Electrochemical machining (ECM): An experimental investigation in to material removal rate (MRR) and volume efficiency (E_V)

Amir Arsalan Bayat[1], Sayed Mohsen Hosseini[1], Amir Hossein Moradi[1], Majid Hashemzadeh[1,2]

[1] Department of Mechanical Engineering, Na.C, Islamic Azad University, Najafabad, Iran
[2] Modern Manufacturing Technologies Research Center, Na.C, Islamic Azad University, Najafabad, Iran

* majid.hashemzadeh@iau.ac.ir

Abstract
Electrochemical machining (ECM) is one of the non-conventional manufacturing techniques that can easily machine metals, especially hard and brittle metals, by a non-contact tool. Although this technique has some advantages such as machining complicated shapes, machining with no residual stress, acceptable surface finishing and low tool wear, due to some reasons it has not been completely commercialized yet. There are several combinations of ECM parameters which are well known to achieve the advantages of this process. The purpose of this research is to investigate into material removal rate (MRR) and volume efficiency (E_V) of the ECM process. For this purpose, a 4 mm-thick mild steel sheet was drilled by ECM with using a 0.64 mm diameter stainless steel needle tool, NaCl electrolyte and various combination of process parameters. The volume of all holes drilled by different condition were obtained. Then, MRR and E_V were achieved. The results of this research indicate that in the range of employed parameters, the efficiency of tool feed rate (E_F) in these experiments varies from 0.00079 to 0.00374 mm/J. The removed volume differs from 2.7 to 9.2 mm^3. The MRR ranges between 0.02 and 0.062 mm^3/s and the volume efficiency (E_V) varies from 0.00083 to 0.00303 mm^3/J.

Keywords
Electrochemical machining, ECM, ECD, Volume efficiency, Material removal rate, MRR

1. Introduction

Nowadays, the application of ECM (electrochemical machining), as one the non-conventional manufacturing techniques, have been increasing in the industries such as automotive, electronics, optics, medical engineering, aircraft industries and die making workshops [1, 2]. This technology is mainly used for machining the electrically conductive materials like metals and hard and brittle metal matrix composites [3]. Beside micro milling and turning, drilling the precise small holes with acceptable quality using ECM technique is one of the most desirable applications in industries which is mostly called ECD [4]. An anodic dissolution process according to Faraday's law occurs between an anodic workpiece and a cathode tool in ECM process. The gap between anode and cathode, electricity condition (current, voltage, current density, pulsed and continuous mode), tool feed rate, electrolyte (type and concentration) and electrolyte flow rate are the most important input parameters in ECM which affect the process performance in terms of surface finish, accuracy and efficiency [5, 6]. Although, the application of ECM process is not affected by strength, hardness or toughness of the workpiece [7], however, it is reported that the metallurgical structure and grain size of the workpiece (e.g. steel with 0.25% plane carbon) influence on the ECM parameters such as final tool gap, current, machining rate, and surface roughness [8]. Adding nanoparticles such as Nano copper particles to the electrolyte to increase the machining removal rate and surface finish is another way to improve the ECM process performance when machining the high carbon high chromium (HCHCr) die steel with a hardness of 63HRc [9]. Material removal process in ECM is done atom by atom at which the removed material sometimes is seen in insoluble form in the used muddy electrolyte. If an insufficient removal of muddy electrolyte occurs, the waste products can settles down on the workpiece as the mud and slob, brings about a problem in the performance of ECM in terms of tool gap and short circuit especially in deep-hole drilling. It is reported that a constant electrolyte flow rate can prevent this problem and enhance the performance of ECM. In ECD of Inconel 718, while the hole becomes deeper, the pressure is linearly increased in order to make a constant electrolyte flow rate, causes the uniform machined holes with higher tool feed rate [10]. Many researchers have investigated into the ECM technology and they have reported the effects of input parameters on the performance and efficiency of the ECM and they have also discussed the potential application of this technology in industries [11]. The investigation into ECM of WC–Co material as a hard workpiece using ultrashort pulses and a mixture electrolyte of sulfuric acid and nitric acid showed that a good surface finish with sharp edge can be obtained by ECM and ECD [12, 13]. In a full factorial experiment, the influence of the ECM parameters on the material removal and surface roughness of stainless steel 310 was investigated. It was found that any increase in the electrolyte flow rate and tool feed rate results in enhancement of material removal rate (MRR). Moreover, surface finish generally increases with increasing flow rate [14]. In an experimental study, the researchers showed that how to simply fabricate an ECM device and they reported that the MRR increases with an increase of electrolyte concentration and tool feed rate [15].

In this research, the effect of four input parameters i.e. voltage, electrolyte concentration, pressure and tool feed rate on the diameter of hole, hole volume, material removal rate (MRR) and volume efficiency during drilling with ECM process have been experimentally investigated. According to the primary experimental results and using the Design Expert software, a series of experiments has been designed. A theoretical equation is presented to predict the orifice diameter of drilled hole. Then, in order to verify the results, the theoretical predictions are compared with experimental results. The volume of holes is calculated using the cross section of holes and finally, material removal rate (MRR) and volume efficiency (E_V) are investigated as the novelty in this research. The results of this research can be useful to improve the ECM process to be more efficient in the future.

2. Material and experiments procedure

2.1. Material

In order to achieve the purpose of the research, mild steel sheet with thickness of 4 mm was used as a workpiece in the experiments. Table 1 shows the chemical composition contents of the applied material.

