supply, the electrolyte flow system, the motion control system, the machining chamber, and the machining tool holding setup as well. All the bypass pressure valves are used here to control the flow of the electrolyte as per requirement. The power source is connected to the pump, the computer, and the x-y-z control system as well. All the details about the parts of this setup are discussed briefly below in Fig. 3.1. Due to Some unwanted limitations, some modification has been done to the tool holding unit and the ETS unit.

### 3.1 Detailed Description of the EC Milling Machine Setup

To observe the characteristics of the machined titanium alloy a developed setup has been primarily used here which consists of mechanical units, electrolytic supply unit, power supply units and control units etc. Fig. 3.1 shows all the units together needed to complete the machining process. The mechanical unit is the basic structure of the Electrochemical machining setup. It helps in workpiece mounting, holding the tool as well as the movement of the tool.

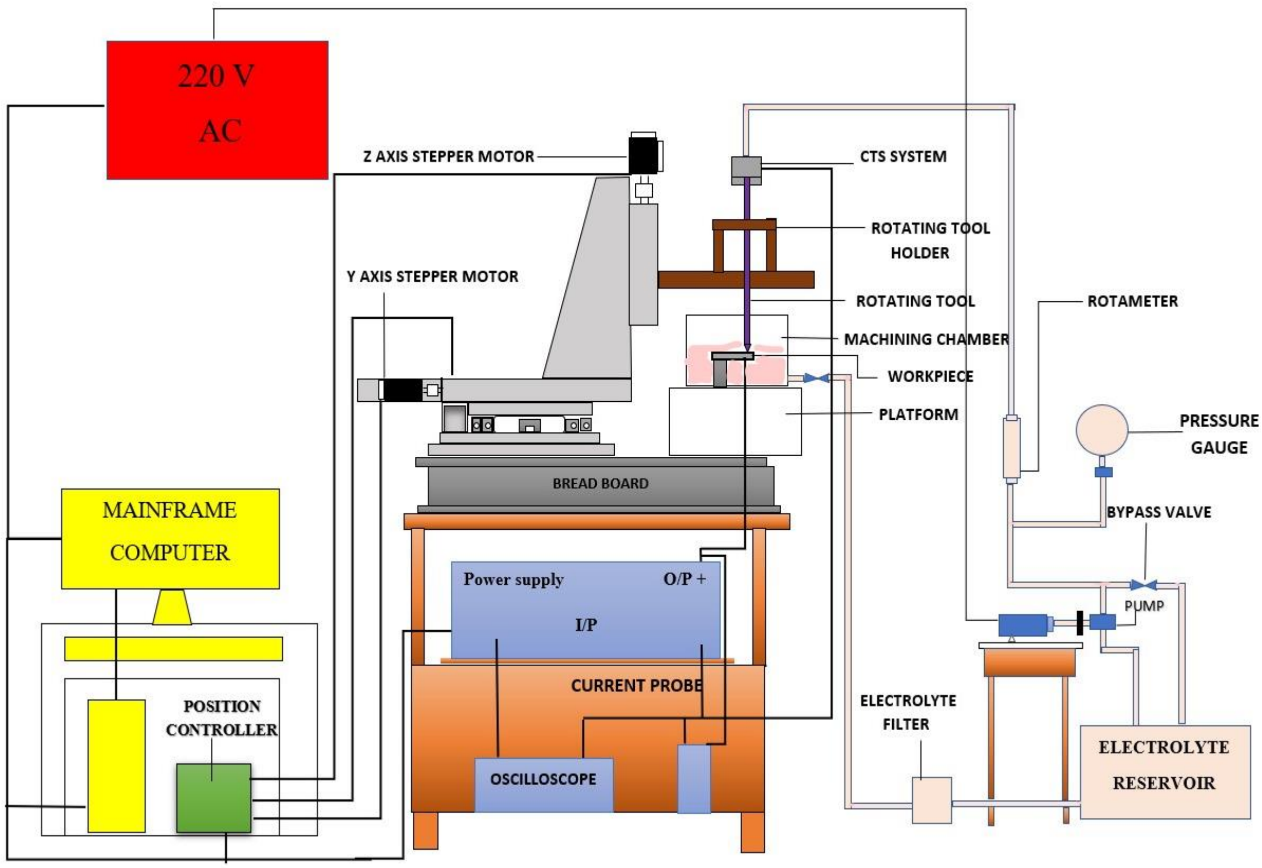


Fig. 3.1 Schematic diagram of the whole EC Milling setup

As the movement of the tool is very much important in the case of electrochemical milling the control of tool movement should be very precise. The mechanical machining unit of the Electrochemical milling setup comprises of Machining chamber, CNC Stage, tool holding arrangement, tool and tool rotation unit.

### 3.1.1 Machining chamber

The machining chamber is a box-like structure made up of Perspex material with dimensions 350mm×250mm×200mm and a wall thickness of 10 mm. It serves two purposes; the first electrolyte is supplied in the machining chamber from the reservoir and second, the work holding arrangement is also constructed within the machining chamber. Perspex is used as the material of the machine chamber because of its electrically non-conductive, chemically inert, and transparent in nature characteristics. The machining chamber is placed above a platform having the dimension of 432mm×300mm×130 mm which is also made up of the same material. The platform is clamped to the breadboard of the base of the XYZ stage by nut and bolted connections. Two outlets are provided at the bottom of the machining chamber with two regulating valves. Flexible pipes carry the electrolyte from the chamber to the reservoir. The work holding device is made up of Perspex where some clear slots are given with the same gap provided in the work table. Therefore, it is possible to clamp different size workpieces in the same work table. The dimension of the work holding device is $220 \times 40 \times 200$ with 6mm clear slots and a 50mm gap.

### 3.1.2 Power supply unit

For the experimentations, a bi-polar 20V-100A pulse DC power supply has been used. In this power supply there are two operating modes, one constant current (CC) mode and another constant voltage mode (CV). In constant current mode, the required current is set and accordingly, voltage is obtained. In constant voltage mode, voltage range is defined and accordingly current is obtained.CC mode is used for machining where the required machining current is very high. The frequency range is 100 mHz to 20 kHz. Response time or the frequency bandwidth at 20 kHz of the power supply is around 18 micro second. Duty ratio can be set within 10 to 90 percent. Response time or the frequency bandwidth at 20 kHz of the power supply is around 18 microseconds. In a single pulse, the pulse profile can be programmed and pulse duration also. Generally, a square pulse profile is mostly used for EC milling purposes but possible with sinusoidal and triangle also. OVP (over-voltage protection), and OCP (over current protection) values can be set in the power supply for protection purposes. OVP and OCP will set the highest boundary of generated voltage and attained current for machining. Fig 3.2 shows the photographic image of the power supply machine.


Fig. 3.2 Photographic view of the power supply machine

### 3.1.3 Motion control system

In this research work, an X-Y-Z linear stage made by Melles Griot, Germany has been adapted for motion control in the EC milling operations. The XYZ stage is a cantilever-type configuration. A cantilever unit is attached where the tool is attached on the front of the cantilever. X and Y movement occurs in two mutually perpendicular axes in the plane parallel to the base of the stage whereas Z movement occurs along the vertical axis only. The main objective of these movements is to position the tool properly over the workpiece for generating different profiles. This X-Y-Z linear stage possesses three-axis (X-Y-Z) which are driven by three stepper motors and their movements of them are controlled by the APT (Advanced Positioning Technology) controller with a resolution of 0.1 microns. It has a maximum of 100 mm X-Y-Z travel. The maximum travel of the stage is 300 × 300 × 300 mm and the maximum load-bearing capacity of the Z-axis slide is 25 kg. This stage has a CNC controller which permits to move on the desired path synchronizing the stepper motor. In this research work, the workpiece is kept stationary.

### 3.1.4 Monitoring system set up

Several devices are adapted to monitor the system during machining such as oscilloscope, multimeter, stopwatch, etc. An oscilloscope is adapted to measure the pulse nature of the power supply as frequency, duty ratio, peak current, etc. A multimeter is used to monitor machining current and machining voltage. A stopwatch is used to determine machining time.

### 3.1.5 Electrolyte flow system

The Electrolyte flow system is an integral part of the EC milling setup which transmits electrolytes from the reservoir to the system. In the electrolyte flow system, all the flow parameters are measured e.g., electrolyte flow rate, flow pressure etc. A gear pump is introduced to circulate the electrolyte from the reservoir to the flow line. The pump has a capacity of 0-20 lpm and the maximum pressure can be 10 $kgf/cm^2$. The pump motor has a power rating of 0.5hp. The pump has the suction and discharge both 0.5 inch. The maximum capacity of the pump is 20 lpm and maximum speed of pump 1440 RPM. As the tool has different type of hole pattern at end for supply electrolyte to the workpiece, the resistance in flow is the main cause of pressure rise. An analog pressure gauge is used to measure pressure in the line which can measure up to10 $kgf/cm^2$. A rotameter is used in the flow line to measure the flow rate of electrolyte. Rotameter is a device that can measure the value of flow rate by positioning the float in the scale which can measure up to 10 lpm. After machining operation, proper cleaning of the line is required to maintain those devices at proper working condition. as the flowing electrolyte is very corrosive in nature. Flexible nylon pipe and PVC pipes of 0.5-inch diameter are used to supply the electrolyte up to internal flushing arrangement. Electrolyte reservoir is a container used to store electrolyte. Electrolyte is taken from reservoir through pump circulated in the system. From the output port of the machining chamber electrolyte mixed with sludge comes back to the reservoir again. Provision of filtering the electrolyte is made by attaching filter with the suction valve. Fresh electrolyte is constantly circulated by pump through the system to ensure optimal machining conditions.

### 3.1.6 Position control unit

Position controller is used for control the tool motion and position precisely. Electrochemical milling completely depends upon the tool motion as the motion of tool is mainly responsible for the accuracy of generated profile. Position control unit of CNC stage controls three stepper motors for three axes which is interfaced with a computer. The movements of the three axes can be obtained through software and controller generated electrical signals with the help of computer programming. Stepper motors rotates in the desired direction by virtue of which lead screws moves by certain distance either in the forward or reverse direction. Controller connected to machine and computer through parallel ports. Getting the maximum speed, reversal of direction, rapid speed change depends on running the motor or the drive electronics components at their maximum permitted voltage. Getting the maximum torque depends on running the motor at its maximum permitted current.

In this electrochemical milling setup Mach 3 is used as a very flexible programme window which is designed to control machines like- milling machines, Lathes etc. as shown in Fig.3.3. Emergency stop provides the capability of stopping the motor at any instant of time in case of emergency which is one of the key features of the position controller. Program is done in G and M code alike CNC controller. The programs are so developed that any change in rotational steps or direction of rotation or delay as required can be incorporated easily.

