International Journal of Scientific Engineering and Research (IJSER)
ISSN (Online): 2347-3878
Impact Factor (2018): 5.426

Experimental Investigation of Different Electrolytes on Stainless Steel 316 Using Electrochemical Micromachining

M. Shunmuga Priyan, Aron Reji Joseph, Jerin Jacob, Jithin P. Thambi

Department of Mechanical Engineering, Loyola Institute of Technology & Science, Thovalai, Kanya Kumari District–629302, India

Abstract: ***Electrochemical Micro-machining process is one of the popular non traditional machining processes which is used to machine materials such as super alloys, Ti-alloys, stainless steel etc. This project involves Faraday's Law of Electrolysis. The aim of the present work is to optimize the ECM process parameters with the combination of SS316 (job material) and Copper electrode (tool material). This project mainly focuses on the experimental investigation of electrochemical micro-machining (ECM) process on stainless steel SS316 by different electrodes on various parameters. Taguchi design of experiment has been used to carry out the design of input process parameters and their levels. Moreover, microscopic characteristic study machined is to determine the surface topography of the electrochemical micro-work piece surface. The experimental results attained the effect of electrolyte concentration and duty cycle which is the most significant factors for the machining of stainless steel SS316 by electrochemical micro-machining (ECM) process. The results of 16 experiments revealed that increases in electrolyte concentration decrease the MRR and surface roughness initially increases then decreases. Further, increase in current increases MRR initially and then decreases, surface roughness also increases. It is also noticed that increase in feed rate MRR decreases and then increases, also surface roughness decreases then increases.***

Keywords: Electrolyte, Stainless Steel 316, Electrochemical Micromachining

1.Introduction

1.1 Introduction of ECM unit

Electrochemical micromachining (ECM) is a non traditional machining process in which electrochemical machining is used to remove material from workpiece. In this process, workpiece is taken as anode and tool is taken as cathode. The two electrodes - work piece and tool are immersed in an electrolyte (NaCl) and the voltage is applied across the two electrodes, the material remove from the workpiece starts. The workpiece and the tool are placed very close to each other without touching. In ECM the material removal take place at atomic level so it produces a mirror finish surface.

The ECMM process is most commonly used to produce complicated shape such turbine blades with good surface finish in difficult to machine material. It is widely used as deburring process. It can be more economical if a copper (Cu) is used as tool since it helps to prevent tool profiling. Using copper tool allows cutting complex shapes with no need for large amount of power supply.

In 1929, an experimental ECM process was developed by W. Gussef, although it was established in 1959 by Anocut Engineering Company. B.R. and J.I. Lazarenko are also credited with proposing the use of electrolysis for metal removal.

1.2. Process

During ECM, there will be reactions occurring at the electrodes i.e. at the anode or workpiece and at the cathode or the tool along with within the electrolyte. Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of stainless steel SS316, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergo ionic dissociation as shown below as potential difference is applied.

$$NaCl \leftrightarrow Na+ + Cl^{-}$$
$$H2O \leftrightarrow H+ + (OH)-$$

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece. Thus, the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$$2H+ + 2e- = H2\uparrow \text{ at cathode}$$

Similarly, the iron atoms will come out of the anode (work piece) as:

$$Fe = Fe+ + 2e^{-}$$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

$$Na+ + OH- = NaOH$$

In practice FeCl2 and Fe (OH)2 would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the sludge. Moreover, there is not coating on the tool, only hydrogen gas evolves at the tool or cathode. As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free. The voltage is required to be applied for the electrochemical reaction to proceed at a steady state. That voltage or potential difference is around 110V to 125 V. The applied potential difference overcomes the following resistances or potential drops. They are:

- The electrode potential
- The activation over potential
- Ohmic potential drop
- Concentration over potential
- Ohmic resistance of electrolyte

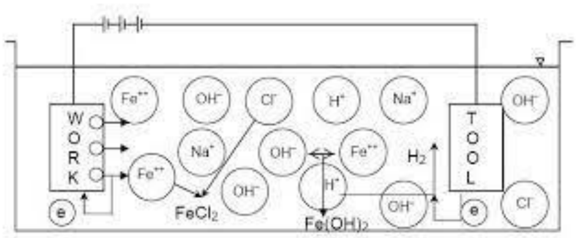


Figure 1.1: Reaction in ECM process

1.3. Equipment

The electrochemical machining system has the following modules:

- Power supply
- Electrolyte filtration and delivery system
- Tool feed system
- Working tank

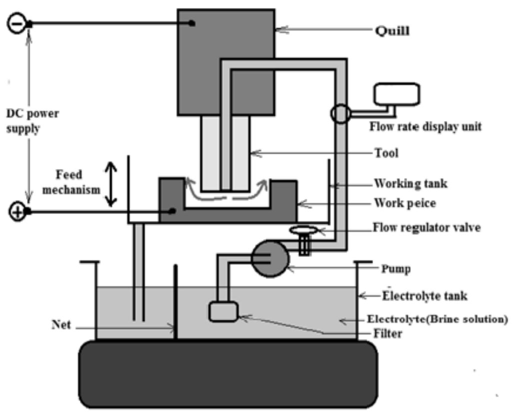


Figure 1.2: Schematic diagram of ECM unit

1.4. The Elements and Parameters of the ECM

The important elements of the ECM are:

1.4.1 Electrolyte

Electrolyte used in this ECM process is Sodium Chloride. The other commonly used electrolytes are sodium nitrate, sodium hydroxide, sulphuric acid etc. These solutions produce an insoluble compound in the form of sludge. It carries the current from the tool to the workpiece. It removes the metal from the workpiece. The solution is filled in the tank for the process. The electrolytes are made of salts.