Table 1. Chemical composition contents of mild steel sheet (% of weight)

Fe	**C**	**Si**	**Mn**	**S**	**Cr**	**Ni**	**Al**	**Co**	**V**	**Ca**

99.1	0.0632	0.0071	0.205	0.0150	0.0415	0.0325	0.0542	0.005	0.002	0.0017

2.2. Design of experiment (DOE)

In the Response Surface Method (RSM), the Central Composite Design (CCD) procedure was employed for design of experiment (DOE). The CCD is one of the response procedure designs that has the ability to investigate the curvature effect of variables and interference effects, as well as obtain a second or higher order regression model. From the experimental results which were published by others, e.g. ECM micro hole drilling [4], ECM of Inconel [5], ECM of Iron [6], ECM of die steel [9, 16], ECM drilling with constant electrolyte flow [10], ECM of WC–Co alloy [12], influence of ECM process parameters [14], effect of NaCl electrolyte [15] and ECM of 304 steel [17], as well as our own results from the initial tests, we used as input to the Design Expert software. In this DOE, the influence of four input parameters (voltage, electrolyte concentration, pressure and tool feed rate) on the diameter of hole were considered. Table 2 indicates the design of experiments. As seen, the number of experiments are 30 in this research.

Table 2. Design of experiments

No	**Voltage (V)**	**Concentration (gr/lit)**	**Pressure (MPa)**	**Feed rate (mm/s)**
1	15.5	25	0.5	0.027
2	5.5	25	0.3	0.037
3	13	20	0.4	0.030
4	15.5	15	0.3	0.027
5	13	30	0.4	0.030
6	10.5	15	0.3	0.037
7	15.5	25	0.5	0.037
8	13	20	0.4	0.030
9	13	20	0.4	0.041
10	10.5	25	0.5	0.027
11	13	20	0.4	0.030
12	8	20	0.4	0.030
13	10.5	15	0.3	0.027
14	18	20	0.4	0.030
15	15.5	15	0.5	0.037
16	13	10	0.4	0.030
17	13	20	0.6	0.030
18	13	20	0.2	0.030
19	13	20	0.4	0.019
20	10.5	25	0.5	0.037
21	13	20	0.4	0.030
22	13	20	0.4	0.030
23	13	20	0.4	0.030
24	10.5	25	0.3	0.027
25	10.5	15	0.5	0.037
26	15.5	15	0.3	0.037
27	15.5	25	0.3	0.027
28	15.5	15	0.5	0.027
29	10.5	25	0.3	0.037
30	10.5	15	0.5	0.027

2.3. ECM experiments

The ECM machine employed in this research was equipped with a CNC table, an electrolyte pump, a pressure gage, a pressure control valve, connecting pipes, an electrolyte container, solution of NaCl + water as electrolyte, a stainless steel needle as tool, a DC power supply, a computer system to control the ECM process. Figure 1 shows the ECM machine applied in this research. Figure 2 indicates the map of applied ECM equipment.

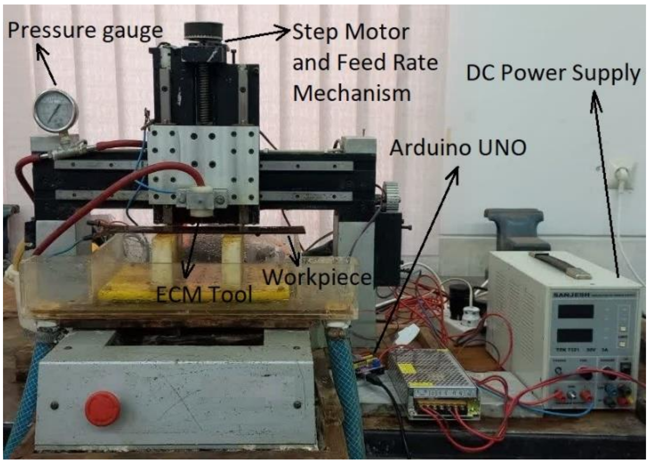


Figure 1. Showing the ECM machine employed in this research

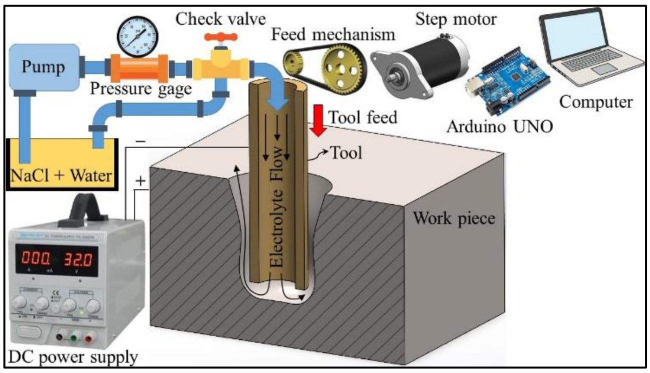


Figure 2. Illustrating the map of applied ECM equipment

According to design of experiments (see Table 2), 30 sets of experiments were done. For any test, the ECM machine was setup according to Table 2 and when all input parameter became stable, the drilling process was started. Tool feed rate was controlled using a step motor and CNC system. In order to increase the precision of results, every experiment repeated 3 times. It means that at the end of experiments phase, there were 90 drilled holes. All processing conditions and ECM parameters applied in this research are indicated in Table 3.

