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Research Paper

Electrochemical Machining: An Investigation in to Material Removal Rate and Volume Efficiency

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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. In this research, a 4 mm-thick St 37 sheet was drilled by ECM with using the various combination of process parameters. The tool feed rate efficiency (E_F) in these experiments varied from 0.00079 to 0.00374 mm/J. The volume of all holes drilled by different condition were obtained. Then the material removal rate (MRR) and the ECM volume efficiency (E_V) were achieved. The results of this research indicate that in the range of employed parameters, the removed volume is 2.7 to 9.2 mm^3, the MRR ranged between 0.02 and 0.062 mm^3/s, the volume efficiency is just 0.00083 to 0.00303 mm^3/J.

Keywords
Electrochemical Machining, Removal Rate, Volume Efficiency

1. Introduction
Nowadays, the application of ECM (electrochemical machining), as one of the non-conventional manufacturing techniques, has been increasing in industries such as automotive, electronics, optics, medical engineering, aircraft industries, and die making workshops for machining electrically conductive materials like metals and hard and brittle metal matrix composites [1-3]. Besides micro milling and turning, drilling the precise small holes with acceptable quality using the ECM technique is one of the most desirable applications in industries, which is mostly called ECD. An anodic dissolution process according to Faraday's law occurs between an anodic workpiece and a cathode tool in the ECM process. The gap between anode and cathode, the electricity current (current density, current, voltage, pulsed and continuous mode), the 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, accurac,y and efficiency [4-6]. Although the application of the ECM process is not affected by the strength, hardness, or toughness of the workpiece, 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 [7]. 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 [8]. Material removal process in ECM is done atom by atom, at which the removed material sometimes is seen in an insoluble form in the used muddy electrolyte. If an insufficient removal of muddy electrolyte occurs, the waste products can settle down on the workpiece as the mud and slob, which 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 the 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, which causes the uniform machined holes with a higher tool feed rate [9]. Many researchers have investigated 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 [10, 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 a sharp edge can be obtained by ECM and ECD [12]. 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 an enhancement of material removal rate (MRR). Moreover, surface finish generally increases with increasing flow rate [13]. In an experimental study, the researchers showed how to simply fabricate an ECM device, and they reported that the MRR increases with an increase in electrolyte concentration and feed rate [14].

In this research, the effect of four input parameters, i.e., voltage, electrolyte concentration, pressure, and tool feed rate, on the diameter of the hole, hole volume, material removal rate (MRR), and volume efficiency during drilling with the ECM process has 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 a 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, the material removal rate (MRR) and volume efficiency (EV) are investigated.

2. Material and experiments procedure

2.1 Material

In order to achieve the purpose of the research, St37 sheet with a thickness of 4 mm was used as a workpiece in the experiments. Table 1 shows the chemical composition of the applied material.

Table 1. Chemical composition contents of St37 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 experiments (DOE)

In the Response Surface Method (RSM), the Central Composite Design (CCD) procedure was employed for the design of the experiment (DOE). The CCD is one of the response procedure designs that can investigate the curvature effect of variables and interference effects, as well as obtain a second or higher order regression model. The experimental results published by others [46, 8-11, 13-16], as well as our own results from the initial tests, were 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 the hole was considered. Table 2 indicates the design of experiments. As seen, the number of experiments is 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 gauge, a pressure control valve, connecting pipes, an electrolyte container, a solution of NaCl + water as electrolyte, a stainless steel needle as tool, a DC power supply, and a computer system to control the ECM process. Figure 1 shows the employed ECM machine when drilling the workpiece.

