Design and Fabrication of Electrochemical MicroMachining (ECMM) Experimental Setup for Micro-hole Drilling

Pranesh Dutta, Anwesa Barman, Abhinav Kumar and Manas Das

Abstract In electrochemical micromachining (ECMM) process, anodic dissolution is used to remove the material in the micron range. With the help of ECMM process, complex contours on the workpiece surface and difficult to cut materials can be machined without any stress on workpiece surface and without any tool wear. This study aims to design and fabricate an ECMM experimental setup and to control the process parameters for smooth machining of miniature components. In the present study, fabrication of microcomponents is carried out on stainless steel (SS-316L) workpiece with helical tungsten carbide micro-tool. The effect of machining voltage on output responses of the fabricated micro-holes is carried out with continuous and pulsed DC power supply. From preliminary experimental analysis, it is observed that as machining voltage increases, material removal rate, overcut and conicity also increase.

Keywords Electrochemical micromachining · Microfabrication · Continuous and pulsed direct current

1 Introduction

There are many non-conventional machining processes where surface texturing can be done. One of the processes is (electro-discharge machining) EDM, but the problem associated is that the debris particles cannot be easily eliminated from machining

P. Dutta
Indian Institute of Technology Bhubaneswar, 752050 Bhubaneswar, India
e-mail: pd29@iitbbs.ac.in

A. Barman · A. Kumar · M. Das (✉)
Indian Institute of Technology Guwahati, Guwahati 781039, India
e-mail: manasdas@iitg.ac.in

A. Barman
e-mail: anwesa02@gmail.com

A. Kumar
e-mail: kumar176103020@iitg.ac.in

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area which leads to unstable machining. Laser beam machining (LBM) may also be employed for surface texturing but its own limitations like the formation of hotspot because of thermal effect. But, in electrochemical micromachining (ECMM), no defective layer is formed after machining. A growing demand for better surface texture and micro-parts has to be met with the increasing demands in several areas like automotive, aerospace, electronics, and others that have made ECMM process an exciting area of research [1].

In ECM, the workpiece acts as anode and connected to positive terminal, whereas the tool acts as cathode and connected to negative terminal of an electrolytic cell. Thus, both the electrodes must be electrically conductive. Generally, a salt solution is being used as an electrolyte to complete the electrolytic cell. The tool is normally made of copper, brass or stainless steel and the gap between the electrodes, i.e. the tool and the workpiece is called as inter-electrode gap (IEG) which is maintained between 0.1 and 0.6 mm [2]. In ECMM, as IEG is small, high flow velocity of electrolyte will vibrate the tool which leads to inaccurate machining. Hence, flow of electrolyte in ECMM is done under gravity [3]. The metal dissolution in ECMM process is governed by Faraday's law of electrolysis.

The tool is advanced towards the workpiece so that the IEG remains constant, to aid in material removal [4]. Figure 1 shows the schematic diagram of ECMM experimental setup.

ECMM offers several advantages over other competing technologies. The tool and the workpiece have no direct contact between them; hence, it avoids problems like elastic deformation, vibration and breakage of tool [5]. Many industries are facing problem to machine hard and brittle material at low cost [6]. This problem can be solved by ECMM.

Lee et al. [7] used ultrashort voltage pulses (100 ns–5 μs) to manufacture micro-probe (tool) of tungsten carbide of 5 μm diameter and 1 mm length to make a hole