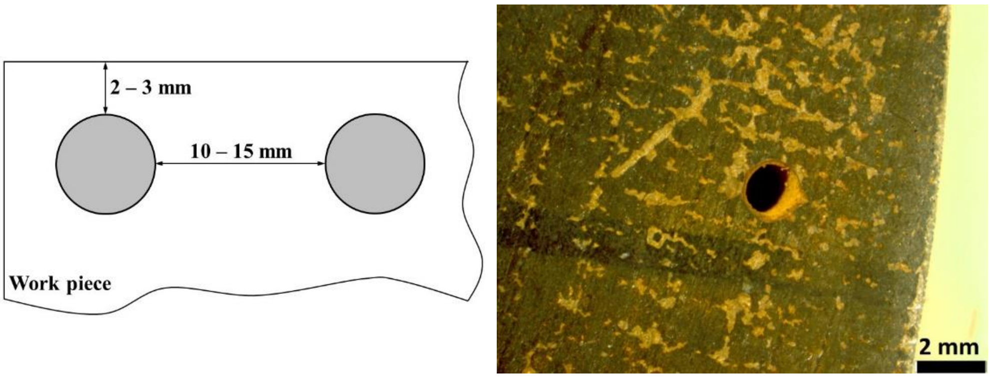
One of the purposes of this research was to investigate the holes volume. In order to find the volume and according to the strategy in this research, finding the cross section profile of the hole in the depth of the sheet was essential. For this purpose, after drilling, the workpiece should be chopped up and then ground in so that the cross section of the hole can be seen. In order to reduce the grinding time, the hole should be drilled as close to the edge of the sheet as possible.

Table 3. Processing conditions and ECM parameters

Processing Parameters	Volume
Workpiece	Mild steel sheet

Sheet thickness (mm)	4 mm
Power supply input voltage (V)	220 AC
Power supply output voltage (V)	0 - 30 DC
Power supply output current (A)	0 – 3
Employed voltage (V)	5.5 – 18
Employed current (A)	1.8
Tool material	Stainless steel needle
Tool outer diameter (mm)	0.64
Tool inner diameter (mm)	0.34
Tool cylindrical surface	Electrically insulated
Tool feed rate (mm/s)	0.019 – 0.041
Electrolyte	NaCl + water
Electrolyte concentration (gr/lit)	10 - 30
Electrolyte pressure (MPa)	0.2 – 0.6
Electrolyte flow rate (mm^3/s)	17.2 – 23.4

Figure 3 shows the map (A) and a micro photo (B) of the hole position on the workpiece. As seen, the hole was drilled about 2 – 3 mm close to the sheet edge.

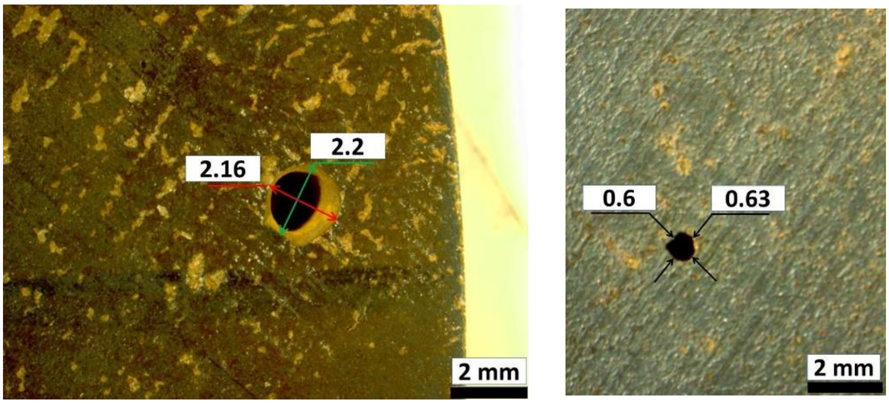


(A) Map **(B) ECM drilled hole**

Figure 3. A) The map of hole positioning close to the sheet edge, B) drilled hole close to the sheet edge (the hole was obtained in test number 10 according to Table 2)

2.4. Hole diameter measurements

In order to study on the diameter of hole, all drilled holes diameter on the top and bottom of the sheet were measured by an optical stereomicroscope model Olympus SZX16 with magnification of 7x to 115x. With using the camera of the stereomicroscope in appropriate magnification, images of the upper and lower hole diameter were taken and then the diameter of the hole was measured using the stereomicroscope software. As Figure 4 shows, all holes were measured in two perpendicular directions. The average of these two measurements was counted as hole diameter.

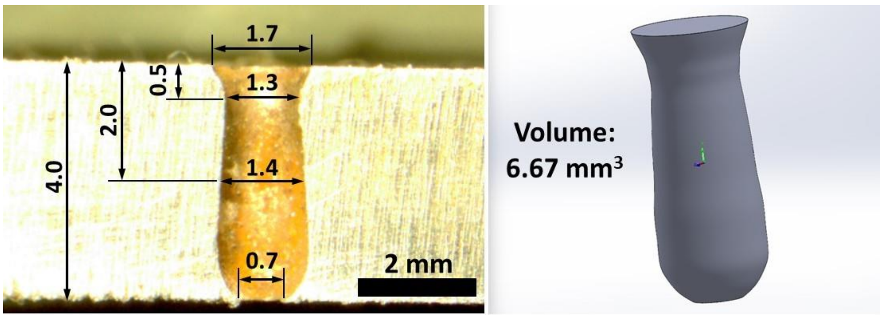


A) Upper diameter **B) Lower diameter**

Figure 4. Measuring of the upper (A) and lower (B) hole diameter in two perpendicular directions. (The hole was obtained in test 14 according to Table 2)

2.5. Hole volume calculation

Studying on the volume of drilled hole was another aim of this research. For this purpose, first the workpiece was chopped up then, with using a grinding machine in metallography lab and a few abrasive paper number from 400 – 1200, all holes were ground precisely to achieve the middle cross section. Using the stereoscope, the diameter of hole in 3 to 5 points of the depth of hole was measured and the photos of the holes cross-section were taken with a suitable magnification. Then, the photos were imported in Solidworks software and with using its modeling tools the holes were carefully 3D modelled and finally, the volume of holes was obtained. Figure 5 shows how to obtain the holes volume.