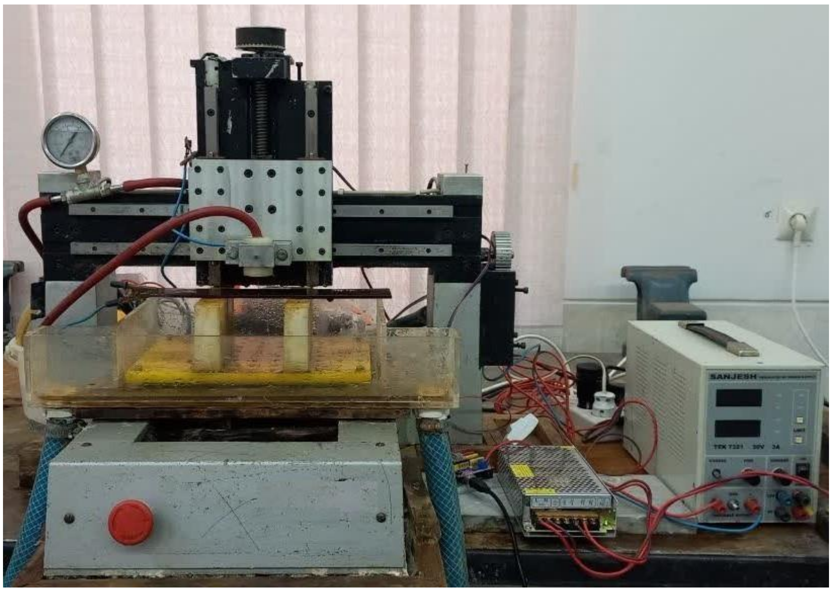


Figure 1. Showing the ECM machine employed in this research

According to the design of experiments, thirty experiment sets were done. For any test, the ECM machine was set up according to Table 3, and when all input parameters became stable, the drilling process was started. The tool feed rate was controlled using a step motor and a CNC system. In order to increase the precision of results, every experiment is repeated 3 times. It means that at the end of the experiment phase, there were 90 drilled holes. Figure 2 indicates the map of the applied ECM equipment. The processing conditions and ECM parameters are indicated in Table 3.

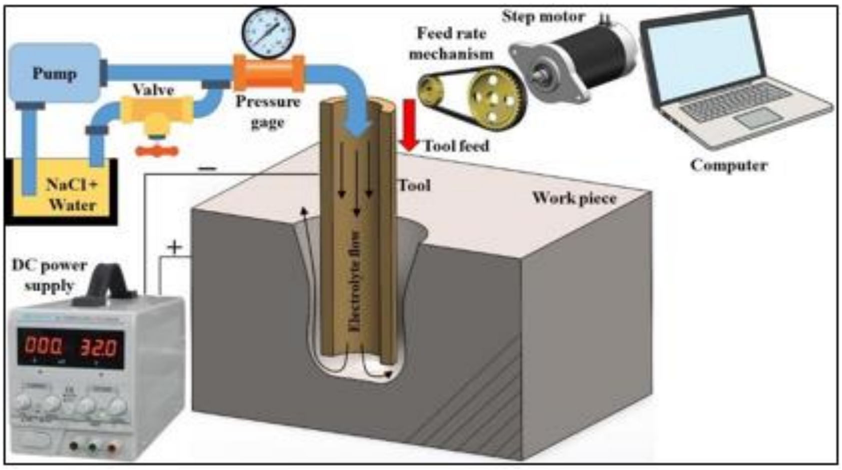
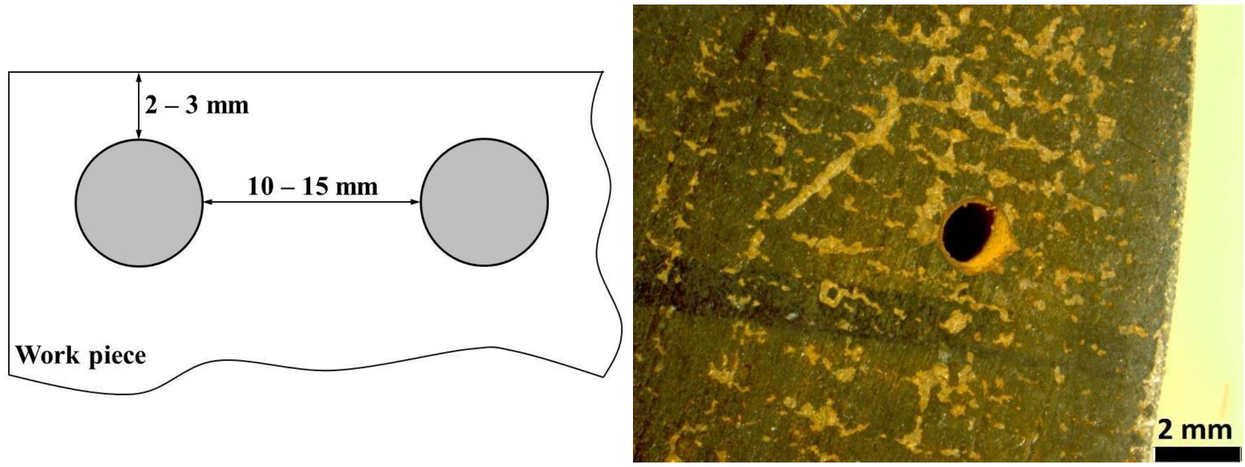