1.4.2 Tool

Tool is also referred here as the cathode. Here most commonly used tool material is copper, titanium, copper tungsten and stainless steel. Copper is mostly found to be the most suitable tool where copper is a metal having highly anti-corrosive properties. The other tool materials are aluminium, graphite, bronze, platinum and tungsten carbide. The accuracy of the tool shape directly affects the workpiece accuracy.

1.4.3 Workpiece

Here it is also referred as the anode. Workpiece should be a good conductor of electricity. So, it is almost limit to the metals only. Here we use SS316 steel as the workpiece. It is a good conductor of the electricity and it have some other properties that to machine in the ECM.

1.4.4 Metal Removal Rate

MRR is an important characteristic to evaluate efficiency of a non-traditional machining process. In ECM, MRR takes place due to the atomic dissolution of the work material. The MRR is calculated with the help of the weight, i.e. the initial weight and the final weight with the time.

1.4.5 Power Supply

Power supply is an important factor in the ECM process. The supply is of Direct Current (DC). the voltage is about 110V to 125 V. The current is about 50 to 40, 000 A. The current density is between 20A/cm^2 to 300A/cm^2.

1.4.6 Surface Finish

There are number of factors which govern the accuracy or the surface finish of the parts produced by the ECM. The major factors include; Machining voltage, Feed rate of electrode, Temperature of electrolyte and the concentration of electrolyte, under ideal conditions with the property designed tooling, ECM is capable of holding tolerance of 0.02 mm. Surface finish in ECM is of the order of 0.2 to 0.8 micron. No burrs and the sharp edges are left on the work piece.

Summary

The present experimental work is focused on the optimization of ECM process parameters for maximum material removal rate (MRR), and the minimum surface roughness (Ra) for the stainless steel (SS-316) as a job material and a Copper (Cu) electrode as a tool material. In ECM process, electrolyte NaCl showed the good results on surface roughness and overcut. Also it had been observed that MRR increases with increase in tool feed rate because of the decrease in machining results.

2.Literature Review

2.1 Introduction

In this chapter, a few selected research papers are discussed regarding the electrochemical machining. ECM is an important machining process several researchers have attempted to improve the performance characteristics of the ECM process by studying the effect of process parameters on the machining process. But the full potential utilization of the ECM process is yet to be achieved. This is due to the complex and undetermined nature and the number of variables involved. Based on the analysis of the reaction mechanism with complexing agents in ECM, the experiments of micro holes on SS316 are carried out. Combined with the experimental results, the electrolyte constituent is selected and optimized. Finally, the reaction characteristic and experimental phenomena are discussed.

Bhattacharya B. (2002), "ELECTROCHEMICAL MACHINING: NEW POSSIBILITIES FOR MICRO MACHINING, " says that, a successful attempt has been made to develop an ECMM setup for carrying out in-depth independent, 18research for achieving satisfactory control of ECM process parameters to meet the micro-machining requirements. The developed ECMM 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 ECMM system setup will be capable of performing fundamental research in the area of ECMM fulfilling the requirements of micro-machining objectives.

SE HYUN AHN (2004), “ELECTRO-CHEMICAL MICRO DRILLING USING ULTRA SHORT PULSES" says that, in this work, ultra-short pulses with tens of nanoseconds duration are used to localize dissolution area. The effect of voltage, pulse duration, and pulse frequency on localization distance was studied. Highquality micro holes with 8-micron diameter were drilled on 304 stainless steel foil having a 20-micron thickness.

MUKHERJEE S.K (2005), “EFFECT OF OVERVOLTAGE ON MATERIAL REMOVAL RATE DURING ELECTROCHEMICAL MACHINING, ” says that It reports about the MRR in electrochemical machining by using over-voltage and conductivity of the electrolyte solution. It is observed that over-voltage plays an important role in the equilibrium gap and tool feed rate. MRR decreases due to an increase in over-voltage and a decrease in current efficiency, which is directly related to the conductivity of the electrolyte solution.

LAURENT CAGNON (2003), “ELECTROCHEMICAL MICROMACHINING OF STAINLESS STEEL BY ULTRA SHORT VOLTAGE PULSES,” says that it discusses the application of ultra-short voltage 11 pulses to a tiny tool electrode under suitable electrochemical conditions enables precise three-dimensional machining of stainless steel. To reach sub-micrometer precision and high processing speed, the formation of a passive layer on the workpiece surface during the machining process has to be prevented by the proper choice of the electrolyte. Mixtures of concentrated hydrofluoric and hydrochloric acid are well suited in this respect and allow the automated machining of complicated three-dimensional microelements. The dependence of the machining precision on pulse duration and pulse amplitude was investigated in detail.