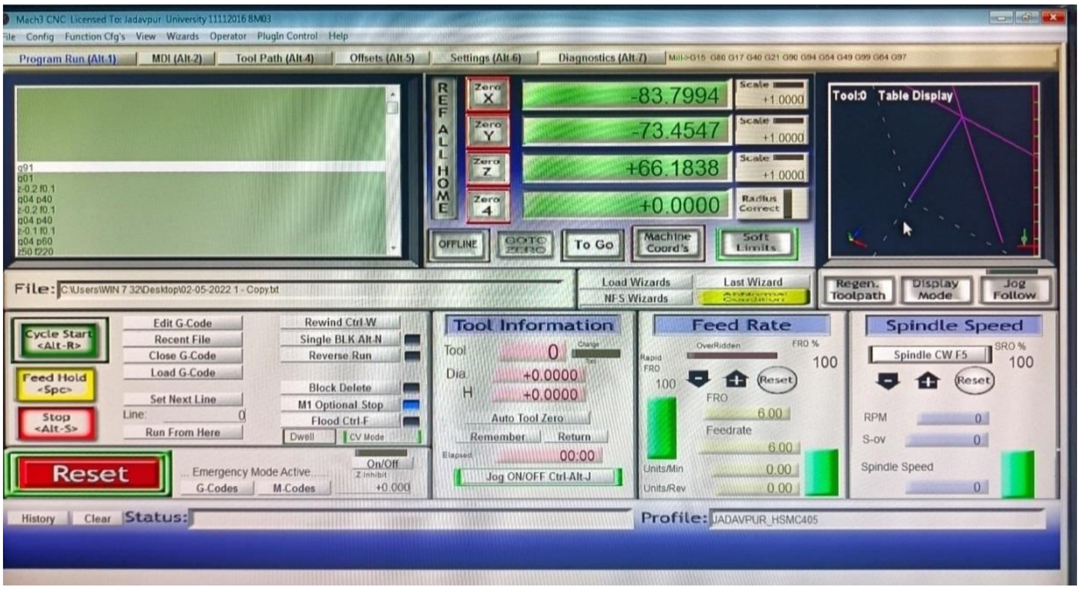


Fig. 3.3 Photographic view of control unit Mach 3 loader

### 3.1.7 Stepper motor controller

EC milling setup has the facility of tool rotation with internal flushing. Tool rotation is provided by a stepper motor and for control of speed, the direction of rotation and steps a separate control unit is used. The Control unit needs a 65V to 285V AC or DC power supply and is also connected to the drive of the stepper motor by six-pin sockets. Four pin sockets are used for 8 limit switches. The Stepper motor controller has a rotary key and six touch keys for giving input of RPM value, direction of rotation, and stop/start. Program can be done in the controller with a maximum number of 50 cycles for each program. Acceleration and deceleration can be provided by the controller for running stepper motor at high speed. In EC milling, setup RPM can be controlled with in 2000 rpm.

## 3.2 Modification of the Tool Holding Attachment Unit in EC Milling Setup

Tool holding arrangement is one of the key components of a mechanical machine units as the electrochemical milling process completely depends on the movement of the tool. This movement helps to generate different complex profiles or contour in the workpiece. The tool with its holding arrangement is mounted in the Z-axis slide and move. The tool holding arrangement should be electrically non -conductive to protect the whole setup body from the current which can cause harm to the operator and create other issues.

### 3.2.1 Various challenges faced on tool holding attachment

The tool holding attachment consists of several components like a copper shaft used as the tool holder, the base on which the tool is rotating, the bearings, bearing holding units and the ETS unit. The tool holding fixture serves two major purposes in the EC milling setup. It is not only used for holding tools but also carried the whole tool rotation unit. The main obstacle in this setup is the leakage of electrolyte while flowing through the shaft. It results in reducing the current flow through the shaft as well as damaging the CNC XYZ stage. Another problem is the weight of the tool holding attachment. The heavy weight of the box was used to cover the tool rotation unit as well as the support for the tool holder. The box was made of Perspex block attached to the stainless-steel angle plate. The extra weight of stainless steel was always a problem while carrying the tool holding attachment. Another challenge was the height of the shaft, due to this phenomenon the eccentricity of the shaft was high. All these problems need to be minimized by modifying the tool holding attachment.

### 3.2.2 Electrolyte through system (ETS) holding unit

An electrolyte through system named ETS unit is connected to the copper shaft to supply the current to the tool from the power supply unit and to provide the internal flushing on the rotating tool. The current conductive electrolytes are supplied to the ETS unit with high pressure to the machining zone of the workpiece. As the ETS unit is connected to the copper shaft. An external thread has been provided on the outer body of the shaft as shown in Fig. 3.4. This is provided so that the ETS unit can be easily removed from the setup for maintenance. The length of the copper shaft has been diminished to reduce the eccentricity of the rotating tool.

### 3.2.3 Stepper motor attachment unit

In electrochemical milling operation tool rotation is one of the most important factors in providing a better surface finish by effective sludge removal. To decrease the eccentricity of the tool, the length of the shaft needs to be reduced. In Fig. 3.4 and in Fig. 3.5 it is shown that the whole ETS system along with the bearings which are provided to hold the shaft is kept on the upper side of the cloth fiber slab. The Stepper motor attachment unit consists of some components like the stepper motor for rotation, the bearing support on the base for tool rotation and the timing pulley arrangement. To reduce the weight of the whole set up only a single cloth fiber slab of dimension 200mm× 200 mm ×20mm is provided. On the top of the slab, a slot has been made to fix the stepper motor which is required for the rotation of the tool. A circular slot is given for the tool rotation and to provide bearing support to the shaft. One ball bearing of number 6202 is used on the base for the rotation of the shaft. Timing pulley and belt arrangement are provided to conduct motion from the stepper motor to the tool holder on the lower side of the slab. One pulley is attached to the stepper motor shaft and another pulley is connected to the tool holding shaft by press-fitting. The distance between them is kept ideally 90 mm. Although a clear slot is given in the place of the slab so that the stepper motor can fit according to the requirement. Timing pulley arrangement helps to transmit motion with precision and no loss of high torque. Pulley and belt are made of excellent abrasion-resistant, rust-resistant and chemical-resistant material. Noise-less operation and negligible elongating of the belt with high efficiency are major advantages of this drive.

### 3.2.4 Tool and ETS holding unit

In between the tool and ETS unit another bearing is needed to support the tool holding shaft. A roller ball bearing of SKF 6202 is used in this scenario. To hold the bearing so that the shaft does not tilt like a cantilever, a square box made up of cloth fiber is used as shown in Fig. 3.4 and 3.5. The cloth fiber is selected because of itsnon-conductive nature. Three square plates with the dimension of 50mm × 50 mm× 10 mm are made up to hold the bearing. Two plates are placed vertically on the slab with the help of a screw system. The third square plate is designed to fit the bearing in it. It is fitted horizontally to the other square plates by a screw thread system. In between the hole of the bearing and the cuboid, the shaft is press-fitted. All these press fits are done just to make the system to leakproof. Fig 3.4 and Fig 3.5, shows the front view and side view of the tool holding unit respectively.

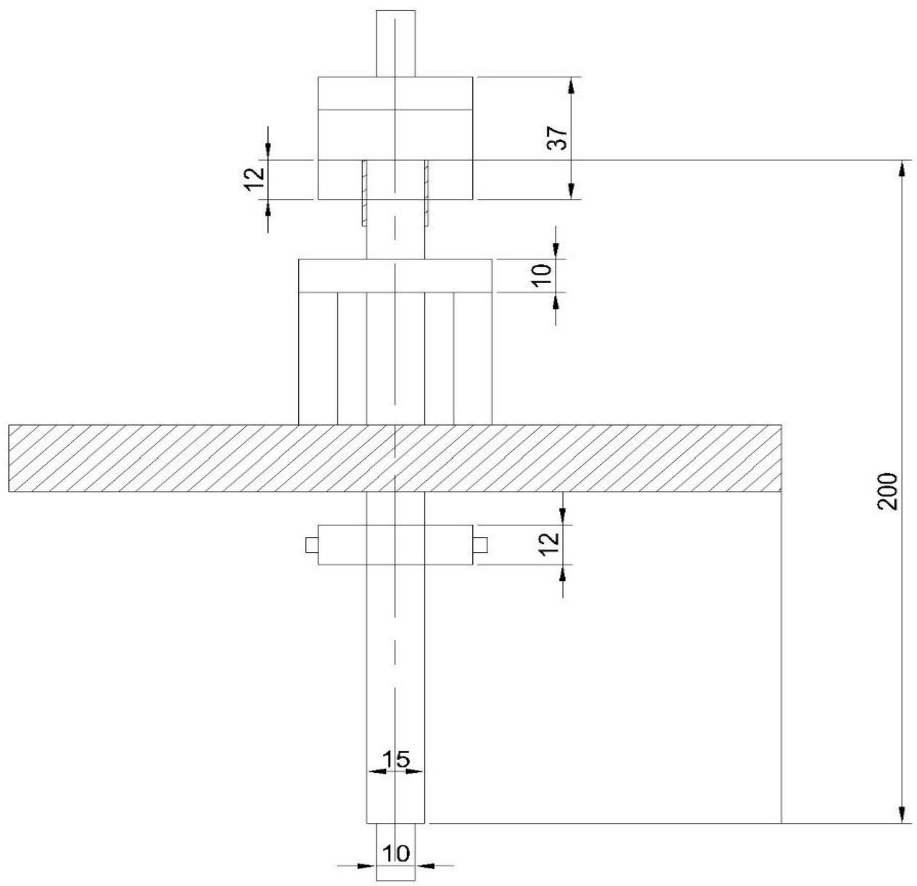


Fig. 3.4 Front view of the modified tool holding unit

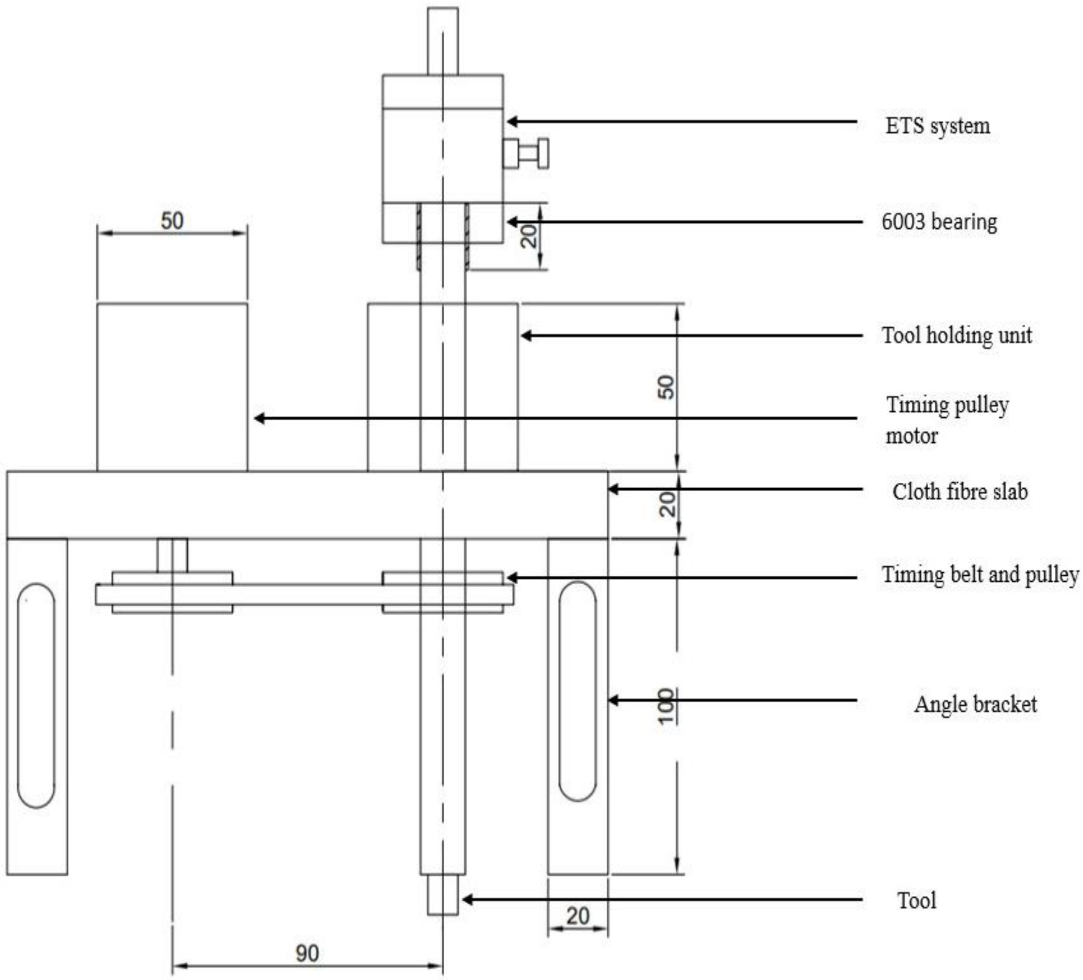


Fig. 3.5 Side view of the modified tool rotating unit

### 3.3 ETS Unit Modification

In EC milling setup tool rotation with internal flashing is better than side flashing. From the literature review, it is concluded that the surface finish is much better when the tool rotation is provided with the flow of electrolytes. To maintain the tool rotation with internal flashing as well as the power supply, an electrolyte through spindle system has been fabricated. The ETS unit is made up of an aluminium hollow shaft and a nozzle placed on the top of the shaft. A flexible pipe from the electrolyte supply line is directly connected to the nozzle placed on top of the aluminium shaft. The copper shaft is connected to the ETS unit by another ball bearing. But the problem was the huge amount of leakage of electrolyte due to the back pressure created by the electrolyte. Due to the leakage, the required current was not enough for machining of TI6Al4V at the premium level. Besides that, leakage of electrolytes could be the reason for the damage to the CNC X-Y-Z stage. Another problem was the damage to the bearing which is used on the ETS unit. To resolve these problems the ETS unit has been modified. In Fig. 3.6 it is shown that another copper shaft with an inner diameter of 17 mm and an outer mm of 20 mm is used on the ETS unit with the help of a ball bearing. The ball bearing is used SKF 6003. The tool rotating c shaft is connected to the other copper shaft of the ETS by a threading method. To reduce the leakage caused by the back pressure two washers are provided in between the nozzle and the bearing. With this change now, the ETS unit can be easily removed from the tool rotating unit to change the damaged bearing due to leakage.