(A) **(B)**

Figure 5. Illustrating the steps to obtain the hole volume. A) Measuring the cross section of hole, B) 3D modeling of the hole (The hole was obtained in test 1 according to Table 2)

3. Results

3.1. Diameter of hole

The upper and lower diameter of hole for all experiments, which were done according to Table 2, are shown in Figure 6. As seen, in the range of applied parameters and condition, the upper hole diameter achieved in this research is varying from 1.4 mm to 2.4 mm. This range for lower hole diameter is between 0.47 mm and 0.9 mm. The dashed lines in Figure 6 indicate the average upper hole diameter (1.86 mm) and the average lower hole diameter (0.7 mm) while the ECM tool diameter is 0.64 mm.

The ratio of upper diameter to tool diameter (D_U/D_T) is 2.9, this ratio for lower diameter (D_L/D_T) is 1.1 and the hole diameter ratio (D_U/D_L) is in the order of 2.7.

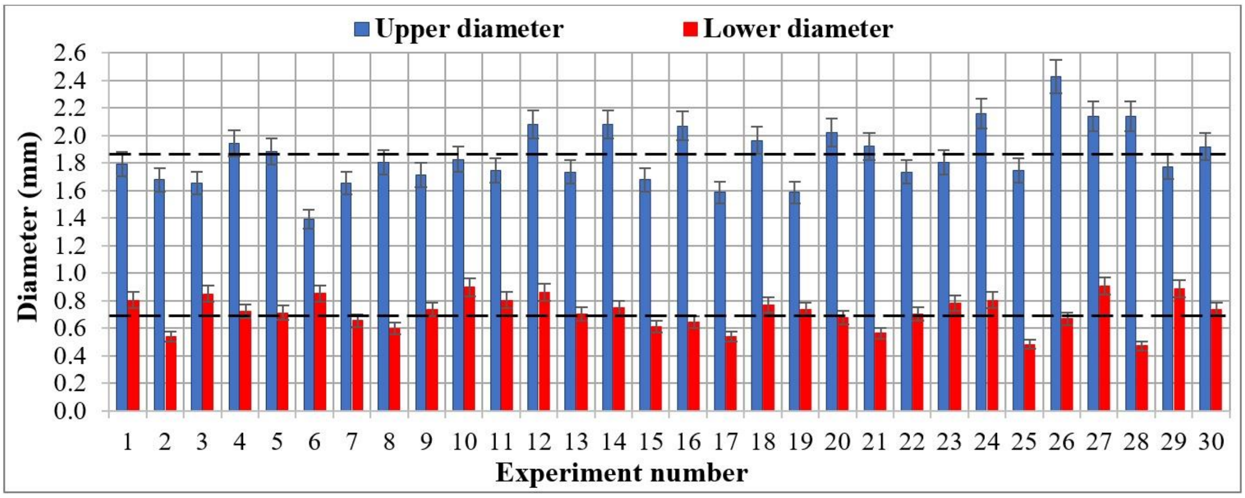


Figure 6. Showing the upper and lower diameter of hole. The x axis is the experiment number according to Table 2. Dashed lines show the average of diameter.

An equation to predict the upper hole diameter was obtained from the Design Expert software, as shown in equation 1. Note that the unit of diameter obtained by this equation.is µm.

$$\begin{aligned} Diameter = \ & (10701.78 + (98.5 * V) - (134.74 * C\ ) - (6673.6 * P) \\ & - (1417 * F) - (7.26 * V * C\ ) - (230.8 * V * P) - (15.2 * V * F) \\ & + (27.96 * C * P) + (17.14 * C * F) + (1075.26 * P * F) \\ & + (10.6 * V^2) + (1.6 * C^2) - (1010.11 * P^2) + (40.234 * F^2) \end{aligned} \quad (1)$$

Where, V is voltage (V), C is electrolyte concentration (gr/lit), P is electrolyte pressure (MPa) and F is tool feed rate (mm/s).

Figure 7 indicates the correlation between experiment and equation 1. The minimum error percentage is 0.17% which happens in experiment 14 and the maximum error percentage is 46% that occurs in experiment 2. In experiment 4, the error percentage is 40% whilst in experiment 25, the error percentage is 2%. Considering all points and on average, the error percentage is about 9% which means that there is an acceptable correlation between experiment and equation 1. As mentioned earlier in this section, the average upper diameter is 1.86 mm whilst the average predicted upper diameter by equation 1 is 1.93 mm which means that in this case, the error percentage is 3.8%. It must be emphasized that such a suitable equation to predict the lower diameter of the holes that can have an acceptable correlation with the experimental results was not obtained.

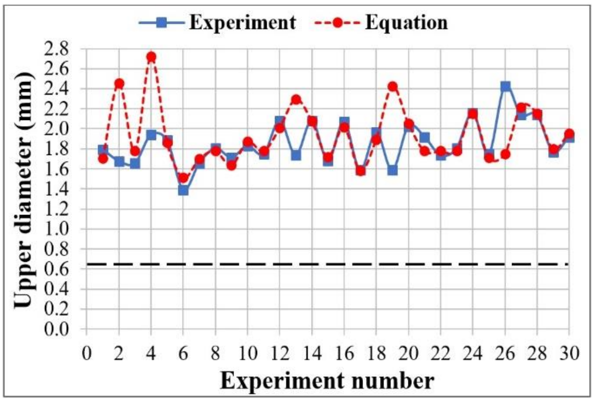


Figure 7. Showing the correlation between experiment and equation 1 for upper hole diameter. The tool diameter is 0.64 mm shown by dashed line.

3.2. Feed rate efficiency (E_F)

The ratio of tool feed rate to electricity power (F/P_E) in some way assesses the feed rate efficiency (E_F) for anodic dissolution penetration into the depth of sheet during the ECM time which is calculated by the following equation:

$$E_F = \frac{F}{P_E} = \frac{F}{V \cdot I} \quad , \quad \left\{ \frac{mm/_s}{V \cdot A} = \frac{mm}{W \cdot s} = \frac{mm}{J} \right\} \qquad (2)$$

Where, V is voltage (V), I is current (A) and F is tool feed rate (mm/s).