JOAO CIRILO DA SILVA NETO ET AL (2006), studied the impact of interceding factors such as feed rate, electrolyte, stream pace of the electrolyte and voltage on MRR, unpleasantness and over-cut in SAE-XEV-F Valve-Steel. Over-cut is the material expelled in over-abundance in the parallel bearing because of unpredictable anodic disintegration. Two electrolytic arrangements NaCl and NaNO3 were utilized of which NaNO3 is answered to have created better results of surface harshness.

BHATTACHARYA ET AL (2005) have introduced the impact of different electrochemical micro-machining parameters like voltage, electrolyte fixation, beat period and recurrence on material evacuation rate, precision and surface completion in infinitesimal area. It is discovered that machining at 3V, 55Hz recurrence and 20g/l electrolyte focus can upgrade the exactness with the most elevated conceivable measure of material removal.

SHI HYOUNG RYU (2008), has endeavored to create safe and eco-friendly ECM by utilizing citrus extract electrolyte. He examined the effect of citric corrosive on tempered steel machining by ECM. The qualities of ECM were studied through citrus extract focus, feed speed and electrical conditions. The anodic metal disintegration of the alloyed carbon steel 100Cr6 was explored by Haisch et al (2001) in NaCl and NaNO3 electrolytes. In-stream channel tests, high current densities up to 70 A/cm2 and tempestuous electrolyte stream speeds were applied. Insoluble carbide particles cause an evident current effectiveness >100% in NaCl and >67% in NaNO3. These particles were enriched at the surface in NaCl arrangement and distinguished by ex-situ examining electron microscopy and vitality dispersive X-beam tests. Subjective mental disintegration models based on the trial results were proposed for the metal disintegration forms in the NaCl and NaNO3 electrolytes.

ZAWISTOWSKI (1990), proposed another arrangement of electrochemical structure machining utilizing general turning devices for improving the electrolyte circulation over the workpiece. Up until now, no exploration work has investigated the impact of electrolyte stream design on ECM destinations; in particular MRR and surface unpleasantness. Positive outcomes acquired through pivoting instruments and improved electrolyte dispersion offers upgrade to additionally examine their impact in ECM.

KONIG ET AL (1997) directed investigations on ECM and detailed that the major impacting factors are electrolyte type, tooling, control instrument and mechanical parts that influence the procedure.

LI YONG (2003), "RESTRICTED ELECTROCHEMICAL MICROMACHINING WITH HOLE CONTROL" says that, a way to deal with electrochemical micromachining was introduced in which side-protected anode, 15 small scale hole control between the cathode and anode, and the beat current are artificially used. Test set-up for electrochemical micromachining is built, which has machining process discovery and hole control capacities; additionally, a beat power supply and a control PC are associated with. Microelectrodes are fabricated by smaller-scale electro-release machining (EDM) and side-protected by compound fume statement (CVD). A miniaturized scale hole control technique is proposed dependent on the major test conduct of electrochemical machining current with the hole fluctuation. Machining probes miniaturized scale opening penetrating, checking machining layer-by-layer, and small-scale electrochemical affidavit are completed. Primer trial results show the plausibility of electrochemical micromachining and its potential ability for better machining precision and littler machining size.

JAIN AND ADHIKARI (2008), have broken down the system of material evacuation in electrochemical flash machining of quartz under various extremity conditions. Invert extremity cuts quartz plate at a quicker rate when contrasted with the immediate extremity. But in turn around extremity overcut, device wear and surface harshness are higher when contrasted with the direct polarity.

ZHIJIAN (2004), conducted a progression of ECM tests utilizing a changeless magnet on the machine instrument. It was demonstrated that the additional vitality gave by the attractive field, diminishes the basic voltage by energizing the particles to higher vitality level. The electric motion assists with combining the polarized particles. The displaying of NC-electro-chemical shape development machining utilizing a rotating instrument cathode has been introduced by Xu Jiawen et al (2005). This machining technology consolidates the upsides of ECM and numerical control (NC) procedures defeating their various disadvantages.

XIAOLONGFANG ET AL (2013), contemplated the Effects of throbbing electrolyte stream in ECM. They endeavored to generate the throbbing stream by a servo-valve in the electrolytic stock channel, which is acquainted with improve the warmth move, material expulsion rate and surface profile. They likewise introduced a multi-material science model coupling of electric, heat, transport of weakened species and liquid flow. Simulation results demonstrate that the throbbing stream has a noteworthy effect on the conveyance velocity, gas fraction, and temperature close to the workpiece surface along the stream direction. They led tests led to check the attainability of the proposed procedure and study impacts of the throbbing stream on material evacuation rate. They found that as the throbbing plentifulness increases, the relative material evacuation rate first increments and afterward diminishes.

ROSENKRANZ ET AL (2005), has analysed the distinctive response results of ECM by quantitatively resolving for beats by a mix, of course, through-small scale cell with a UV–spectrometer and a heartbeat generator.

V.K. JAIN ET AL (2008), has reported that the electrochemical spark machining method has been effectively used for cutting quartz utilizing controlled feed and a wedge edged tool. In ECSMWRP, a deep cavity on the anode (as a tool) and workpiece interface are formed because of substance response. The cutting is possible regardless of the possibility that we make small size auxiliary electrode.