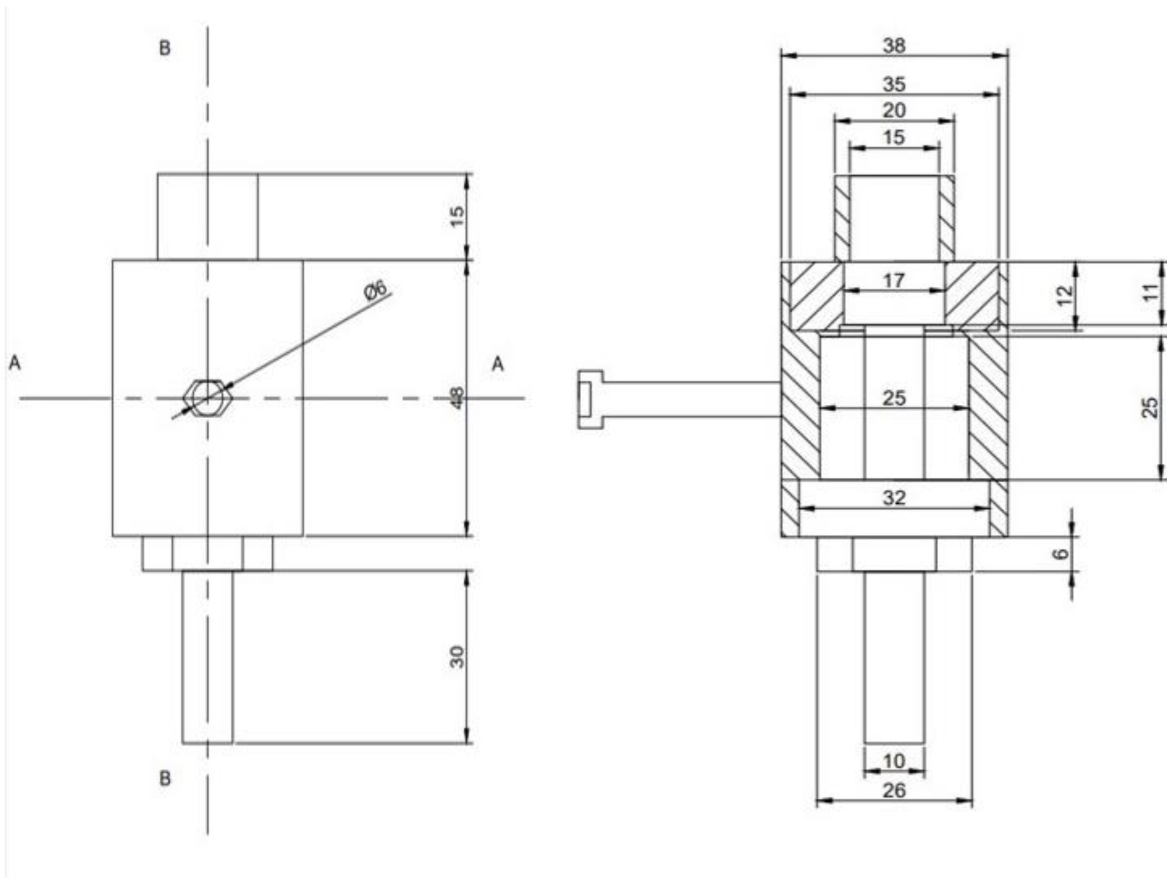


Fig. 3.6 ETS unit modification

# Chapter 4

## 4. EXPERIMENTATIONINTO EC MILLING OF Ti6Al4V

The main aim of electrochemical milling is to produce different shapes of complex 3D or surface profile dimples by virtue of a simple shaped tool. Conventional electrochemical machining completely removes material and produces a shape the same as the mirror image of the tool leading to complexity in tool design. In this study, experimental results have been discussed on Ti6Al4V by electrochemical milling process utilizing indigenously developed setup as described in chapter 3.

## 4.1 Experimental Planning

Some preliminary experimentations into EC milling of titanium alloy have been done to identify the suitable range of the process parameters to investigate the effects of various process parameters on the performance characteristics of EC milling. Experiments of EC milling were carried out on the experimental setup that has been explained in chapter 3.

### 4.1.1 Selection of tool

Experiments of EC milling were carried out on titanium base superalloy plate to demonstrate the effects of machining parameters on the various performance characteristics. A cylindrical solid and hollow tool made of pure copper (Cu) has been selected as the tool. The high conductivity value was the main purpose for using uncontaminated Cu as tool material. The sidewall of the tool was properly protected by Teflon tape for the minimization of the overcut due to stray current.

The increment in stray current effect plays a vital role and deteriorates the accuracy of the corner radius and side edges of the machined profile. Insulation of the tool wall is required as the tool sinks into the machining zone bare portion resulting in taperness of the sidewall and more value of width. Solid and hollow tools both have the same outer diameter of 10 mm. Sludge removal is one of the main criteria for having good machining accuracy and a high rate of material removal. The smaller value of the inner hole diameter was one of the main reasons behind the higher value of surface roughness. The uniformity of the machining zone is also principally dependent on the inner hole dimension.

The main constraint of EC milling with solid tool was improper removal of sludge with compare to hollow tool with internal flushing. In case of machining with solid tool, two nozzles are used to supply the electrolyte in the direction inclined with the tool axis which is perpendicular to the anode surface. In case of solid tool, the lack of availability of electrolyte at the instantaneous machined zone and availability of excess amount of electrolyte near the machining zone combined with stray current effect leads to formation of irregular edges, rough impression in the vicinity of the machining. As the availability of the electrolyte is not uniform and material removal is inhomogeneous in the machining zone, the flatness of the machined surface was hampered with higher value of overcut. The material removal rate as well as machining accuracy is directly influenced by the flow velocity and pattern of electrolyte flow in the inter electrode gap. A thin layer of sludge was observed in intermediate stage of machining which leads to short circuit. In case of hollow tool, the electrolyte flows through the inner hole of tool directly enters into the instantaneous machining zone. The main advantage of the rotating hollow tool is as the electrolytes flow radially outward with high flow velocity and the entire sludge was carried out in ultra-fine granular form and the rotational motion of the tool always helped to achieve the flat base of the machining zone. No layer of sludge was observed during the use of hollow tool. Thus, in this study, for improving the accuracy of the machining zone hollow tool is chosen instead of solid tool.

### 4.1.2 Electrolyte for EC milling

In Electrochemical milling choice of electrolyte is very important as example Sodium Chloride (NaCl) with high concentration is used for machining stainless steel in conventional electrochemical machining,Sodium chlorate ($NaClO_3$) and sodium nitrate ($NaNO_3$) are used in case of mild steel etc. Sodium Chloride (NaCl), Sodium Bromide (NaBr), and Sodium Nitrate ($NaNO_3$) can be easily used as electrolytes for machining Ti6Al4V by electrochemical machining. Researchers have done experiments with these electrolytes at different concentration to find out proper electrolyte and the optimal concentration for accurate machining of Ti6Al4V.

In case of electrochemical machining concentration of electrolyte is so important that a very low concentration results in non-uniform dissolution and unstable machining due to depletion of ions. On the other hand, high concentration of electrolyte deteriorates the accuracy of the machined profile due to a very high concentration of ions. Machining of titanium is relatively different from electrochemical machining of commonly used materials because titanium has a huge tendency of forming a passive oxide layer. The tenacious passive oxide layer film which makes titanium very useful as a corrosion-resistant material renders the electrochemical machining of this material. With simple chloride and nitrate electrolytes, high applied potential differences (50V) are often required to achieve machining condition although the passive films are then broken only at weak points causing deep attacks at grain boundaries.

Only proper selection of electrolyte leads to breaking of this passivating layer and make it transpassive in order to carry out electrochemical dissolution. There are two main types of electrolyte passive and non-passive. Passive electrolyte such as $NaNO_3$ contain oxidising anions provides better precision and control due to formation of a protective oxide film. $NaNO_3$ with 1(M) concentration results in lower side and length overcut, sharp edges, lower material removal. Whereas NaCl is non passivating in nature and non-passivating electrolytes contain more aggressive anions which help in breaking down the passive oxide layer films at moderate voltage up to 20V and remove huge number of cat ions from anode results higher amount of material removal. As material removal rate is increased dimensional accuracy of machining zone get reduced. Otherwise more the hydrogen ($H_2$) gas generation at the anode more easily the passive oxide layer breaks. In this study NaCl and $NaNO_3$ mix electrolyte was used. Reason behind the use of $NaNO_3$ in the mix electrolyte to overcome the shortcomings of the NaCl electrolyte and use of NaCl in the mixed electrolyte has increased the generation of hydrogen bubbles at anode surface, resulted in complete removal of passive layer from the pre machined anode surface. Some basic experiments were conducted with same aqueous solution of 0.5 M, 1M and 1.5M solution concentration. Researchers have successfully conducted EC milling of Ti6Al4V with 0.5 M mixed electrolyte of NaCl and $NaNO_3$.

Increment in concentration mainly improves MRR but after a certain level of concentration accuracy of the machined zone was deteriorated due to presence of excess amount of NaCl. Therefore, from the basic experiments it was observed that machined zone has not been deteriorated as far as surface finish and overcut were concerned. Material removal has increased with the increment of concentration without compromising the accuracy of the machined zone with 1M mix electrolyte; therefore, finally 1M solution was chosen in other parametric study.

### 4.1.3 Workpiece property

In this study, titanium alloy grade V (Ti6Al4V) with 5mm thick (5×30×50) was chosen as workpiece. It is mainly a high strength temperature resistant alloy. Actual composition of the alloy should be known before starting experiments.It consists of titanium, aluminium and vanadium by 90%, 6%, 4% weight basis and 84%, 11%, 5% atomic weight basis respectively. Different elements with their composition are shown in Table 4.1.

Table 4.1 Composition of Ti6Al4V

| Elements of alloy | Atomic weight basis | Weight basis |
|---|---|---|
| Ti | 84 % | 90% |
| Al | 11% | 6% |
| V | 5% | 4% |

Different mechanical and electrical properties of the Ti6Al4V grade V alloy are shown in Table 4.2.