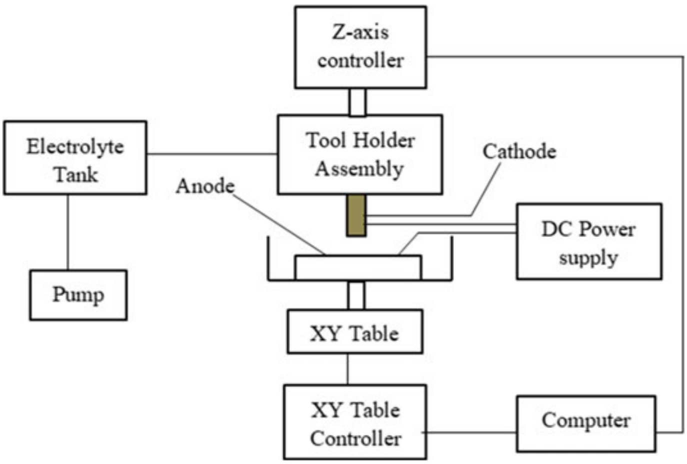


Fig. 1 Schematic diagram of ECMM setup

of 50 μm diameter. They used STS420 disc as workpiece and HCL (0.5 M) as electrolyte. It was found that for same duty factor, the groove depth is different for different on and off-time as these have a great impact on machining depth. As the on time increases, the groove depth increases for the same duty cycle. It was found that as voltage increases, the machining depth also increases for the same pulse duration (1 μs). Ghosal et al. [8] generated micro-features by ECMM taking workpiece as stainless steel SS-304. It was found that the localization of current during machining is the major difficulty in getting sharp and accurate micro-features. This leads to overcut and conicity in the vertical wall. To decrease this, a conical micro-tool of taper angle 13° is used and normalized current density was calculated from the distribution of equipotential lines along the cross section of micro-channel. At the exit side of micro-channel, maximum current density was found. From their simulation study, it was predicted that slots without taper can also be generated with conical micro-tool. Finally, they have found that both conical and straight micro-tools can be employed to produce taper less micro-slots.

Zhu et al. [9] created micro-dimple array of 240 μm diameter and various depths on hard chrome coating with the help of ECMM and did friction test on that surface. It was found that under load of 500 N applied in normal direction, the friction coefficient reduces significantly for the component having micro-dimple array on its surface. After a certain depth in micro-dimple array, the coefficient of friction stated to increase. Qian et al. [10] created micro-dimple array of 240 and 280 μm diameter and various depths on the hard chrome coating with the help of through mask ECMM and did friction test on that surface. They also found that under a load of 500 N in normal direction, the friction coefficient reduces significantly for the surface having micro-dimples array with more diameter under less sliding velocity.

2 Design and Development of ECMM Experimental Setup

This section provides a detailed explanation of all the components used to fabricate ECMM experimental setup. The following components are discussed below.

2.1 Motorized XYZ Gantry Stage

The motorized XYZ gantry stage is made up of aluminium alloy and steel with black anodized finishing. The maximum load-carrying capacity for *X*- and *Y*-axes is 20 kg, whereas for *Z*-axis is 5 kg. The *X*- and *Y*-axes have resolution of 10 μm and *Z*-axis of 2.5 μm. The *XYZ* axes are placed over three lead screws individually.

Table 1 Specification of spindle motor

Sl. No.	Parameters	Value
1	Diameter	65 mm
2	Length	200 mm
3	Power	1.5 KW
4	Voltage	220 V
5	Speed	10–24,000 rpm
6	Frequency	0–400 Hz
7	Resolution	0.05 mm
8	Lubrication	Grease
9	Cooling	Air cooled

Table 2 Specification of VFD

Sl. No.	Parameters	Value
1	Input voltage	220 V
2	Output voltage	208–240 V
3	Input frequency	48–63 Hz
4	Output frequency	0–400 Hz
5	Input phase	Single phase
6	Output phase	Triple phase

2.2 Spindle Motor and VFD

A high-speed air-cooled spindle is attached to the *Z*-axis plate for rotating the tool. Aluminium housing is used to hold the spindle in vertical position. The specification of spindle is described in Table 1.

The spindle is controlled by a variable frequency drive (VFD) which is used to control the speed of the spindle. VFD has a precision of 6 rpm. The specification of VFD is described in Table 2.

2.3 Tool Holder and Tool

A helical tool is selected for doing the machining of the workpiece. As stated in the literature, helical rotating tool helps in removing the debris particles from the machining zone (IEG) very efficiently. The specification of tungsten carbide helical tool has been described in Table 3.