JERZY KOZAK ET AL (1991), investigated the hypothetical and trial examination of the relationship between the characteristic shape measurements imported upon the workpiece surface by the micro-features of the tool electrode under given machining conditions. This work incorporated the investigation of electrochemical insulating groove features, copying of grooves and slots miniholes. Restricting cases of micro-ECM is considered for duplicating and micro-shaping utilizing-profiled tool cathodes.

J.A. WESTLEY ET AL, examined about the steady electrolyte flow. This paper tries to recognize the elements, for example, insulation prerequisites that can identify with other parts of ECM. These perceptions would then be utilized by while creating ECM electrodes. Work has been done in this paper by taking new cathodes for removing the casting gate.

MUNDA J (2010), "INVESTIGATION INTO THE INFLUENCE OF ELECTROCHEMICAL MICROMACHINING PARAMETERS ON RADIAL OVERCUT THROUGH RSM-BASED APPROACH" highlights the features of the development of a mathematical model for correlating the interactive and higher-order influences of various machining parameters. This paper also highlights mathematical models for analyzing the effects of various process parameters on the machining rate and overcut phenomena. These parameters can be used to achieve the maximization of the metal removal rate and the minimum overcut effects for optimal accuracy of shape features.

2.2 Inference of Literature Review

The literature survey helped to successfully design, construct and conduct the experimentation of this research work. Some of the major ideas learnt from the literature survey are listed below:

1. The specific studies of each process parameters made by various authors on for MRR and Dimensional deviation are helpful to understand the behaviour of each parameter.
2. Necessary ideas were obtained for making a suitable tool for the current study.
3. Clear outline about Taguchi methodology and various other optimization techniques were learnt.

3.Experimentation

3.1 Experimental Setup

This experiment is setup on the ECM. The figure shows the experimental apparatus. The system includes:

1) An Electrolyte holding tank
2) A pumping system to pump the electrolyte
3) An experimental apparatus chambers
4) Tool feed rate controller
5) A rectifier

Figure 3.1: Picture of ECM Setup

During the experiment, the electrolyte flowing through the tool to the workpiece will overflow through the chamber to the electrolyte holding tank. A filter is used before the electrolyte is re-circulated to the holding tank.

In the experiment, 10g/L of NaCl was used as the electrolyte. A stainless steel is used as the work-piece, the work-piece is set on the work-piece holder. The aim is to make hole on the work-piece. Desired voltage, feed rate, Ton, Toff and the duty ratio is set on the system. Then starting the process, at the same time stopwatch is started to note the time taken for making a hole on the work-piece. After the hole is developed, the work-piece is taken for the weight measurement for the calculation of the MRR. The Initial Weight, Final Weight and the time is also noted for the further calculation. This process continues till the aim of the experiment. Then the work-piece is taken to the VMS to find the circularity of 16 holes made in the work-piece. The initial machining gap, i.e. (the gap between the tool and the workpiece) was 0.26 mm. The tool feed rate was 0.4 mm/min during the test; the workpiece was weighed again that determine the weight loss during the machining process. Machining surface was inspected with a microscope. Machining dimensions, such as diameter and depth of the machined pocket, were also measured with a microscope.

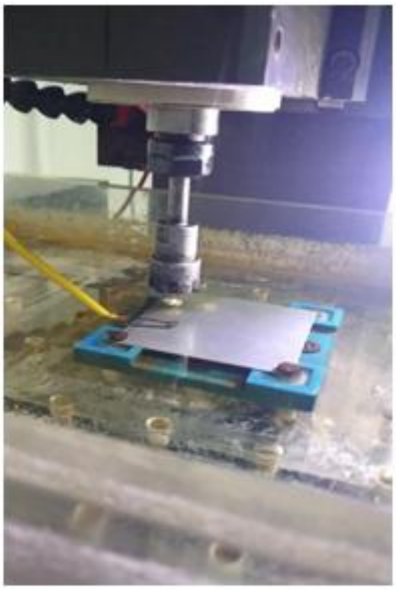


Figure 3.2: Picture of drilling a hole on SS316 steel

3.2 Technical data of ECM

Tool area – 30 mm2
Cross head stroke – 150 mm
Job holder – 100 mm opening x 50 mm depth x 100mm width
Tool feed motor – DC Servo type
Power – better than 85
Protections – overload, short circuit, single phasing.
Operation modes – manual/automatic
Timer – 99.9 min
Supply – 420V 10%, 3 phase 50Hz
Z axis control – forward, reverse, auto forward/reverse, through microscope.
Tool feed – 0.2 to 2 mm/min
Electrical output Rating–0-300 amps. DC at any voltage from 0 - 20V
Efficiency – better than 80% at partial and full load condition

3.3 Specification of Workpiece

Here we use SS316 stainless steel as the work piece, for this experiment. It is the most versatile and most widely used of all steels. Its chemical composition, mechanical properties, weldability and corrosion/oxidation resistance provide the best all-round performance stainless steel at relative cost. It also has excellent low temperature properties and responds well to hardening by cold working. If intergranular corrosion in the heat affected zone may occur, it is suggested that SS316 steel is used.

Typical application:

SS316 is used in all industrial, commercial and domestic fields because of its good corrosion and heat resisting properties. Some application includes:

- Tanks and Containers for large variety of liquids and solids.
- Process equipment in the mining, chemical cryogenic, food, diary and pharmaceutical industries.