Table 4.2 Different properties of Ti6Al4V alloy

| Property | Value | Units |
|---|---|---|
| Atomic volume | 0.01 | $m^3$/kmol |
| Density | 4.512 | $Mg/m^3$ |
| Bulk modulus | 1250 | GPa |
| Compressive strength | 1080 | MPa |
| Ductility | 0.18 | |
| Elastic limit | 910 | MPa |
| Endurance limit | 566 | MPa |
| Fracture toughness | 107 | $MPa.m^{1/2}$ |
| Hardness | 3730 | MPa |
| Modulus of rupture | 1080 | Mpa |

| | | |
|---|---|---|
| Poisson's ratio | 0.37 | |
| Shear modulus | 45 | GPa |
| Tensile strength | 1200 | MPa |
| Young's modulus | 119 | GPa |
| Maximum service temperature | 690 | K |
| Melting point | 1933 | K |
| Specific heat | 570 | J/kg.K |
| Thermal conductivity | 7.3 | W/m.k |

### 4.1.4 Selection of electrochemical milling process parameters and responses

In this study, initially simple dimples were machined on the workpiece to find out the most influential process parameters and their suitable range to study their impact on various responses of EC milling. Voltage, input current, pulse type and pulse frequency and duty ratio were taken as electrical process parameters of EC milling. However, feed, milling layer depth, initial inter-electrode gap, electrolyte type and concentration, electrolyte pressure and flow rate, tool rotation and rotational speed were taken as non-electrical parameters of EC milling. In case of EC milling, out of those electrical and non-electrical process parameters, feed rate and milling layer depth and tool rotation were the most influencing process parameters as reported by the researchers. In EC milling, tool rotation has a greater impact on the EC milling performance characteristics. Rotation improves various responses of EC milling by effective sludge removal and supply of fresh electrolytes at every instantaneous machining zone. High rotational speed cannot be used with high milling layer depth as it deteriorates the surface finish with some impressions of the electrolyte flow lines at the machined profile. This was due to the decrement of electrode gap and high-pressure electrolyte with high outward radial force from combined effect of electrolyte flow velocity and tool rotational speed. So, during experimentation moderate value for electrode rotation was fixed at 500 rpm. Electrical process parameters e.g., voltage, input current, pulse type, pulse frequency and Duty ratio was kept constant during experimentation. As per as various EC milling performances were concerned 20 V voltage difference, 20 Amp input current with square pulse, 500 Hz pulse frequency and 0.5 duty ratio is selected. In case of macro-EC milling around

20V voltage was sufficient to overcome passivation nature of workpiece surface and material removal was started. Mainly, pulsed DC is effective in ECM to remove the sludge efficiently from the inter electrode gap during pulse off time. In case of EC milling, combined effect of tool rotation with internal flushing results in efficient sludge removal therefore, in EC milling the pulse off time has been kept very low. High value of pulse on time directly increases the material removal and also the average machining current value. The table 4.3 depicts all the fixed machining parameters taken for EC milling experimentation.

Table 4.3 Fixed process parameters

| | |
|---|---|
| Input Voltage (V) | 20 (pulsed DC) |
| Cut off Current (Amp) (Over current potential) | 20 |
| Pulse Type | Square Pulse |
| Pulse Frequency (kHz) | 0.5 |
| Duty Ratio | 0.5 |
| Electrolyte Type | $NaCl + NaNO_3$ Aqueous Solution |
| Electrolyte Concentration | 1M |
| Initial Inter Electrode Gap (mm) | 0.3 |
| Electrolyte flow pressure ($kgf/cm^2$) | 0.2 |
| Electrolyte flow rate (lpm) | 2 |
| Tool rotational speed (rpm) | 500 |

### 4.1.5 Tool path planning

Machining of a dimple type of depth of 0.5 mm has been done on the Ti6Al4V workpiece. Dimples are machined by means of an electrochemical milling process intotal six steps. Ineach step the electrode was controlled to move along a predefined path along z direction only. Each step of the moving of electrode along z direction is followed by a waiting period called dwell time. Dwell time is used to specify a number of seconds that the movement of the axis is given a pause at a given point, while the other functions of the machine is continued to function. In this experiment also dwell time was given after each stage of moving of the electrode along z axis while the other functions like tool rotation, electrolyte flow and the passing of current was continued throughout the whole process. This helps to remove the sludge at every point after the machining in each stage. This leads to surface improvement as well as decreases the chances of spark between the tool and the workpiece. In strategy (i), at the first step the electrode was directed to move 0.2 mm depth along z-axis with the feed of 0.1mm/min followed by a dwell time of 20 seconds. Next another step the same movement was repeated so that a total of 0.4 mm depth can be covered by the electrode with 20 sec of dwell time after each 0.2 mm movement of tool on a downwards direction. At the fifth stage, the electrode was directed to go downwards up to 0.1 mm with a feed of 0.1mm/min. Then various dwell times of 20 sec, 40 sec, 60 sec and 80 sec were given in different experiments to observe the results. This whole process is repeated in the different experiments while the dwell time used in the second and fourth stages is 40 sec each. This strategy is named strategy (ii). The inter-electrode gap was given as 300 microns. The figure explaining both the strategies and the flow chart of the whole experimental procedure details has been represented below in Fig 4.1 and in Fig 4.2 respectively.

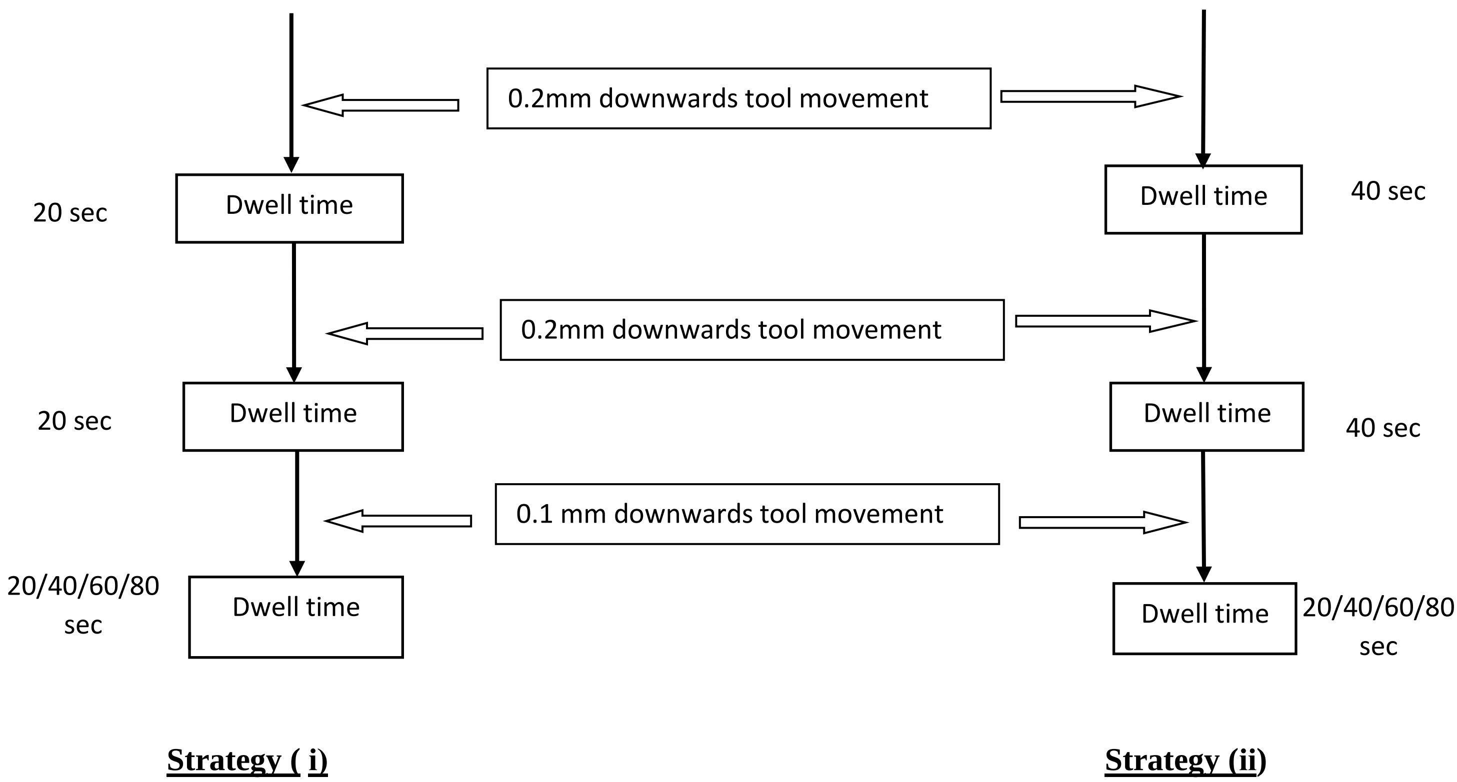


Fig. 4.1 Flow chart of tool path planning

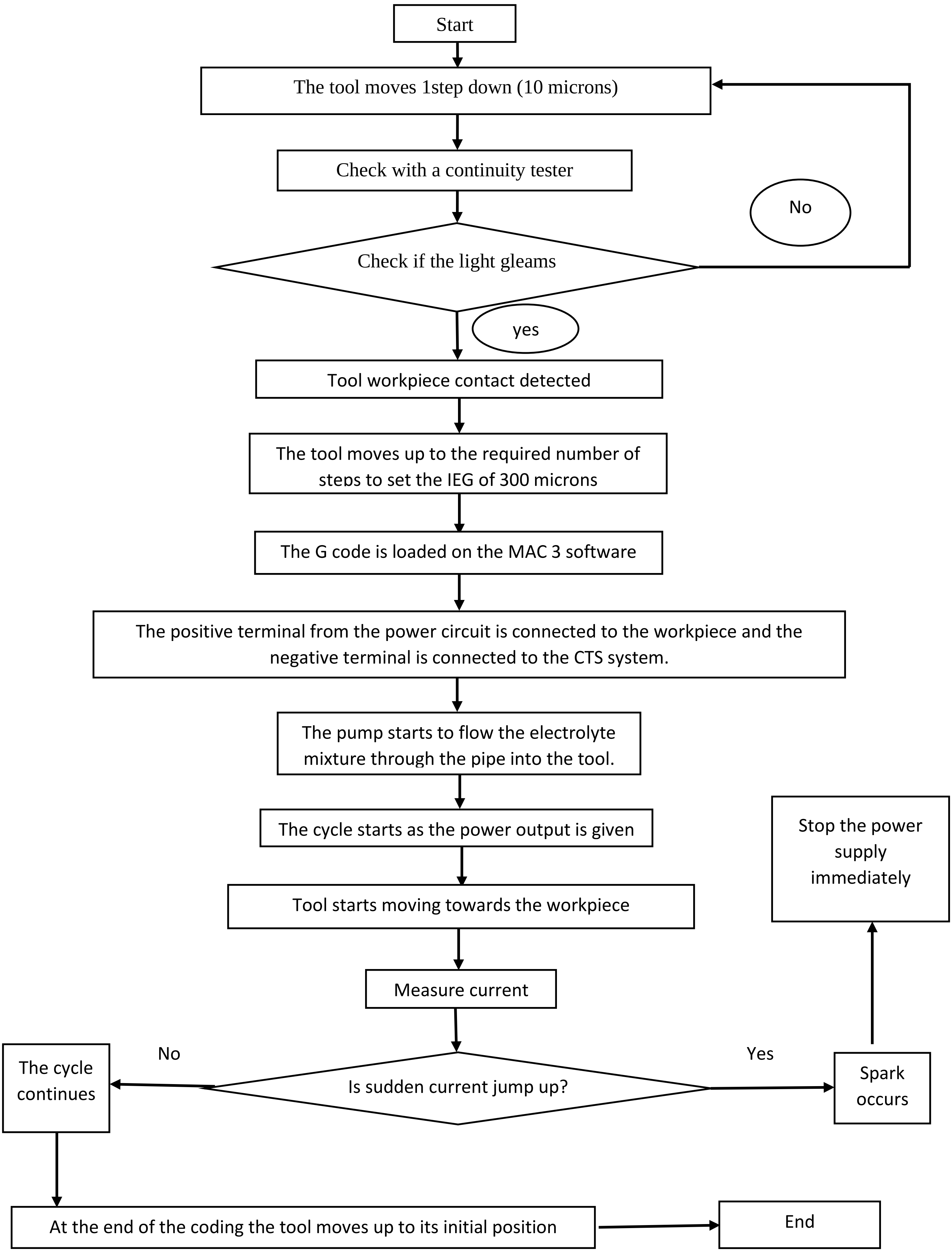


Fig. 4.2 Flow chart of the EC milling process

### 4.1.6 Planning of measurement

The surface roughness of the machined profile has been measured by the Telysurf portable surface roughness measuring instrument (SJ 410), made by Mitutoyo. The maximum travel length was 1.5 mm. The tip of the roughness tester was made of diamond material and had a diameter of2 microns.