Table 3 Specification of the helical tool

Sl. No.	Parameters	Value
1	Material	Tungsten carbide
2	Shank diameter	3.175 mm
3	Helical diameter	0.5 mm
4	Electrical conductivity	5×10^7 S/m

2.4 Machining Chamber

The machining chamber consists of an electrolyte bath where the machining is done and a job holding system. The machining chamber is made up of Perspex material as it was chemically unreactive to the electrolyte that is used in the machining process. The workpiece holding fixture is placed in the machining chamber and is designed in such a way that it can hold any size of workpieces. The workpiece holder is also made up of Perspex material.

2.5 Electrolyte Circulation System

In the electrolyte supply system, electrolyte is supplied to the machining chamber with the help of gravity. An inlet pipe of 6 mm diameter is attached from filter. The electrolyte removed from the machining chamber is sent to the sedimentation tank. The heavy particles in the electrolyte will sediment down in this chamber with the help of gravity. Electrolyte is then pumped out from sedimentation chamber to the storage tank with the help of the pump. The flow rate of pump is controlled by a potentiometer attached to the pump. Speed controller controls the flow by controlling the voltage supplied to the pump. Electrolyte then flows down from the storage tank to the filter with help of a 4-mm-diameter pipe where small particles are removed, and clean electrolyte is provided back in machining chamber. The specification of the pump is described in Table 4.

Table 4 Specification of motor

Sl. No.	Parameters	Value
1	Input voltage	230 V
2	Power	0.05 kW
3	Head	15 m
4	Flow rate	240 L/h

2.6 Power Supply Unit

There are two modes of power supply which are given to the ECMM process. The one is the continuous DC power supply and the other one is pulse DC power supply.

Continuous DC Power Supply
DC dual power supply is used to supply continuous DC to workpiece with the help of wire which is connected to the screw in workpiece holder. In this case, voltage is maintained constant.

Pulse DC Power Supply
A power supply is used to apply pulse DC to the tool and workpiece with the help of a special thin wire. This wire is used because it generates a negligible amount of noise while transferring signal. Pulse DC signal is generated using LabVIEW® software in a computer. This signal is transmitted from computer to power supply with the help of general-purpose interface bus (GPIB) cable. The signal generated in LabVIEW® is shown in Fig. 2.

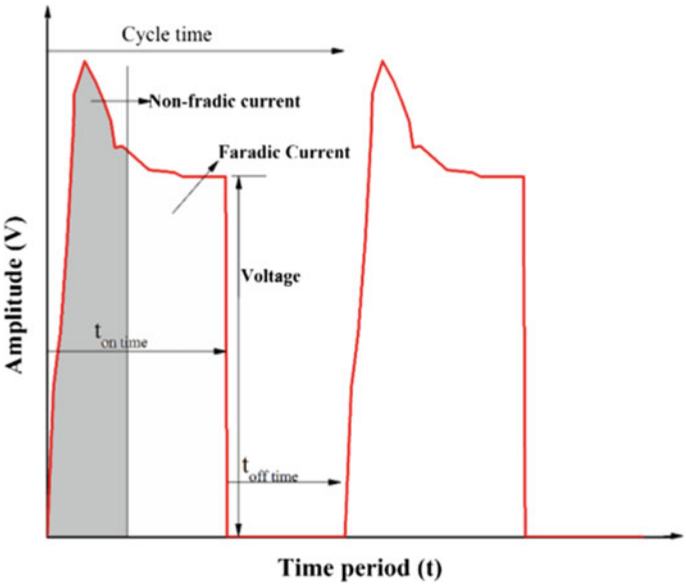


Fig. 2 Voltage signal generated using LabVIEW®

3 Results and Discussion

In ECMM process, preparation of electrolyte solution plays an important role in material removal rate. A 3 wt% solution of sodium nitrate ($NaNO_3$) is taken as electrolyte. Workpiece is made up of stainless steel (SS316L). The workpiece is cut in the dimension of 80 × 28 mm from a sheet with help of EDM machine. The workpiece sides are grinded in a grinding wheel to remove the heat-affected zone from the workpiece. The machined surface is then polished with the help of a sandpaper and cleaned with acetone to remove impurities from the machined surface. Experiments are carried out at different voltages, and the results are compared with continuous DC and pulse DC. Preliminary experimental investigation is conducted to find out the influence of process parameters of ECMM on material removal rate (MRR), overcut and conicity of the micro-holes fabricated on SS316L workpiece as described below.