3.3.1 Metal Removal Rate

SS316 alloy is chosen for the trial workpiece, SS316 treated steel used to lead this investigation. SS316contain an addition of Molybdenum that gives it improved corrosion resistance. This is particularly apparent for pitting and crevice corrosion in chloride environments. It is accessible in a huge scope of items, structures, and completes than some other material. It has great framing and welding attributes. The decent structure of evaluation 316 it to be seriously drawn with moderate strengthening which has made this evaluation prevailing in the assembling of drawn spotless parts, for example, pots and sinks. Evaluation 316L, the low carbon version of SS316, is immune to grain boundary carbide precipitation (sensitisation).This makes it suited to use in heavy gauge welded components. Evaluation 316H with its high carbon. It discovers its application at elevated temperature. The austenitic structure of Stainless Steel 316 gives excellent toughness, even at cryogenic temperatures. The MRR is defined as the amount of material removed from the workpiece per unit time. The MRR can be calculated from the volume of the material removal or from the weight difference before and after machining.

$$MRR = (Wi - Wf) \div Txp$$

3.3.2 Composition

Table 3.1: Composition ranges for 316 grade stainless steel

		C	Mn	Si	P	S	Cr	Mo	Ni	N
316 Wt.%	Max	-	-	-	0	-	16.0	2.00	10.0	-
	Min	0.08	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10
316L Wt.%	Min	-	-	-	-	-	16.0	2.00	10.0	-
	Max	0.03	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10
316H Wt.%	Min	0.04	0.04	0	-	-	16.0	2.00	10.0	-
	Max	0.10	0.10	0.75	0.045	0.03	18.0	3.00	14.0	-

3.3.3 Mechanical Properties

Table 3.2: Mechanical properties of SS316 stainless steel

Grade	Tensile strength (MPa) min	Yield strength 0.2% proof (MPa) min	Elongation (%in50mm) min	Hardness Rockwell B	Hardness Rockwell (HB)max
316	515	205	40	95	217
316L	485	170	40	95	217
316H	515	205	40	95	217

3.3.4 Physical Properties

Table 3.3: Physical properties for annealed grade 316stainless steel

Grade	Density (kg/m^3)	Elastic Modulus (GPa)	Mean Co-eff. of Thermal Expansion (µm/m/°C)			Thermal Conductivity (W/m.K)		Specific Heat (J/kg.K)	Electrical Resistivity (nΩ.m)
			0 to 100°C	0 to 100 °C	0 to 100°C	At 100°C	At 500°C	0 to 100°C	
316/L/H	8000	193	15.9	16.2	17.5	16.3	21.5	500	740

3.3.5 Selection of Machining Parameters and their levels

Table 3.4: Selection Parameters

Process parameter	**Level 1**	**Level 2**	**Level 3**
Voltage (V)	110	117.5	125
Feed Rate (F)	0.4	0.55	0.7

3.3.6. Corrosion Resistance

Excellent in a range of atmospheric environments and many corrosive media - generally more resistant than 316. Subject to pitting and crevice corrosion in warm chloride environments, and to stress corrosion cracking about 60 °C. Consider resistance to potable water with up to about 1000 mg/L chlorides at ambient temperatures, reducing to about 500 mg/L at 60^{o}C.

316 is usually regarded as the standard "marine grade stainless steel", but it is not resistant to warm sea water. In many marine environments 316 does exhibit surface corrosion, usually visible as brown staining. This is particularly associated with crevices and rough surface finish.

1. Annealing

Heat from 1010^oC to 1120^oC and cool rapidly in air or water. The best corrosion resistance is obtained when the final annealing is above 1070^oC and cooling is rapid.

2. Stress relieving

SS316 can be stressed relieved at 450^oC-600^oC for one hour with little danger of sensation. A lower stress relieving temperature of 400^oC maximum must be used.

3. Hot working

Initial forging and pressing: 1150^oC to 1260^oC Finishing temperature: 900^oC to 925^oC.

1.3.7 Experimental Procedure

- Initial weight of the workpiece was measured.
- Workpiece and tool are fixed in the chamber.
- After setting the control parameter experiment was conducted for 20 minutes.
- Final weight of the workpiece is measured.
- MRR of the process is calculated.

	3.5.8 SELECTION PARAMETERS	
SL.NO.	**PARAMETERS**	**VALUES**
1	**Power supply**	
	Type	Direct current
	Voltage	100 to 125V
	Current	50 to 40,000 A
	Current Density	0.1A/mm^2 to 5A/mm^2
2	**Electrolyte**	
	Material	SS316
	Temperature	20O to 50O ^oC
	Flow rate	20Ipm /100A/current
	Pressure	0.5 to 20 bar
	Dilution	100 g/1 to 500g/1
3	**Working Gap**	0.1mm to 2mm
4	**Overcut**	0.2mm to 3mm
5	**Feed rate**	0.4 to 0.7 mm/min
6	**Electrode Material**	Copper
7	**Surface Roughness**	0.2 to 1.5µm

4.Results and Discussions

In this chapter, main objectives are metal removal rate, and various calculations of feed rates while drilling the holes on steel.