The unit of Equation 2 (mm/J) implies that how much anodic dissolution penetration is occurred for every Joule energy entered the depth of work piece which can be considered as an approximate measure of feed rate efficiency during the ECM time. Figure 8 illustrates the ratio of F/P_E or feed rate efficiency (E_F) for every experiments done in this research. In the range of used ECM parameters, the minimum and maximum ratio of F/P_E is 0.00079 and 0.00374 mm/J which obtained at experiment 19 and 2 respectively. As seen from Table 2, the parameter of voltage is the main difference between these two experiments. With a certain feed rate (i.e. 0.037 mm/s), experiment 2 drilled the hole with a lesser voltage (i.e. 5.5 V) in comparison with experiment 19.

Fig 9 shows the ratio of F/P_E versus upper diameter of the hole. As seen, the upper diameter slightly reduces with increase in the ratio of F/P_E. In other words, by increasing the anodic dissolution penetration into the depth of material for each Joule, the hole has slightly narrowed. Increase in the F/P_E is caused either by decreasing the voltage, decreasing the current or both or by increasing the feed rate. In Figure 9 and in the range of applied experiments parameters, increase in the F/P_E is provided by reduction in the voltage from 18 – 5.5 V.

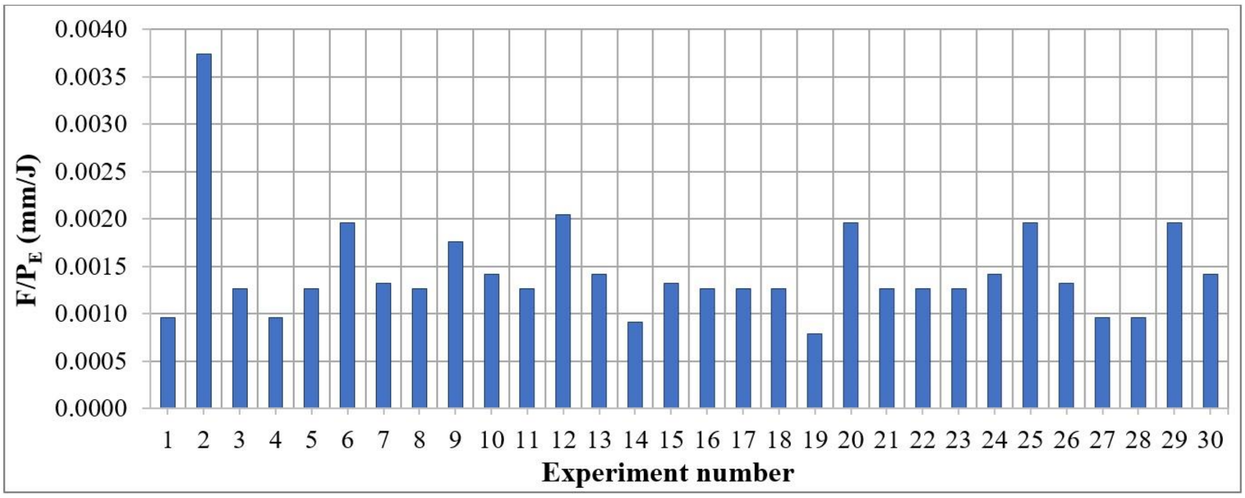


Figure 8. The ratio of F/P_E, called feed rate efficiency (E_F), for every experiment.

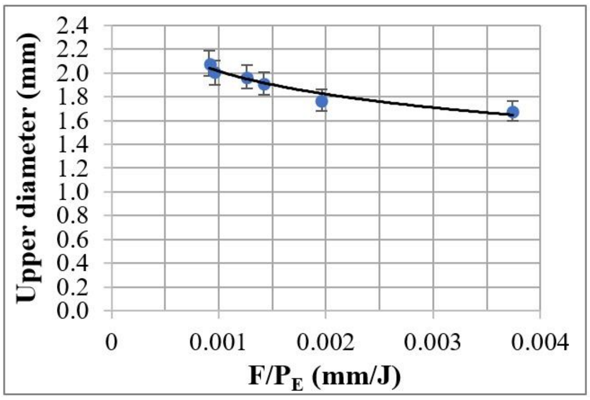


Figure 9. Upper diameter versus the ratio of F/P_E

3.2. Material Removal Rate (MRR)

Material removal rate (MRR) is the volume of material removed from the electrochemical machining zone per time unit (usually per second) and can be calculated by the following equation:

$$MRR = \frac{V_h}{t} = \frac{V_h \cdot F}{T} \quad , \quad \left\{\frac{mm^3}{s}\right\} \qquad (3)$$

Where MRR stands for the material removal rate (mm^3/s), V_h denotes the volume of hole (mm^3), t is the ECM time (s), T is the sheet thickness (mm) and F is tool feed rate (mm/s). The removed volume is the volume of material to be electrochemical machined in which transformed from the solid state into metal dissolution. In order to study on the MRR, at first the volume of holes must be obtained. Figure 10 indicates the volume of the holes for every experiments done in this research. In the range of employed ECM parameters, the minimum and maximum volume of the hole is 2.7 mm^3 and 9.2 mm^3 which obtained at experiment 2 and 28 respectively. Considering all experiments, the average volume of holes in this research is in the order of 5.7 mm^3.