3.1 Effect of Voltage on MRR

The machinability of ECM depends on the electrical conductivity of the electrolyte, feed rate of electrode and inter-electrode gap. Initial IEG is maintained at 0.01 mm. Constant DC and pulse DC power supply are supplied with frequency of 1.3 Hz having duty cycle of 60%.

Figure 3 shows the variation of MRR with respect to voltage. When pulse DC current is applied, during off-time of power supply, the machined products are flushed from the machining zone. This in turn reduces the stray machining. Holes are fabricated on 500-μm-thick plate of SS316L using a helical tool of diameter 500 μm at 10 V with continuous DC and pulse DC as shown in Figs. 4 and 5, respectively.

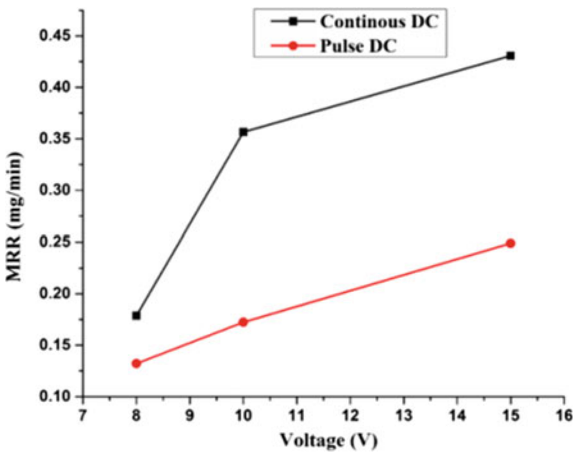


Fig. 3 Comparison between the effect of continuous DC and pulse DC voltage on MRR

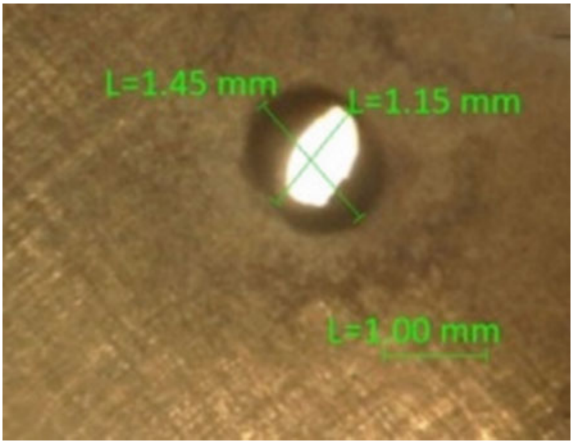


Fig. 4 Hole produced using 10 V continuous DC

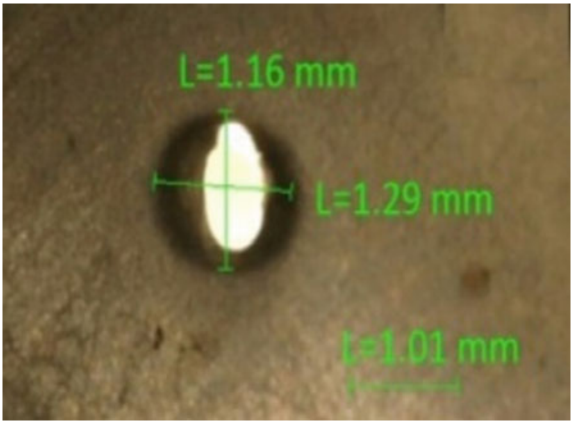


Fig. 5 Hole produced using 10 V pulse DC

During ECMM, oxide layer is formed over the workpiece surface. To break this, sufficient amount of voltage should be applied. Using $NaNO_3$ as electrolyte, the amount of voltage required to break this oxide layer is high and at high voltage, stray machining takes place which leads to inaccurate holes. Due to this, other end of the hole seems like elliptical.