4.1 Analysis of Experiment and Discussion

ECM processing relies upon the electrical conductivity of the electrolyte, feed rate of the anode, between cathode hole and terminal stream rate the influence of different machining parameters hole on MRR. The cathode feed rate enormously affects MRR and it increases with increments in feed rate. This outcome was normal because of the material removal rate increments with the feed rate because the machining time decreases. All things considered; the machining time diminishes. MRR additionally increments with a bigger distance across an anode; in any case, the impact is not exactly the feed rate on MRR. The cathode stream rate and conductivity have a next with no impact are not exactly the feed rate on MRR. The anode stream rate and conductivity has next with no impact on MRR and doesn't give any definitive proof of any effect on MRR and doesn't give any decisive proof of any effect on MRR.

4.2: MRR Investigation Report

Table 4.1: MRR Investigation Report

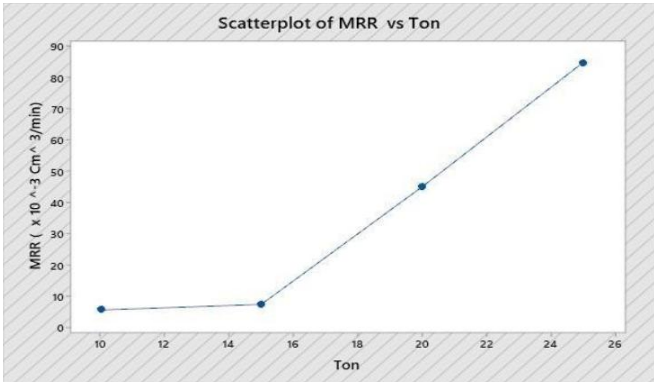
Sl.No.	**Voltage (V)**	**Feed Rate (mm/min)**	**T_{ON}**	**T_{OFF}**	**Weight Before (g)**	**Weight After (g)**	**Time (min)**	**MRR (cm3/min)**
1	110	0.4	13	7	7.98063	7.97342	20:46.1	$0.35x10^{-3}$
2	110	0.5	14	6	7.97342	7.96761	14:37.4	$0.40x10^{-3}$
3	110	0.6	15	5	7.96761	7.96296	15:34.5	$0.32x10^{-3}$
4	110	0.7	16	4	7.96896	7.95721	13:28.2	$0.88x10^{-3}$
5	115	0.5	13	7	7.95721	7.95195	13:15.4	$0.4x10^{-3}$
6	115	0.4	14	6	7.95195	7.94551	16:34.7	$0.39x10^{-3}$
7	115	0.7	15	5	7.94551	7.93971	13:23.2	$0.43x10^{-3}$
8	115	0.6	16	4	7.93971	7.93052	15:53.6	$0.59x10^{-3}$
9	120	0.6	13	7	7.93052	7.92125	21:08.9	$0.43x10^{-3}$
10	120	0.7	14	6	7.92125	7.91655	12:02.1	$0.39x10^{-3}$
11	120	0.4	15	5	7.91655	7.90909	17:14.6	$0.43x10^{-3}$
12	120	0.5	16	4	7.90909	7.90422	13:28.6	$0.36x10^{-3}$
13	125	0.7	13	7	7.90422	7.89685	14:28.0	$0.51x10^{-3}$
14	125	0.6	14	6	7.89685	7.88981	15:01.6	$0.46x10^{-3}$
15	125	0.5	15	5	7.88981	7.88217	16:54.7	$0.46x10^{-3}$
16	125	0.4	16	4	7.88217	7.87482	17:22.1	$0.42x10^{-3}$

4.3: Circularity Inspection Report

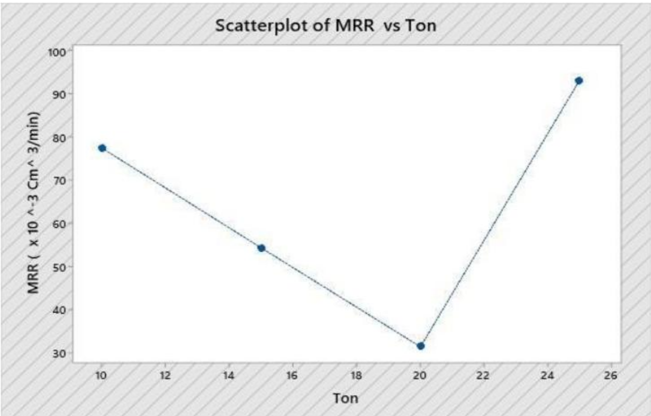
Table 4.2: Circularity Inspection Report

Sl. No.	Specification	Electrolyte	D_{OUT} (mm)	D_{IN} (mm)	Error (D_{OUT}-D_{IN}) (mm)
1	DIAMETER	NaCl	2.054	1.334	0.72
2	DIAMETER	NaCl	1.877	0.983	0.894
3	DIAMETER	NaCl	1.899	0.927	0.972
4	DIAMETER	NaCl	1.891	0.948	0.943
5	DIAMETER	NaCl	2.001	0.974	1.027
6	DIAMETER	NaCl	1.969	1.196	0.773
7	DIAMETER	NaCl	1.929	1.102	0.827
8	DIAMETER	NaCl	2.015	1.241	0.774
9	DIAMETER	NaCl	2.241	1.581	0.66
10	DIAMETER	NaCl	2.018	0.951	1.067
11	DIAMETER	NaCl	2.071	1.221	0.85
12	DIAMETER	NaCl	1.918	0.823	1.095
13	DIAMETER	NaCl	2.328	1.308	1.02
14	DIAMETER	NaCl	2.184	1.277	0.907
15	DIAMETER	NaCl	2.184	1.454	0.73
16	DIAMETER	NaCl	2.137	1.231	0.906