The width overcut was calculated by the difference between the width of the slot and the diameter of the tool, divided by two. Contour scope made to travel through three distinct locations from that three-location width overcut has been measured. The depth of the profile was measured in a single run of the contour scope profile. The three deepest points of the machining zone have been taken. For calculating width overcut following relationship has been used.

$$W_{oc} = \frac{W_{ob} - D}{2} \qquad \text{Eqn 4.1}$$

Where, $W_{oc}$ is the measured overcut value, $W_{ob}$ is the obtained width of the machining zone and D is the diameter of the tool.

## 4.2 Results and Discussion

Experiments were conducted to find out the best set of process parameters which results in a lower value of overcutting and a lower value of surface roughness. From the obtained results it was clear that using dwell time while creating some dimples could be one of the major factors in reducing the surface roughness of Ti6Al4V. It was also observed that the value of the average radius of curvature and surface roughness was decreased by using a rotating tool with internal flushing. Tool rotation also improves the amount of material removal rate but with a small increment in overcutting. In these experiments, various process parameters are being used to obtain better surface finish for machined titanium alloy.

### 4.2.1 Influence of dwell time on surface roughness

Surface roughness is the main indicator of the quality of the surface produced which can be influenced by the amount of charged supplied, flow rate of the electrolyte, tool rotational speed, and initial inter-electrode gap. In the case of a higher amount of material removal (roughing operation) high voltage, small initial inter-electrode gap and high feed rates are beneficial on the other hand for a good surface finish low voltage, small inter-electrode gap and high feed rates are beneficial. Surface roughness of the machined surface also depends on other factors e.g., rate of material removal and quality of the sludge produced e.g., sticky or non-sticky, soluble or insoluble, etc. The sludge generated by mixed electrolytes causes less deterioration to machine performance than $NaNO_3$ electrolytes when used distinctively. In this study sludge produced is insoluble and light but a little sticky in nature. A thin sticky sludge layer observed during machining is the reason for a higher value of roughness in the case of without rotation. The high rotational speed of the tool electrode produces a better surface finish since the rotation provides better discharge mobility by including a more turbulent flow of electrolytes. The tool rotational speed and the edge rounding radius of the tool are the major contributing factor in case of obtained surface roughness. Now dwell time is introduced in this experiment to observe the changes in surface roughness. In this experiment, the dwell time of 20 seconds was given after the first movement of the tool electrode along the z-axis through 0.2 mm. After that , the same process is repeated again. At the last stage, the electrode was directed to move 0.1 mm along z-axis followed by the last dwell time of 20 sec, 40 sec, 60 sec and 80 sec in different experiments as discussed in Strategy (i).

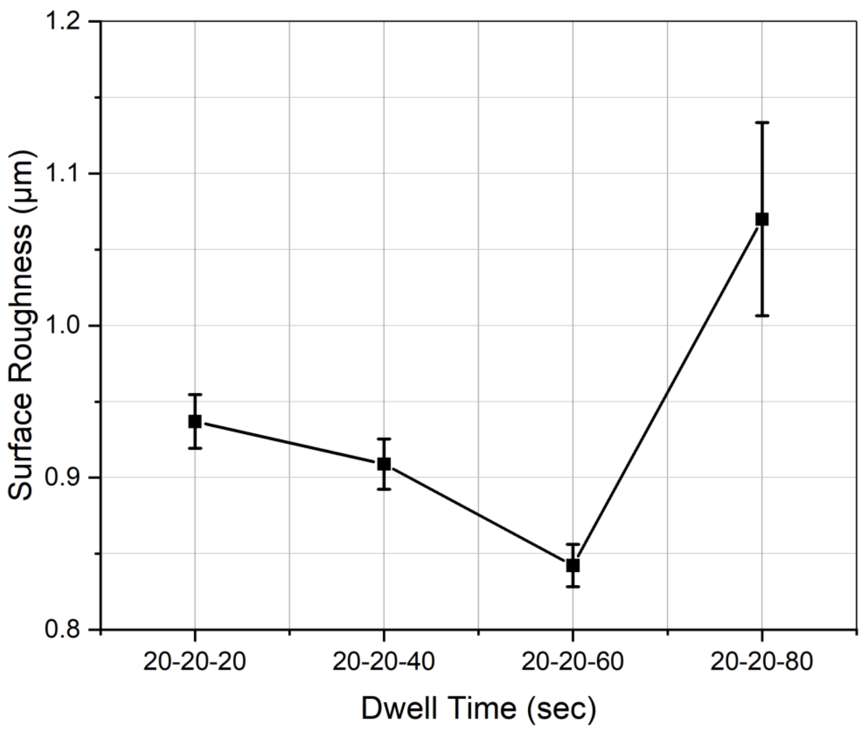


Fig. 4.3 Variation of surface roughness with dwell time with Strategy (i)

In Fig. 4.3, it was clearly observed that with the increase of dwell time at the last stage the surface roughness decreased up to a certain level when the dwell time is 60 seconds and then it started to increase. As the dwell time increases the tool stays at a particular place and helps to remove the sludge created by the electrolytes. But when the dwell time was given 80 seconds at the last stage, it started to increase the gap between the tool and the workpiece which resulted in the poor surface finish due to the effect of low current produced.

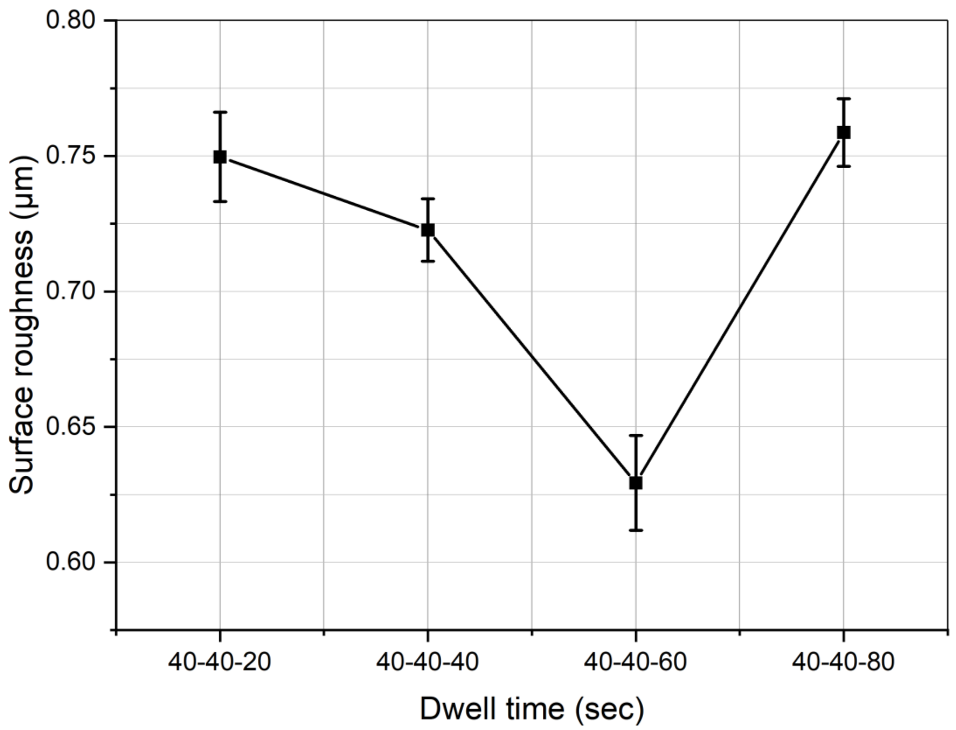


Fig. 4.4 Variation of surface roughness with dwell time with Strategy (ii)

Another set of experiments were conducted with the same procedure but this time the dwell time for the first two cases was taken as 40 seconds and at the last stage, various dwell times were used to observe the surface profiles on the machined workpiece. Out of all the experiments, the best parameter for the surface finish was taken as 60 seconds dwell time on the last stage using Strategy (ii) as shown in Fig. 4.4. Increasing dwell time in the first two stages from 20 sec to 40 sec produces extra time for the sludge removal. In these experiments the highest Ra value was achieved at 0.6293 μm when the tool was moved 0.2 mm downwards followed by 40 sec dwell time again the tool was gone 0.2 mm downwards direction followed by 40 sec dwell time and at the last stage the movement of tool was 0.1 mm downwards then 60 seconds dwell time was given.

### 4.2.2 Influence of dwell time on width overcut

In the ECM process, the stray current effect is an uncontrollable phenomenon that leads to the removal of material from the undesired portion of the workpiece which results in inaccuracy in the machined profile. The width of the machining zone is always increased with the decrease in feed rate for a particular voltage and given depth. The same trend has also been followed in the case of tool rotation. With the increase in feed rate, the interaction time between tool and workpiece is reduced leading to a lesser amount of material removal from the anode surface at a single layer. Width overcut is also occurred due to the stray current effect from only the bare portion of the tool. In this study during experimentation, only the flat tool tip is exposed and the other portion of the tool is properly insulated. At a high feed rate value required time is very less to complete a single pass and the tool sinks in the machining depth at a faster rate. Starting from the initial inter-electrode gap the exposed neighbouring anode surface has got only a few passes to interact with the bare flat tool head. In addition, with less interaction time the high electrolyte flow velocity results in a lower amount of electrolyte available in the exposed neighbouring anode surface which is the main disadvantage of sinking ECM.  On the other hand,the exposed anode surface in the vicinity of the machining zone cannot react with available electrolytes due to the proper insulation of the cylindrical sidewall of the tool as the tool sinks in the further passes. The change in overcut was also observed introducing the dwell time. The overcut is decreased with respect to the increase of dwell time up to a certain period and then it started to increase.

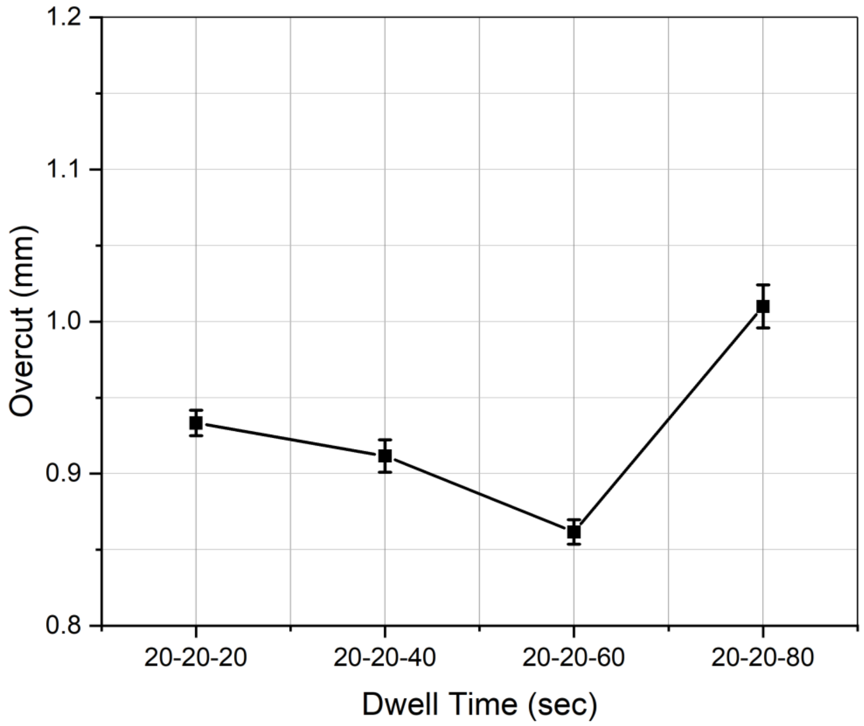


Fig. 4.5 Variation of overcutting with dwell timewith strategy (i)

In this experiment, the dwell time of 20 seconds was set after the first movement of the electrode along the z-axis through 0.2 mm with the feed rate of 0.1 mm/min. After that, the same process is repeated again. At the last stage, the electrode was directed to move 0.1 mm along thez-axis followed by the last dwell time of 20 sec,40 sec, 60 sec, and 80 sec as discussed in strategy (i) in Fig 4.5, it is clearly observed that with the increase of dwell time at the last stage the overcut is decreased up to a certain level when the dwell time is 60 seconds and then it started to increase. When the dwell time is increased, it helps to decrease the $TiO_2$ layer from the workpiece which leads to lower overcut. A decrease of current when the dwell time is increased is also a reason for lower overcut but when the dwell time is increased to 80 seconds at the last stage it leads to increase the depth between the tool and the workpiece. This causes the material removal from the undesired portion of the workpiece.