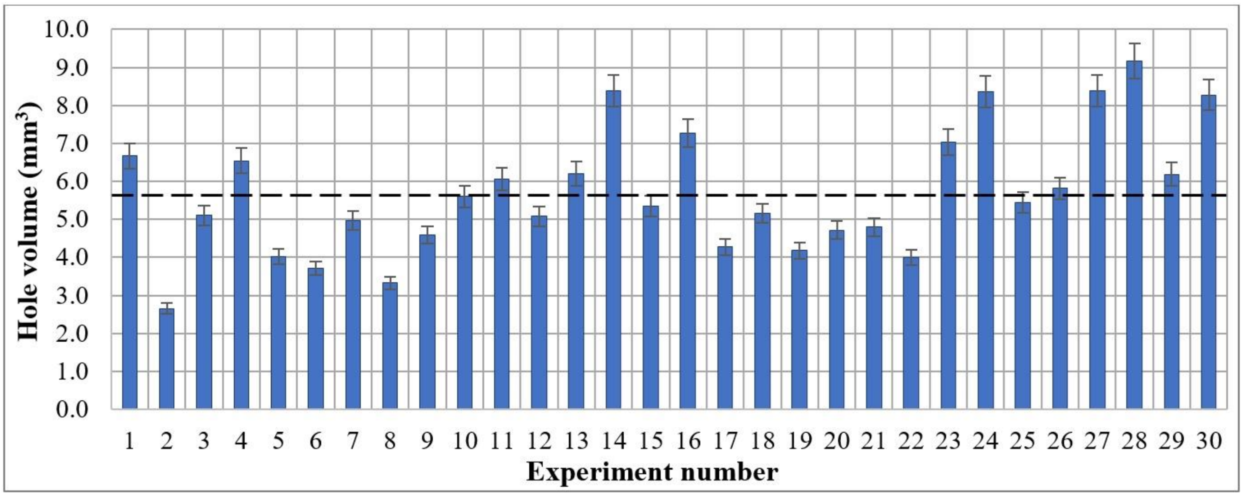


Figure 10. Volume of hole for every experiment. Dashed line shows the average of volume.

Figure 11 shows the material removal rate (MRR) for all experiments. As seen and in the range of applied ECM parameters and process condition, the minimum and maximum MRR is 0.02 mm^3/s and 0.062 mm^3/s which achieved at experiment 19 and 14 respectively. The average MRR in this case is in the order of 0.043 mm^3/s.

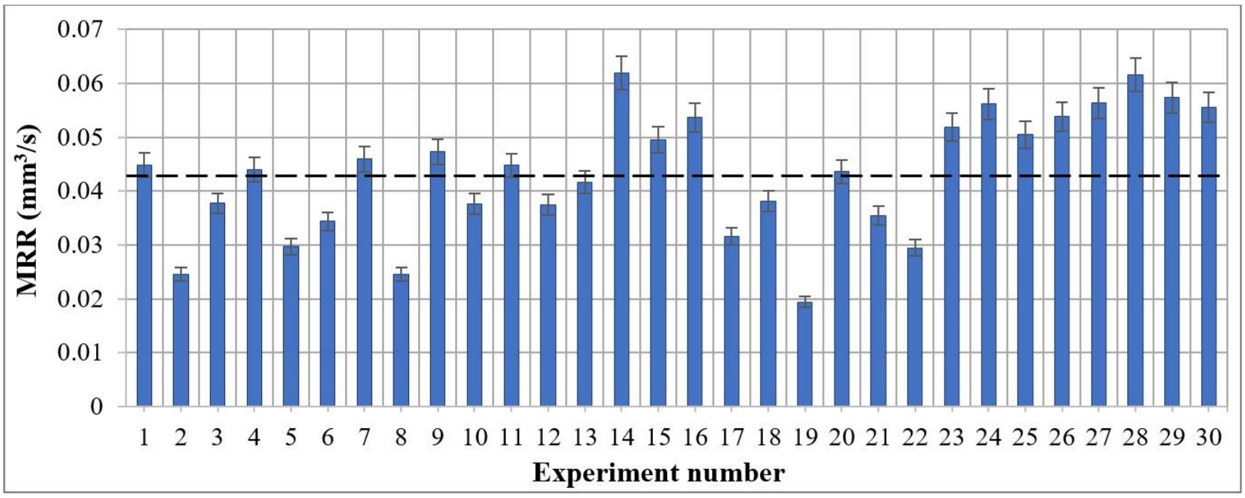
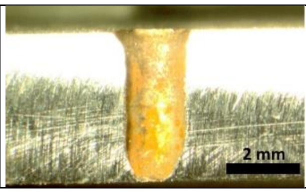
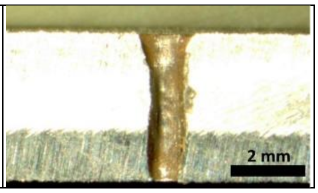


Figure 11. Material removal rate (MRR) for every experiment. Dashed line shows the average of MRR.

In order to comparison experiments 14 and 19 (having the minimum and maximum MRR respectively), the ECM parameters for these experiments are rewritten in Table 4. As seen, while the electrolyte concentration and pressure are the same for both experiments, voltage and tool feed rate for experiment 14 are more than those are for experiment 19.

Table 4. Comparison the experiment 14 and 19

Experiment number	**14**	**19**
Volume (mm^3)	8.38	4.17
Feed rate (mm/s)	0.03	0.019
MRR (mm^3/s)	0.062	0.02
Voltage (v)	18	13
Concentration (gr/lit)	20	20
Pressure (MPa)	0.4	0.4

Cross section of the hole		

With a certain current, when the voltage increases, the amount of energy entering the anodic dissolution front rises. In this case, if other parameters contributing to this dissolution process are in sufficient values, the material removal rate increases (see Figure 12).