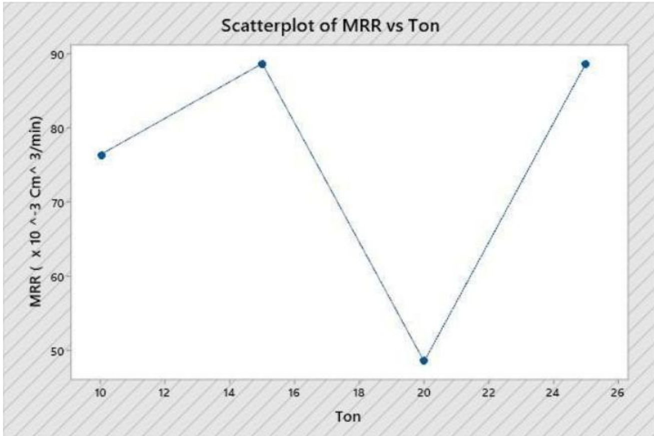
Graphs:



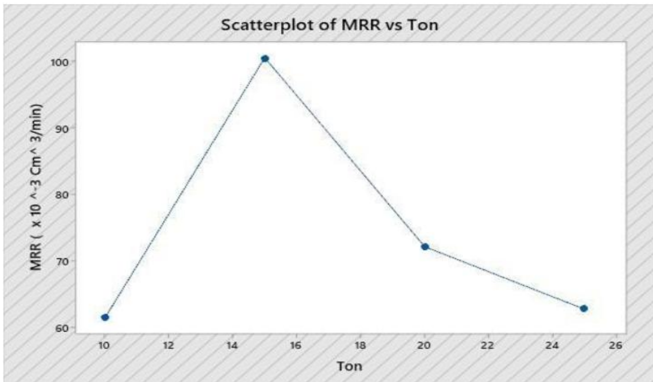
(i) Scatter plot of MRR vs Ton at 110V



(ii) Scatter plot of MRR vs Ton at 115V

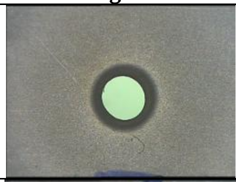
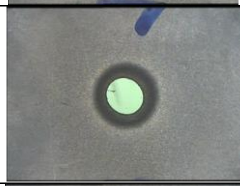
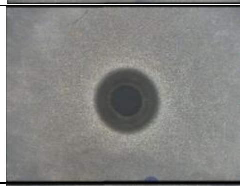
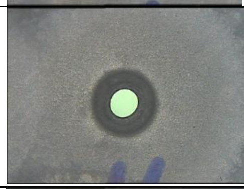
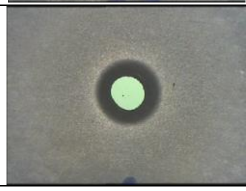
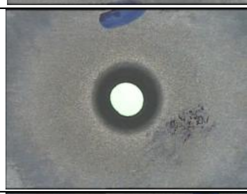
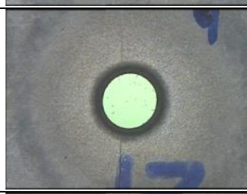
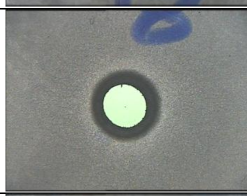
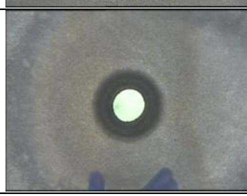


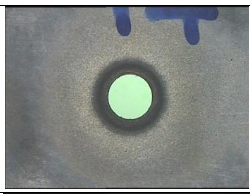
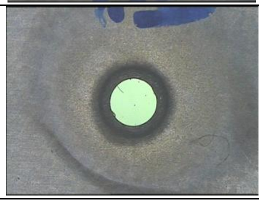
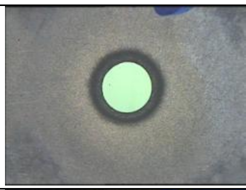
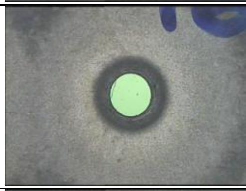
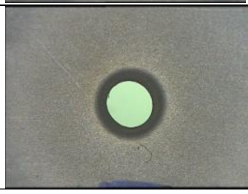
(iii): Scatter plot of MRR vs Ton at 120V



iv): Scatter plot of MRR vs Ton 125V

Table 4.3: Experimental Results

Sl. No.	Parameters	Figure
1	At V = 110V, F = 0.4	
2	At V = 110V, F = 0.5	
3	At V = 110V, F = 0.6	
4	At V = 110V, F = 0.7	
5	At V = 115V, F = 0.5	
6	At V = 115V, F = 0.4	
7	At V = 115V, F = 0.7	
8	At V = 115V, F = 0.6	
9	At V = 120V, F = 0.6	
10	At V = 120V, F = 0.7	

11	At V = 120V, F = 0.4	
12	At V = 120V, F = 0.5	
13	At V = 125V, F = 0.7	
14	At V = 125V, F = 0.6	
15	At V = 125V, F = 0.5	
16	At V = 125V, F = 0.4	

References

[1] K. P. Rajurkar, M. M. Sundaram. Et al. 2013. Review of Electrochemical and Electrodischarge Machining.