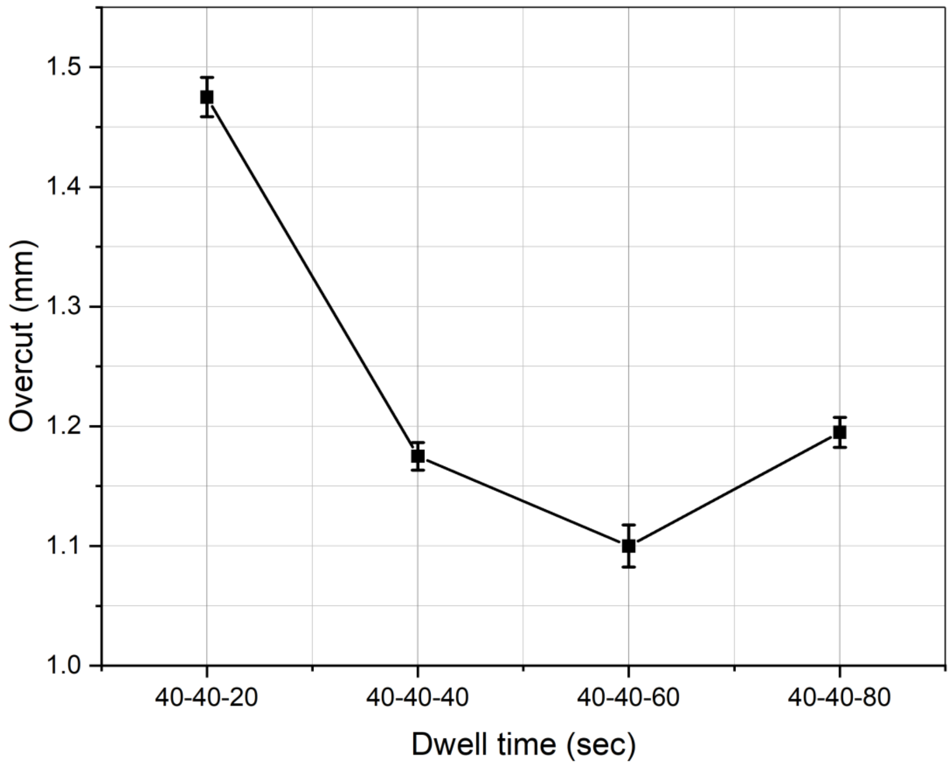


Fig. 4.6 Variation of overcutting with dwell timewith strategy (ii)

In Fig. 4.6, strategy (ii) has been used to observe the overcut of the machined surface. As the dwell time is increased up to 40 sec in the first two stages, the depth between the workpiece and the tool is increased in each stage which causes higher overcutting with respect to the first strategy. Fig. 4.7-4.10 are the photographic images of the machined surface of the workpiece Ti6Al4V using strategy (ii). As the primary objective of this thesis is to improve surface roughness, the strategy for the lowest Ra value has been taken for further experiments. Although the best parameter of dwell time for the lowest overcut was observed when the tool was moved 0.2 mm downwards followed by 20 second dwell time. Then,the tool was covered 0.2 mm depth followed by 20 sec dwell time. And at the last stage the tool was directed to 0.1 mm downwards followed by 60 sec dwell time.

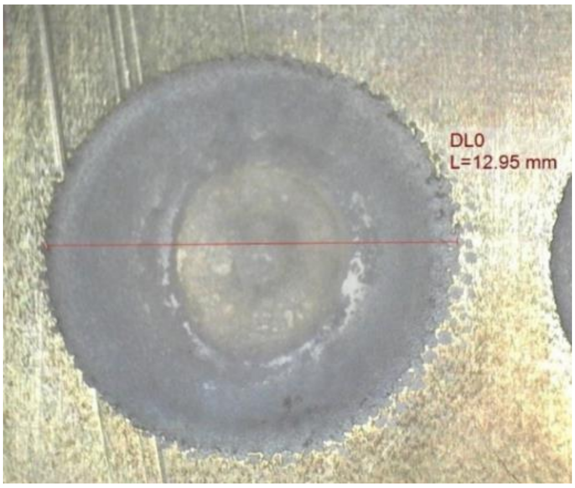


Fig. 4.7 Photographic view of machined profile (dwell time 20 seconds at last stage)

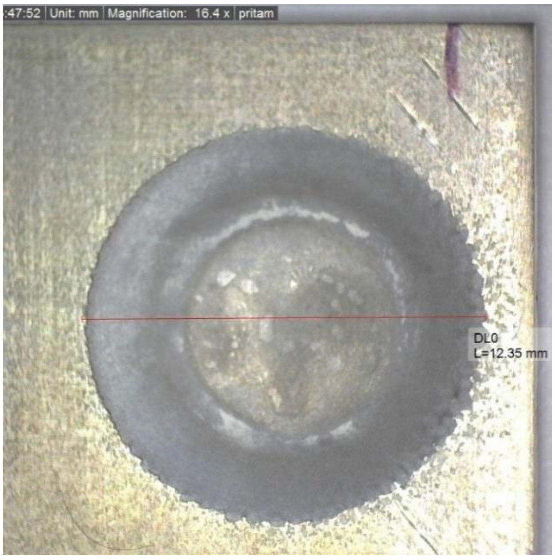


Fig. 4.8 Photographic view of machined profile (dwell time 40 seconds at last stage)

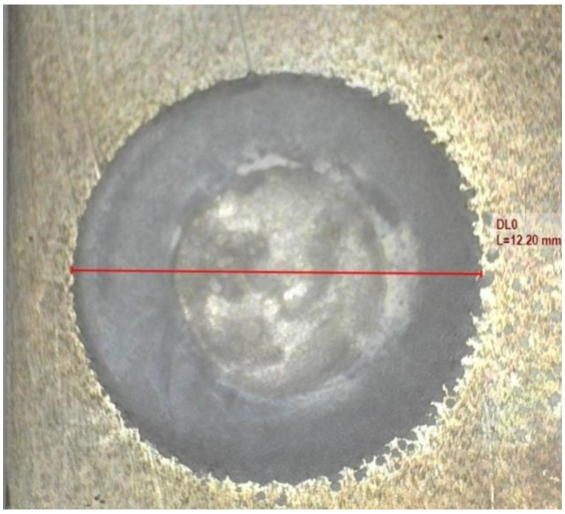


Fig. 4.9 Photographic view of machined profile (dwell time 60 seconds at last stage)

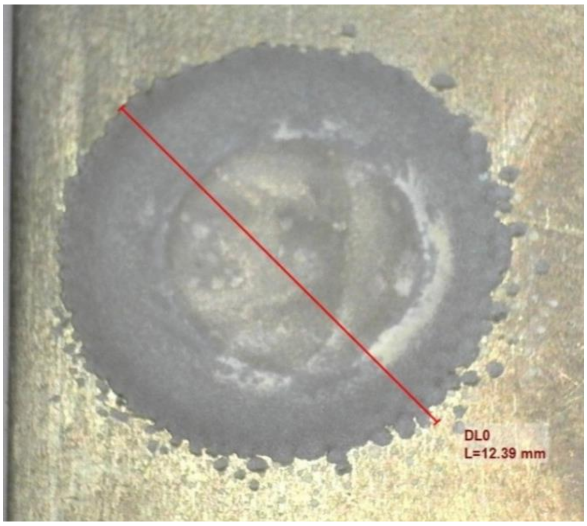


Fig. 4.10 Photographic view of machined profile (dwell time 80 seconds at last stage)

After completing pilot experimentation optimal machining has been achieved at the condition where the dwell time was selected as 40 seconds after the first stage where the tool was directed to move 0.2 mm along the z-direction. Then again, the tool was directed the same as the previous so that after the second stage the tool had covered a total of 0.4 mm depth followed by a second dwell time of 40 seconds. Subsequently, the tool was directed to move along 0.1 mm and at the last, the dwell time should be given 60 seconds at optimum level. From Fig. 4.9, it can be observed the best machined surface with lowest Ra value. At this level the value of the surface roughness was 0.6293 µm. Fig 4.10 is the worst machined surface in terms of surface finish. When the dwell time was given 80 seconds at the last stage, it started to increase the gap between the tool and the work piece which resulted in the poor surface finish due to the generation of low current. From the Fig. 4.10, it has also been observed that severe pitting occurred along the periphery of the machined profile.

# Chapter 5

## 5. INFLUENCE OF ETHYLENE DIAMINE TETRA ACIDIC ACID (EDTA) FOR THE IMPROVEMENT OF SURFACE ROUGHNESS AND ACCURACY DURING EC MILLING DURING Ti6Al4V.

The main aim of electrochemical milling is to produce different shapes of surface profile dimples by virtue of a simple shaped tool. Conventional electrochemical machining completely removes material and produces a shape the same as the mirror image of the tool leading to complexity in tool design. In this study, experimental results have been discussed on Ti6Al4V by electrochemical milling process utilizing indigenously developed setup as described in chapter 3 and with the best parametric results from chapter 4. In these experiments, the changes in electrolyte concentration were observed with the addition of a chelating agent EDTA.

### 5.1 Anodic Dissolution of Ti6Al4V in EDTA

The Ethylene diamine tetra acetic acid (EDTA) is a polyprotic acid containing four carboxylic acid groups and two amine groups with lone-pair electrons. It is observed that the anodic dissolution of titanium alloys is a very complex job with respect to other metals in ECMM. The anodic dissolution of titanium alloys is a very complex task when compared with other metals in ECMM. Titanium and its alloys have excellent corrosive resistance due to the presence of a stable $TiO_2$ layer on its surface. This oxide layer is formed when it comes in contact with an oxygen-containing environment. The oxide layer formed is highly passive in nature and hinders the anodic dissolution of titanium alloys. EDTA disodium salt is a kind of complexing agent with a chemical formula of $Na_2H_2Y$ (where Y is $C_{10}H_{12}N_2O_8$) and has the ability to react with most of the metal ions and forms a soluble complex compound. The possible chemical reactions which occur in the mixture of NaCl, $NaNO_3$ and EDTA of titanium alloy grade 5 (Ti6Al4V) are:

At cathode:

$$2H^{+} + 2\,e^{-} \rightarrow H_2\uparrow \qquad \text{Eqn. 5.1}$$

At the interface of anode and electrolyte:

$$2H_2O \rightarrow 4H^+ + O_2 \uparrow + 4e^-$$ Eqn. 5.2

$$Ti^{2+} + 2NO^-_3 \rightarrow TiO_2 + N_2 + 2O_2\uparrow$$ Eqn. 5.3

$$Ti^{2+} + H_2O \rightarrow TiO_2 + H_2\uparrow$$ Eqn. 5.4

$$TiO^{2+} + 2OH^- \rightarrow TiO_2 + H_2O$$ Eqn. 5.5

$$TiO^{2+} + H_2Y^{2-} \rightarrow TiOY \text{ complex} + 2\,H$$ Eqn. 5.6

## 5.2 Experimental Planning

Electrochemical milling was carried out on the Ti6Al4V workpiece to demonstrate the effects of machining parameters on the various performance characteristics. Experiments were conducted on the indigenously developed EC milling setup that was explained in chapter 3 and with all the best parameters as discussed in chapter 4. In this experiment, EDTA was mixed in various concentrations with one mole of NaCl and one mole of $NaNO_3$ electrolyte solution to observe the surface roughness of the workpiece. From the literature review, it has been reported that around 0.1%molar concentration of EDTA can be used in 1 mole NaCl + NaNO3 electrolyte. A total of eight experiments have been conducted with different EDTA concentrations varying from 0.05 % to 0.1 %. The same experimental procedure has been carried out during each experiment as discussed in chapter 4.