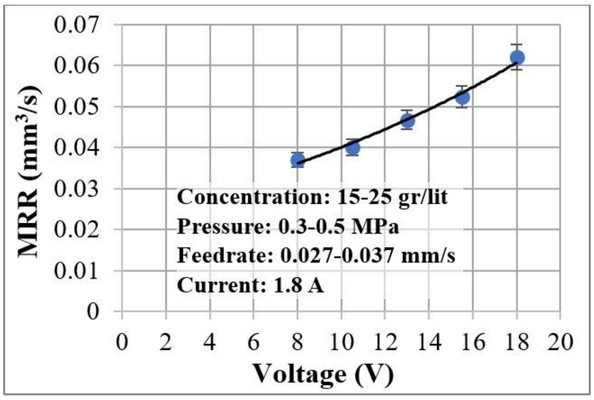


Figure 12. Material removal rate versus voltage

3.3. Volume Efficiency (E_V)

ECM volume efficiency (E_V) means that by any combination of ECM parameters in an anodic dissolution, how much material can be dissolved with each joule of electrical energy. By knowing the volume efficiency, the ECM parameters can be optimized in order to get lower ECM cost. The ECM volume efficiency can be described by the following equation.

$$E_V = \frac{V_h}{P_E \cdot t} = \frac{V_h \cdot F}{P_E \cdot T} = \frac{V_h \cdot F}{V \cdot I \cdot T} = \frac{MRR}{V \cdot I} \quad , \quad \left\{\frac{mm^3}{J}\right\} \qquad (4)$$

Where, E_V is volume efficiency (mm^3/J), V_h is volume of hole (mm^3), P_E is electrical power (W), t denotes the ECM time (s), F is tool feed rate (mm/s), T is sheet thickness (mm), V is voltage (V), I is current (A) and MRR stands for material removal rate (mm^3/s).

Figure 13 shows the volume efficiency for all experiments done in this research. As seen, the lowest volume efficiency is related to experiment 19 while the highest efficiency was obtained in experiment 29 which are 0.00083 mm^3/J and 0.00303 mm^3/J respectively.

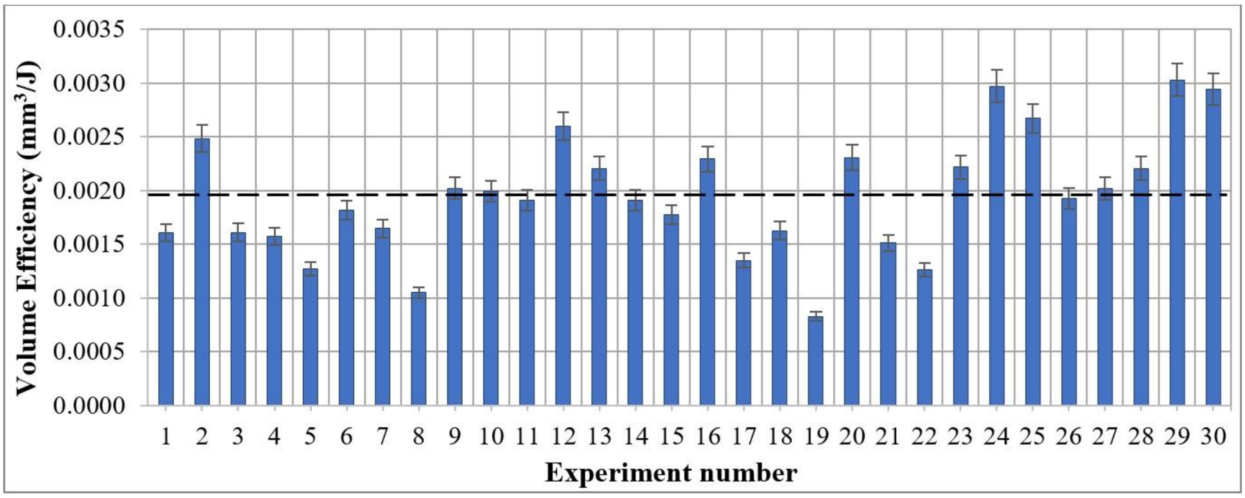


Figure 13. Volume efficiency (E_V) for every experiment. Dashed line shows the average of E_V.

Table 5 indicates the ECM parameters for four experiments with lowest efficiency and four experiments with highest efficiency. As seen, the voltage in highest efficiency group is less than that for lowest efficiency; moreover, the tool feed rate for highest efficiency group is higher than that for lowest efficiency. Considering all the effective parameters, it seems that when the capacity of dissolving the workpiece material by any combination of parameters is sufficient, the use of high feed rate to some extent that short circuit does not occur can increase the machining efficiency.

Table 5. Different combination of ECM parameters for lowest and highest volume efficiency in this research.

	Lowest Efficiency				Highest Efficiency			
Experiment	**19**	**8**	**5**	**17**	**25**	**30**	**24**	**29**
Vol. Efficiency (mm^3/J)	**0.00083**	**0.00105**	**0.00127**	**0.00135**	**0.00267**	**0.00294**	**0.00297**	**0.00303**
Voltage (v)	13	13	13	13	10.5	10.5	10.5	10.5
Concentration (gr/lit)	20	20	30	20	15	15	25	25
Pressure (MPa)	0.4	0.4	0.4	0.6	0.5	0.5	0.3	0.3
Feed rate (mm/s)	0.019	0.03	0.03	0.03	0.037	0.027	0.027	0.037

As a case comparison, the volume efficiency in ECM drilling is lower than that for laser piercing. For example, in an experimental laser piercing study [18], a typical hole with a volume of 0.4 mm^3 with using a power of 1000 W and 2 bar nitrogen was pierced on 2 mm thick mild steel sheet in irradiation time of 0.014 s. By considering equation 3, the volume efficiency for laser piercing of this hole is 0.017 mm^3/J. In another hole with using the same power and assist gas pressure, the volume is 0.8 mm^3 and the irradiation time is 0.06 s, so the volume efficiency becomes 0.013 mm^3/J. In that laser piercing study, the volume efficiency in laser piercing is about 5 times more than that for highest ECM drilling efficiency achieved in this research (i.e. 0.00303 mm^3/J). It must be noted that the thickness of sheet in the laser piercing study is 2 mm whilst the thickness in this research is 4 mm. Even if we assume that by reducing the thickness from 4 to 2 mm in this research, the ECM volume efficiency increases by 2 times (i.e. 0.00606 mm^2/J), the efficiency of ECM still is about 2.5 times less than that for laser piercing.