[2] Kong Quancun, Liu Guodong, Li Yong et al. Preparation of hollow electrode used for micro ECM. Optics and Precision Engineering.

[3] Zhu, H. Y. Xu “Improvement of electrochemical machining accuracy by using dual pole tool" Journal of Materials Processing Technology vol. 129pp. 1518, 2002.

[4] S. K. Mukherjee, S. Kumar, P. K. Srivastava, Arbind Kumar "Effect of valance on material removal rate in electrochemical machining of SS304" Journal of Materials Processing Technology2 02 pp. 398401, 2007.

[5] Sekar T. , Marappan R. , "Improving Material Removal Rate of Electrochemical Machining by Using Rotating Tool", International Journal of Machine Tools & Manufacture vol. 44pp. 6063, 2008.

[6] M. Malapati B. Bhattacharyya, J. Munda "Experimental study on electrochemical micromachining" Journal of Materials Processing Technology vol. 169pp. 485492, 2005.

[7] J. Ciriloda Silva Neto, E. Malaquias da Silva, M. Baccida Silva, "Intervening variables in electrochemical machining", Journal of Material Processing Technology, vol. 179, pp. 9296, Brazil, 2006.

[8] H. Hocheng, Y. H. Sun, S. C. Lin, P. S. Kao "A material removal analysis of electrochemical machining using flat-end cathode" Journal of Materials Processing Technology vol. 140pp. 264268, 2003.

[9] U. Mallick, "Estimation of MRR by using U-shape Electrode in Electrochemical Machining", M. Sc thesis, National Institute Technology, India, 2009.

[10] Ferraris E, Castiglioni V, Ceyssens F, Annoni M, Lauwer B and Reynaerts D 2013 ECM drilling of Ultra- high aspect ratio micro holes with insulated tools Journal of Manufacturing Technology 62pp. 191-194.

[11] Tong hao, Li Yong, Zhan long and Li Baoquan 2013 Mechanism design and process control of micro ECM for drilling spray holes of diesel injector nozzles Journal of Precision Engineering 37pp. 213-221.

[12] Lee ES, Park JW, Moon YH (2002) A study on electrochemical micro machining for fabrication of micro grooves in an air-lubricated hydro dynamic

bearing. Int J Adv Manuf Technol 20:720–726.

[13] Bhattacharyya B, Munda J (2003) Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain. Int J Mach Tool Manuf 43:1301–1310

[14] Malapati M, Bhattacharyya B (2011) Investigation into electrochemical micromachining process during micro-channel generation. Mater Manuf Process 26:1019–1027

[15] Kirchner V, Cagnon L, Schuster R, Ertl G (2001) Electrochemical machining of stainless steel microelements with ultrashort voltage pulses. Appl Phys Lett 79:1721–1723

[16] Kim BH, Na CW, Lee YS, Choi DK, Chu CN (2005) Micro electrochemical machining of 3D microstructure using dilute sulfuric acid. Ann CIRP 54(1):191–194.

[17] Bard AJ, Faulkner LR (2001) Electrochemical methods 2nd ed. Wiley, Hoboken 26. Schuster R, Kirchner V, Allongue P, Ertl G (2000) Electrochemical micromachining. Science 289:98–101

[18] Ghoshal B, Bhattacharyya B (2013) Influence of vibration on micro-tool fabrication by electrochemical machining. Int J Mach Tool Manufact 64:49–59

[19] Bard AJ, Faulkner LR (2001) Electrochemical methods 2nd ed. Wiley, Hoboken 16. 44

[20] Schuster R, Kirchner V, Allongue P, Ertl G (2000) Electrochemical micromachining. Science 289:98–101

[21] Ghoshal B, Bhattacharyya B (2013) Influence of vibration on micro-tool fabrication by electrochemical machining. Int J Mach Tool Manufact 64:49–59

[22] S. H. Ahn, S. H. Ryu, D. K. Choi, and C. N. Chu, "Electro-chemical micro drilling using ultra short pulses, " Precision Engineering, vol. 28, no. 2, pp. 129–134, 2004. View at: Publisher Site | Google Scholar

[23] R. Goswami, V. Chaturvedi, and R. Chouhan, "Optimization of electrochemical machining process parameters using Taguchi approach," International Journal of Engineering Science and Technology, vol. 5, no. 5, pp. 999–1006, 2013. View at: Google Scholar

[24] T. Sekar and R. Marappan, "Experimental investigations into the influencing parameters of electrochemical machining of AISI 202," Journal of Advanced Manufacturing Systems, vol. 7, no. 2, pp. 337–343, 2008.

[25] Z. Brusilovski, "Adjustment and readjustment of electrochemical machines and control of the process parameters in machining shaped surfaces," Journal of Materials Processing Technology, vol. 196, no. 1-3, pp. 311– 320, 2008.