## 5.3 Results and Discussion

Here strategy (ii) has been used with 60 seconds at the last stage as that strategy was proved to be the best suitable for minimum surface roughness and accuracy. In four different concentrations, EDTA was mixed with 1M NaCl and $NaNO_3$ mixture. All the parameters were kept the same as the previous. In the first set of experiments, different concentrations of EDTA were used. Out of which 0.075 mole EDTA was found best electrolyte to find the better surface roughness. Then duty cycle has been varied keeping the other parameters constant.

### 5.3.1 Effect on surface roughness and overcut with different concentrations of EDTA

The surface roughness and the radial overcut have been observed when holes are drilled with the help of EDTA at different concentrations. Here a total number of eight experiments have been conducted to see the exact result of the workpiece. As $NaNO_3$ is a passive electrolyte, it supports reducing the rate of the reactions. At the machining of Ti6Al4V with the solution of NaCl and $NaNO_3$, a layer of $TiO_2$ is formed. This thick layer of $TiO_2$ was one of the major causes for the rough surfaces as well as large radial overcuts. To maintain a thin layer of $TiO_2$ EDTA can be used. EDTA helps to reduce the formation of $TiO_2$ as it is a chelating agent. It forms soluble complexes with titanium ions as shown in Equations 1 to 6. In Fig. 5.1, it is shown that the surface roughness decreases with the increase of the molar concentration up to 0.075 M EDTA used in the electrolyte of 1 M NaCl and 1 M $NaNO_3$. On further increasing of the concentration of EDTA on the electrolyte material removal rate decreasesand the Ra value increases rapidly.

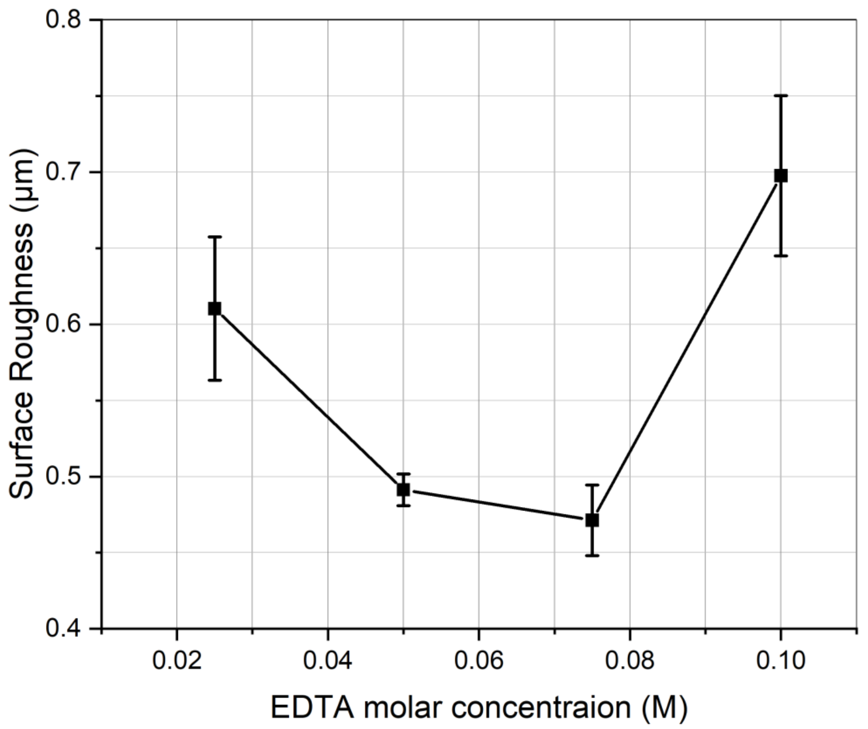


Fig. 5.1 Variation surface roughness with molar concentration of EDTA

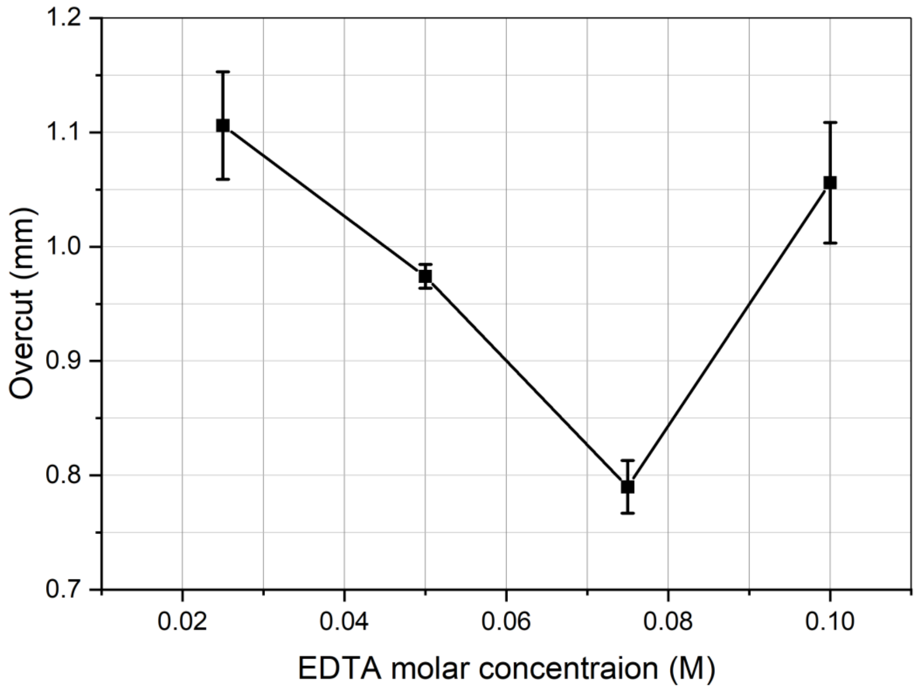


Fig. 5.2 Variation of overcutting with the molar concentration of EDTA

In Figure 5.2, it is clearly depicted that the increase of EDTA up to 0.075 M reduces the formation of $TiO_2$. EDTA is a chelating agent, which forms soluble complexes with titanium ions. It is very important to maintain a thin layer of $TiO_2$ while machining so that only stray currents are reduced. The reduced stray currents help to diminish the radial overcut. In these sets of experiments, the optimum results were come out that the electrolyte of 1 M $NaNO_3$ and 1 M of NaCl could be mixed with 0.075 M EDTA to get a better surface finish as well as the lowest overcut while EC milling of Ti6Al4V. The optimum average surface roughness value was calculated as 0.47133 µm.

### 5.3.2 Influence of duty cycle on surface roughness and accuracy

The duty cycle is defined as the pulse width on a certain period. It is mathematically defined as the percentage of the signal period where the signal is considered. It is directly proportional to the frequency of the pulse wave. In our experiment, the duty cycle could be controlled on the power supply machine. The range of duty cycle could be set within 10-90 %. In our latest experiment, the lowest surface roughness value was measured as 0.47133 μm. To improve further some experiments have been done on various duty cycles. The electrolyte used here is the mixture of 1 mole NaCl,1 mole $NaNO_3$and 0.75 mole EDTA. The duty cycle is taken as 30%, 50%, 70%, 90%. With the change of the duty cycle, the voltage and the current have also differed. The OVP and OCP were set as 20 volts each. The different values of voltage and current found in different duty cycles are shown in the Table 5.1 below.

Table 5.1 The variable list of voltage and current with respect to different duty cycle

| Duty cycle (%) | Voltage (V) | Current (A) |
|---|---|---|
| 30 | 6.00 | 2.9-3.2 |
| 50 | 9.90 | 5.5-5.7 |
| 70 | 13.90 | 6.4-6.8 |
| 90 | 17.90 | 8.2-8.8 |

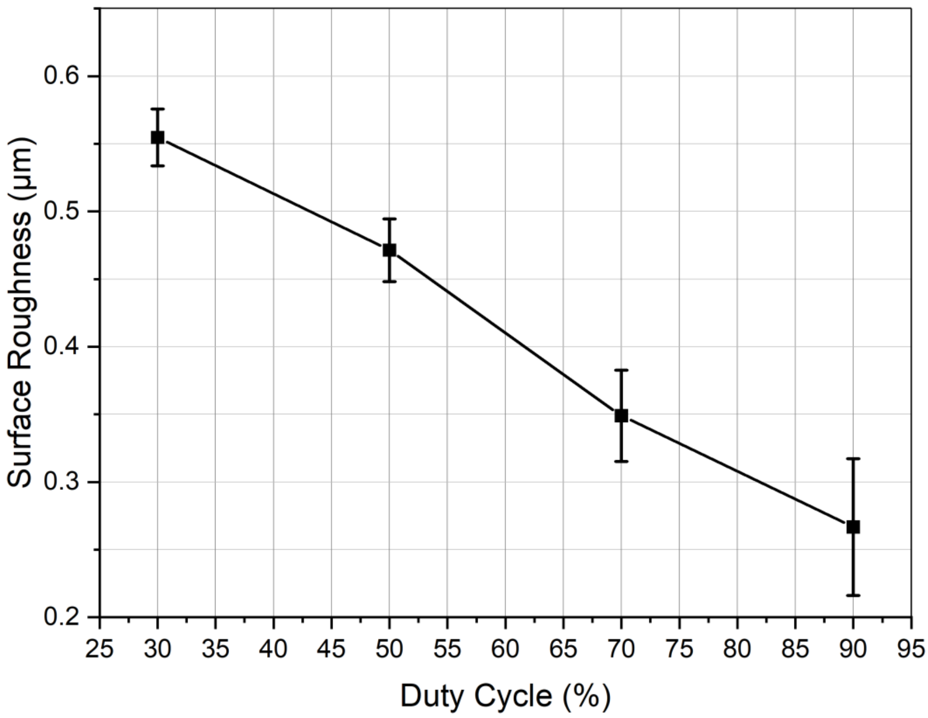


Fig. 5.4 Influence of surface roughness with the duty cycle

All the other parameters are taken as same as in previous experiments. The dwell time sequence was taken as 40 sec, 40 sec and 60 sec in three stages as discussed in chapter 4. The influence of the duty cycle on surface roughness is shown in the Fig,5.4. In the graph shown in Fig. 5.4, it is depicted that with the increase in duty cycle surface roughness decreases. At the highest duty cycle, 90% of the current produced is also in the range of 8.2-8.8 A. The amount of current increase results in a high machining rate and it helps to improve the surface also. In the experiment, the lowest value of surface roughness has been achieved at a 90% duty cycle with a voltage of 17.90 V and a current of 8.2-8.8 A with a square pulse width. Although the pulse of time is decreased with the increase of duty cycle which may hamper the surface finish, the dwell time after every stage of tool directed to downwards direction and tool rotation helps to remove the sludge with the time interval.