4. Conclusion

In this study, the influence of voltage, electrolyte concentration, pressure and tool feed rate on the diameter of hole, hole volume, material removal rate (MRR) and volume efficiency (E_V) during drilling by ECM process were experimentally investigated. The general output of this research confirms that:

- In the range of ECM parameters and process condition applied in this research, the upper diameter becomes approximately 2 - 3 times wider than the tool diameter (i.e. 0.64 mm).
- The ratio of tool feed rate to electricity power (F/P_E) in some way assesses the efficiency for anodic dissolution penetration of the tool into the depth of sheet during the ECM time.
- For given ECM parameters such as electrolyte concentration, pressure, feed rate and current, the upper diameter decreases with increasing the ratio of F/P_E.
- The ratio of upper diameter to lower diameter (D_U/D_L) is in the order of 2.7 which indicates that the hole shape generally is conical.
- The material removal rate (MRR) obtained in this research varies from 0.02 mm^3/s to 0.062 mm^3/s. For given electrolyte concentration, pressure, feed rate and current, the MRR increases with increasing voltage.
- ECM volume efficiency (E_V) means that by any combination of ECM parameters in an anodic dissolution process, how much material can be dissolved with each joule of electrical energy. The volume efficiency in this research varies from 0.00083 to 0.00303 mm^3/J.
- Apart from the surface quality and machining accuracy, it seems that the volume efficiency of ECM drilling is relatively low compared to other non-conventional machining processes such as laser piercing. More experimental study is needed to increase the efficiency of this process.

5. References

[1] Kurita T, Hattori M. A study of EDM and ECM/ECM-lapping complex machining technology. International Journal of Machine Tools and Manufacture. 2006;46(14):1804-10.
[2] Kasdekar DK, Parashar V. Principal component analysis to optimize the ECM parameters of Aluminium alloy. Materials Today: Proceedings. 2018;5(2, Part 1):5398-406.
[3] Kaliappan S, Pravin P, Saravanan K, Thanigaivelan R. Development and performance optimization of ecm parameters on scrapped alloy wheel metal matrix composites. High Temperature Material Processes: An International Quarterly of High-Technology Plasma Processes. 2024;28(2).
[4] Zishanur Rahman M, Das AK, Chattopadhyaya S. Microhole drilling through electrochemical processes: A review. Materials and Manufacturing Processes. 2018;33(13):1379-405.
[5] Singh A, Anandita S, Gangopadhyay S. Microstructural analysis and multiresponse optimization during ECM of Inconel 825 using hybrid approach. Materials and Manufacturing Processes. 2015;30(7):842-51.
[6] Lohrengel MM. PULSED ELECTROCHEMICAL MACHINING OF IRON IN NaNO3: FUNDAMENTALS AND NEW ASPECTS. Materials and Manufacturing Processes. 2005;20(1):1-8.
[7] Zeng Y-B, Yu Q, Wang S-H, Zhu D. Enhancement of mass transport in micro wire electrochemical machining. CIRP annals. 2012;61(1):195-8.
[8] Rajurkar KP, Hewidy MS. Effect of grain size on ECM performance. Journal of Mechanical Working Technology. 1988;17:315-24.
[9] Sekar T, Arularasu M, Sathiyamoorthy V. Investigations on the effects of Nano-fluid in ECM of die steel. Measurement. 2016;83:38-43.

[10] Wang X, Qu N, Fang X, Li H. Electrochemical drilling with constant electrolyte flow. Journal of Materials Processing Technology. 2016;238:1-7.
[11] Sen M, Shan HS. A review of electrochemical macro- to micro-hole drilling processes. International Journal of Machine Tools and Manufacture. 2005;45(2):137-52.
[12] Choi SH, Kim BH, Shin HS, Chu CN. Analysis of the electrochemical behaviors of WC–Co alloy for micro ECM. Journal of Materials Processing Technology. 2013;213(4):621-30.
[13] Yuan CJ, Bakar A, Roslan MN, Cheng CW, Rosekhizam M, Ghani JA, Wahid Z. Electrochemical machining (ECM) and its recent development. Jurnal Tribologi. 2021;28:20-31.
[14] Pandey RK, Senthil P, Boriwal L, Malviya A. Experimental investigation on influence of ECM process parameters on responses using full factorial design. Materials Today: Proceedings. 2017;4(2):3666-71.
[15] Ramakrishna M, Rao SV. Fabrication of ECM and study of its parameters in NaCl electrolyte. Materials Today: Proceedings. 2021;46:934-9.
[16] Sathiyamoorthy V, Sekar T, Elango N. Optimization of processing parameters in ECM of die tool steel using nanofluid by multiobjective genetic algorithm. The Scientific World Journal. 2015;2015(1):895696.
[17] Singh R, Dhami S, Rajput N. Comparison of EDM and ECM machined AISI 304 steel: Surface roughness, hardness and morphological characteristics. Materials today: proceedings. 2022;48:965-74.
[18] Hashemzadeh M, Powell J, Voisey KT. Fibre laser piercing of mild steel – The effects of power intensity, gas type and pressure. Optics and Lasers in Engineering. 2014;55:143-9.