3.2 Effect of Voltage on Overcut

Voltage has great impact on overcut. The overcut and conicity are discussed below:

$$\text{Overcut} = (D_o - D_t)/2 \tag{1}$$

$$\text{Conicity} = (D_o - D_e)/2 \quad (2)$$

The tool and workpiece arrangement is shown in Fig. 6. Electrochemical reactions produce hydrogen gas at surface of micro-tool. As voltage increases, hydrogen gas bubbles break down which results in the occurrence of micro sparks in machining area. This micro-spark causes uncontrolled machining from the workpiece surface, and finally larger overcut is formed. So, at higher voltage zone, the overcut increases more rapidly. Overcut also depends on nature of current applied. When pulse DC is applied at 1.3 Hz of 60% duty cycle, there is significant reduction in overcut as shown in Fig. 7.

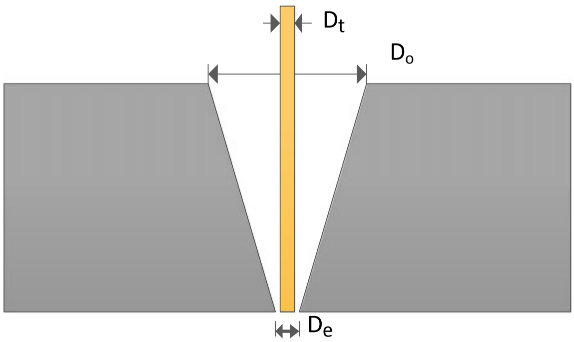


Fig. 6 Tool and workpiece arrangement while drilling a micro-hole in ECMM process

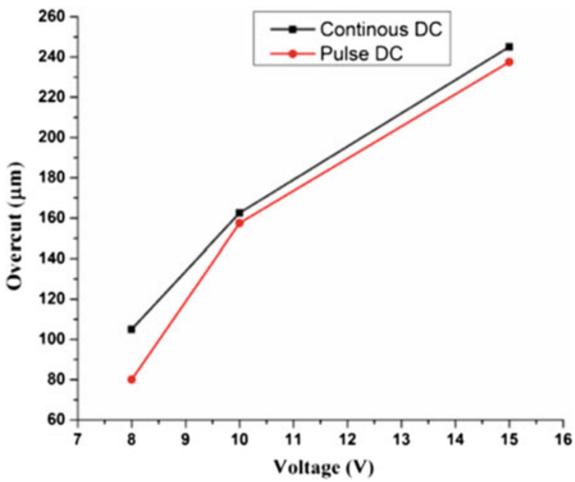
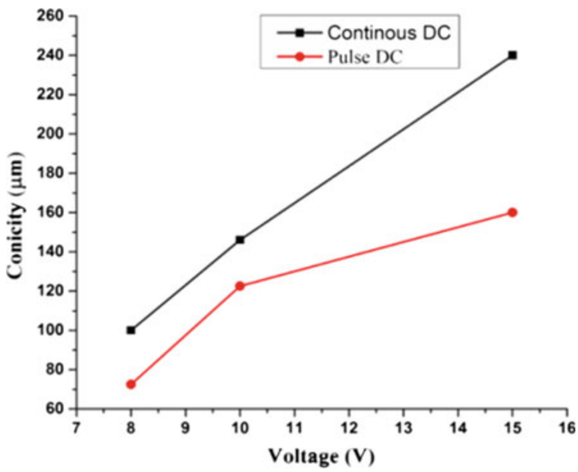


Fig. 7 Effect of voltage on overcut of micro-hole

Fig. 8 Effect of voltage on conicity of micro-hole



3.3 Effect of Voltage on Conicity

From Ohm's law, current density (J) obeys $J = -\sigma \nabla V$, where σ is the electrolyte conductivity and V is the applied voltage.