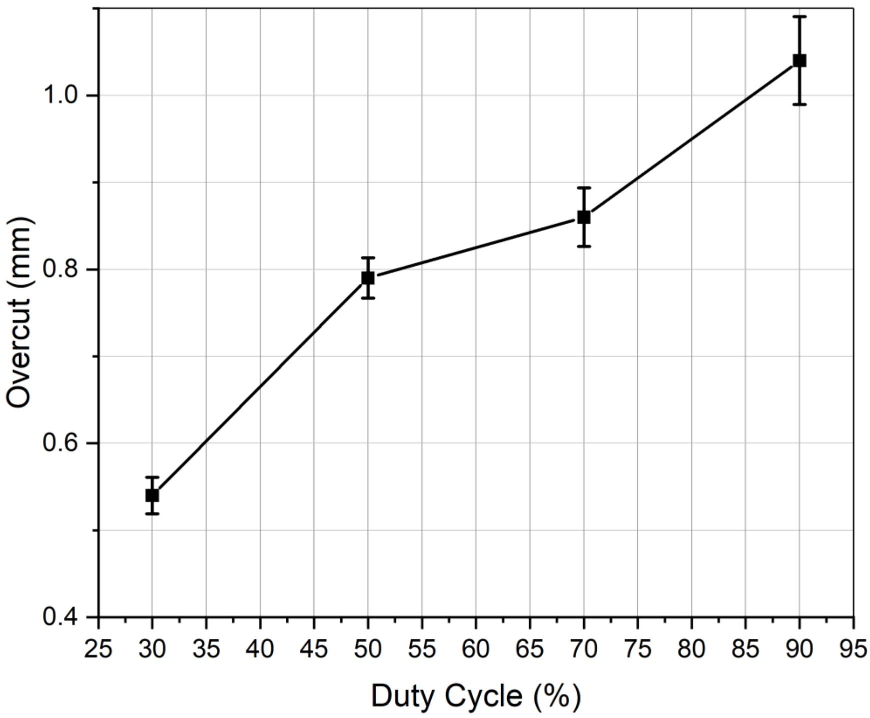


Fig. 5.5 Influence of accuracy with the duty cycle

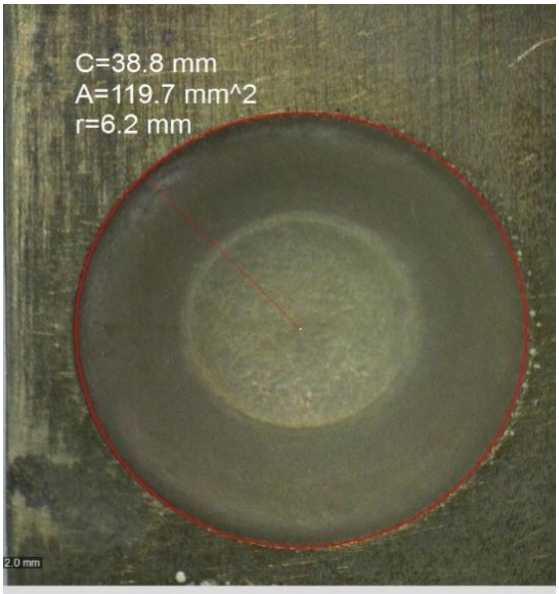


Fig. 5.6 The photographic view of the machined surface using best parameter setting

In Figure 5.5, it is clearly observed that with the increase of duty cycle the overcut tends to increase due to a higher stray current effect. With 30% duty cycle the current produced at a very low rate which caused lower machining as well as lower overcut. The increased current leads to the removal of material from the undesired portion of the work piece which resulted in inaccuracy in the machined profile. At the highest duty cycle 90% the overcut was around 1.04 mm.

In Fig. 5.6, the photographic view of the best machined profile with lowest surface roughness has been shown. It was achieved when the tool was directed to move 0.2 mm depth at the first stage with the feed of 0.1 mm/min followed by 40 seconds dwell time. This process was repeated twice according to Strategy (ii). At the last stage the tool was moved to 0.1 mm to downwards direction followed by 60 seconds of dwell time. EDTA was used in electrolytes with the mixture of 1 M NaCl and 1M $NaNO_3$ in distilled water. Duty cycle was considered as 90%. All the other parameters were kept constant as discussed in chapter 4. In this experiment the best surface roughness was achieved i.e. 0.267 µm.

# Chapter 6

## CONCLUSIONS

During this study, the investigation for the influence of various process parameters on performance characteristics like surface finish and accuracy through the EC milling process has been effectively completed. For the study, a laboratory EC milling setup with various units has been successfully modified. From the investigation, relationships between EC milling process parameters like dwell time, duty cycle and different performance criteria such as surface finish, accuracy, etc. have been observed. The following conclusions can be drawn from the obtained experimental results and observations:

(i) From all the experiments, it can be observed that the modified EC milling setup is capable of performing EC milling operations in difficult-to-machined material i.e., Ti6Al4V so that different investigations for surface finish and accuracy can be carried out.

(ii) Dwell time is one of the most influencing parameters for the better surface roughness and accuracy of machined titanium alloy. To observe the influence of dwell time two strategies have been used. In strategy (i), the tool was directed to move downwards 0.2 mm in the first stage followed by 20 sec dwell time, this process was repeated again so that the total tool movement to downwards direction became 0.4 mm. and at the last stage the tool was moved downwards to 0.1 mm followed by different dwell time of 20 sec, 40 sec, 60 sec and 80 sec.

(iii) In strategy (ii), the same process was repeated with the dwell time of 40 sec in the first two cases. The lowermost Ra value was achievedas0.6293 µm. With the same parameters, the lowest overcut accomplished was 0.861 mm. Both these results have been accomplished when the second strategy was used with the 3$^{rd}$ dwell time kept at 60 sec during machining of Ti6Al4V.

(iv) A complexing agent of ethylene di-amine tetra acidic acid (EDTA) has been successfully introduced along with the electrolyte to improve the surface finish and accuracy during machining of the titanium alloy. EDTA helps to reduce the layer of $TiO_2$ on the work piece surface.

(v) With the mixture of 1M $NaNO_3$ and 1M NaCl and 0.075 M of EDTA, the EC Milling of the titanium alloy resulted in obtaining best surface finish of 0.4713µmand lower overcut of 0.761 mm.

(vi) Duty cycle is also an important parameter to achieve the best surface finish of machined Ti6Al4V. It has been observed that at a higher duty cycle amount of current increases which enhanced the surface finish of the machined profile.

(vii) With all the best parameter combinations, using EDTA in the electrolyte mixture and at 90% duty cycle, the lowest surface roughness has been achieved i.e., 0.267 µm.

Analysis based on test results of this study will help manufacturing engineers to utilize EC milling successfully for the purpose of machining Ti6Al4V with a good surface finish and accuracy. Different parts with multiple features of this particular HSTR alloy are widely used in the biomedical implants and armour industry very frequently nowadays.

**Future Scopes of work**

The present research work through various parametric analyses will act as a guideline to the manufacturing engineers for the application of the EC Milling system more efficiently in actual practice. However, this area of research still requires further improvement of the process to achieve better applicability. At the end, it is felt that certain studies need to be done to improve the EC Milling process as follows:

(i) The indigenously modified setup can also be used for carrying out further investigation during the generation of complex shapes with a good surface finish on other HSTR alloys such as cobalt, nickel, etc.

(ii) In-depth study should also be performed considering other major influencing process parameters of EC milling e.g., tool rotation speed, voltage, current, frequency, different mixtures of electrolyte concentration and the pattern of electrolyte flow, etc. to find the better surface finish of Ti6Al4V.

(iii) Mathematical model and simulation considering different process parameters can also be investigated in EC milling of Ti6Al4V.

(iv) Investigation can be done for the further improvement of the accuracy of this machined Ti6Al4V workpiece with different parameters in micro-EC milling set up.

# References

(1) S.Sarkar, S.Mitra, B.Bhattacharyya, "Mathematical modelling for controlled electrochemical deburring (ECD)", Journal of Materials Processing Technology, (2004), 147, 241–246

(2) W. Vanderauweraa, M. Vanloffelta, R. Perezb, B. Lauwersa, "Investigation on the performance of macro electrochemical milling", Procedia CIRP, (2013), 6, 356–361

(3) Rajurkar, K.P., Zhu, D., McGeough, J.A., Kozak, J., De Silva, A.,1999, New Developments in Electrochemical Machining, Annals of the CIRP 48, p.567-579.

(4) P. S. Pa, "Effective form design of electrode in electrochemical smoothing of end turning surface finishing", Journal of Materials Processing Technology (2008), 195, 44–52.

(5) B. Bhattacharyya, S. Mitra, A.K. Boro, Electrochemical machining: new possibilities for micromachining, Robotics and Computer Integrated Manufacturing 18 (2002) 283–289.

(6) B. Bhattacharyya, J. Munda, Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain, Journal of Materials Processing Technology 140 (2003) 287–291.

(7) V. Rathod, B. Doloi and B. Bhattacharyya, Electrochemical Micromachining (EMM): Fundamentals and Applications.

(8) M. D. Nguyen, M. Rahman, Y.San Wong, "Transitions of micro EDM/SEDCM/micro ECM milling in Low resistivity deionized water", International Journal of Machine Tools & Manufacture‖ (2013), 69, 48–56.

(9) K. Mishra, D. Dey, B. R. Sarkar, and B. Bhattacharyya, Modeling on Volumetric Material Removal for Fabrication of Complex Shapes by EC Milling of Ti6Al4V, Journal of The Electrochemical Society, 165 (9) E388-E396 (2018).

(10) Chuanyun Zhanga, Jialu Yaob, Congyuan Zhangc, Xiaolei Chena, Jiangwen Liua, Yongjun Zhanga, Electrochemical milling of narrow grooves with high aspect ratio using a tube electrode, Journal of Materials Processing Tech. 282(2020)116695.

(11) K. Mishra, D. Dey, B.R. Sarkar, B. Bhattacharyya, “Experimental investigation into electrochemical milling of Ti6Al4V’, Journal of Manufacturing Processes 29(2017) 113-123.

(12) Minglu Wang, NingsongQu, Investigation on material removal mechanism in mechano-electrochemical milling of TC4 titanium alloy, Journal of Materials Processing Tech. 295(2021).

(13) Yukui Wang, Han Wang, Yuxin Zhang, Minshan Song, Guanxin Chi, Zhenlong Wang, Experimental study on micro electrochemical slab milling using disc tool electrode. Procedia CIRP 95(2020) 754-759.

(14) S. Hinduja, J. Pattavanitch. Experimental and numerical investigations in electrochemical milling‖, CIRP Journal of Manufacturing Science and Technology, (2016), 12, 79–89.

(15) C. Chen, J. Li, S. Zhan, Z. Yu, W. Xu, “Study of micro groove machining by micro-ECM”, Procedia CIRP, (2016), 42, 418 – 422.

(16) B. Ghosal, B. Bhattacharyya, “Investigation on the profile of microchannel generated by electrochemical micromachining”, Journal of Material Processing Technology, (2015), 222,410-421.

(17) Y. Liu, D. Zhu, L. Zhu, “Micro electrochemical milling of complex structures by using in situ fabricated cylindrical electrode”, International Journal of Advanced Manufacturing Technology, (2012), 60,977–984.

(18) Z. Xu, X. Chen, Z. Zhou, P. Qin, D. Zhu, “Electrochemical machining of high-temperature titanium alloy Ti60”, Procedia CIRP, (2016), 42, 125 – 130.

(19) S. D. Dhobe, B. Doloi, B. Bhattacharyya, “Surface characteristics of ECMed titanium work samples for biomedical applications”, International Journal of Advanced Manufacturing Technology, (2011) 55, 177–188.

(20) T. Grove, J. Köhler, B. Denkena, “Residual Stresses in Milled E-Annealed Ti6Al4V” Procedia CIRP 13 (2014) 320 – 326.

(21) D. Van. Camp, J. Bouquet, J. Qian, J. Vleugels, B. Lauwers, " Investigation on hybrid mechano-electrochemical Milling of Ti6Al4V", Procedia CIRP (2018), 68, 156-161

(22) Chuanyun Zhang, Jialu Yao, Congyuan Zhang, Xiaolei Chena, Jiangwen Liua, Yongjun Zhanga, "Electrochemical milling of narrow grooves with high aspect ratio using a tube electrode" Journal of Materials Processing Tech. 282(2020)116695.

(23) Guijie Wang, Zhanqiang Liu, Jintao Niu, Weimin Huang, Baolin Wang, "Effect of electrochemical polishing on the surface quality of nickel-titanium shape memory alloy after milling" Journal of materials research and technology. 2020;9(1);253-262.

(24) A. Speidela, J. M. Smitha, D. A. Walshb, M. Hirscha, A. Clarea, "Electrolyte jet machining of titanium alloys using novel electrolyte solutions", Procedia CIRP, (2016), 42, 367–372.

(25) MukeshTak, Vedanth Reddy S Abhijeet Mishra, Rakesh G. Mote, "Investigation of pulsed electrochemical micro-drilling on titanium alloy in the presence of a complexing agent in electrolyte'' Journal of Micromanufacturing 1(2) 142–153.

(26) Daihua He, Jing Du, Ping Liu, Xinkuan Liu, Xiaohong Chen, Wei Li, Ke Zhang, Fengcang Ma, "Influence of EDTA-2Na on the hydroxyapatite coating deposited by hydrothermal-electrochemical method on Ti6Al4V surface" Surface & Coatings Technology, 365 (2019) 242-247.

(27) McGeough, J.A., "Principles of Electrochemical Machining", 1974, 978-1-5041-1885-9, Springer US.