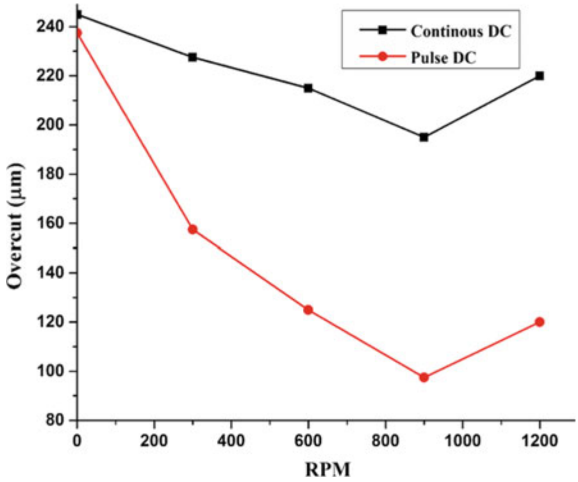
When pulse DC is applied, localization effect increases. Higher value of applied voltage can break the oxide layer over the whole range of electric field and increases the stray machining, thus producing non-uniformly shaped holes. As voltage increases, Joule heat generated at the IEG varies locally the conductivity of the electrolyte. At bottom of the hole, the electrolyte temperature is more than the top part. As removal of heat is difficult from the bottom, it causes non-uniform electrolyte conductivity between top and bottom. Hence, at higher voltage, conicity increases as shown in Fig. 8.

3.4 Effect of Tool Rotation on Overcut

Overcut can further reduce by rotating tool, as it will reduce the formation of H_2 gas bubbles. Electrolyte conductivity has also an effect on overcut. At high RPM, small bubble is formed which decreases the conductivity of electrolyte.

Thus, less material is removed from the IEG; hence, overcut decreases as observed in Fig. 9.

Fig. 9 Effect of tool rotation on overcut of micro-hole

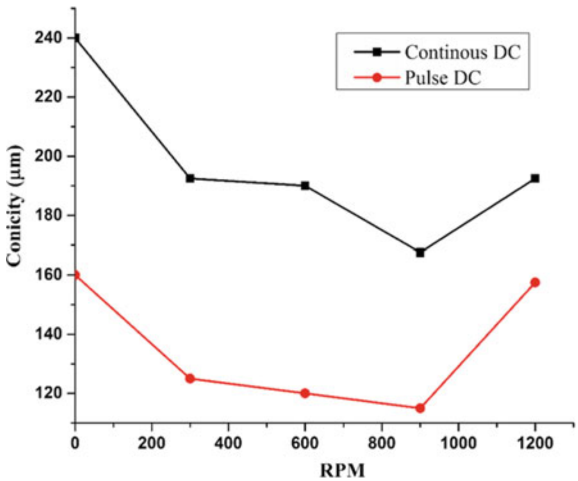


3.5 Effect of Tool Rotation on Conicity

Conicity, like overcut, decreases with increase in speed of rotating tool. When a helical tool is rotated in clockwise direction, it makes the electrolyte to flow in axial upward direction.

It helps to remove the machined debris and heat from IEG which in turn gives a close uniformity of electrolyte conductivity between bottom and top portions of the machined zone. Hence, as tool RPM increases, conicity decreases as shown in Fig. 10. The conicity increases after 1000 rpm because of the increase in vibration of the spindle at higher RPM which is transmitted to the tool.

Fig. 10 Effect of tool rotation on conicity of micro-hole



4 Conclusions

An electrochemical micromachining setup is designed and fabricated. By using this electrochemical micro-machining (ECMM) experimental setup, micro-holes are fabricated on stainless steel workpiece of grade 316L using helical tool made up of tungsten carbide. The feed rate of 70 μm/min is applied, and 3 wt% sodium nitrate solution is used as electrolyte. Different types of power supply are applied with varying voltage. Their effect with respect to MRR, overcut and conicity had been observed.

1. As current density increases on increasing the voltage, thus MRR increases.
2. During ECMM, hydrogen gas is formed. At higher voltage, these gases break down which leads to uncontrolled machining. Thus, overcut increases.
3. As voltage increases, Joule heat generated in the IEG varies locally the conductivity of the electrolyte. Thus, conicity increases.
4. As tool rotation increases, the bubbles start to break down which reduces the conductivity, and hence overcut reduces.
5. When tool speed is increased, it increases electrolyte flow in axial upward direction. It helps to remove the machined debris and heat from IEG which in turn gives a close uniformity of electrolyte conductivity between bottom and top portions of the machined zone. Thus, conicity reduces on higher tool rotation.

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