Figure 2. Illustrating the map of applied ECM equipment

Table 3. Processing conditions and ECM parameters

Processing Parameters	Volume
Workpiece	St37 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 A
Employed voltage (V)	5.5 – 18
Employed current (A)	1.8
Tool material	Stainless steel needle
Toll outer diameter	0.64 mm
Toll inner diameter	0.34 mm
Toll cylindrical surface	Electrically insulated
Toll 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

One of the purposes of this research was to investigate the cross-sectional profile of the hole in the depth of the sheet. For this purpose, after drilling, the workpiece should be chopped up and then ground 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. Figure 3 shows the map of the hole position on the workpiece. As seen in the figure, the hole was drilled about 2–3 mm close to the sheet edge.



(A) **(B)**

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 1)

2.4 Hole diameter measurements

In order to study the diameter of the hole, all drilled holes on the top and bottom of the sheet were measured by an optical stereomicroscope model Olympus SZX16 with magnification of 7x to 115x. Using the camera of the stereomicroscope at an appropriate magnification, images of the upper and lower hole diameters 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 the hole diameter.

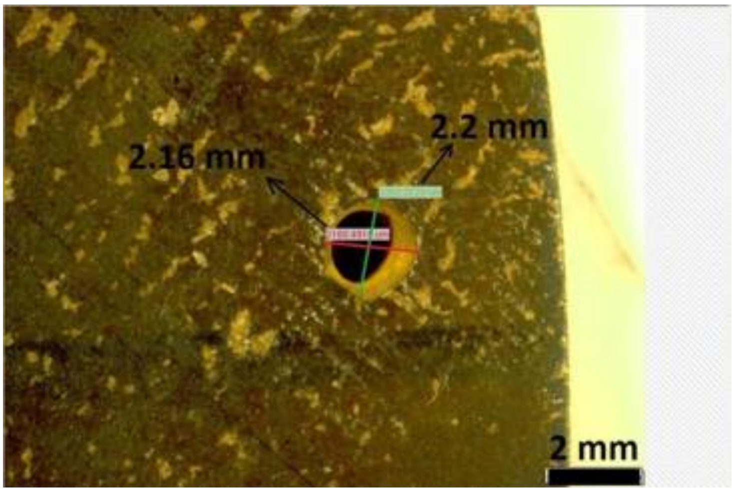


Figure 4. The diameter of the hole in two perpendicular directions (the hole was obtained in test number 14 according to Table 1)

2.5 Hole volume calculation

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

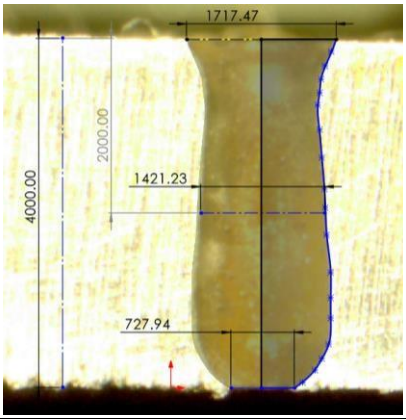
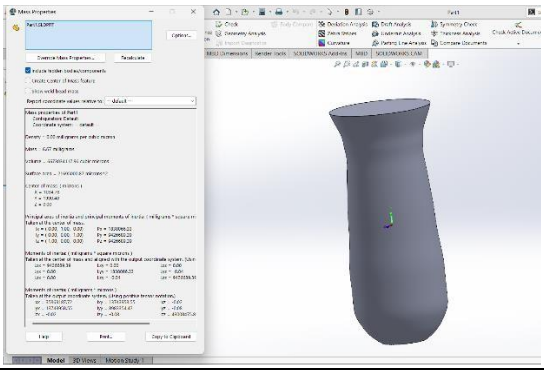
	Step 1: Stereoscope measures the width of hole on the hole cross section. This measurement can be a criteria for sketch drawing in next step.
	Step 2: The photo of hole cross section is imported in Solidworks and with using the sketch tool and other modeling tools the shape of hole is 3D modeled carefully.
	Step 3: After 3D modeling, the volume of hole is obtained by mass properties tool.

Figure 5. Illustrating the steps to obtain the hole volume

3. Results

3.1 Diameter of hole

The upper and lower diameters of holes for all experiments, which were done according to Table 1, are shown in Figure 6. As seen, in the range of applied parameters and conditions (Table 1), the upper hole diameter achieved in this research is between 1.4 mm and 2.4 mm. This range for the 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 tool diameter is 0.64 mm. The ratio of upper diameter to tool diameter (DU/DT) is 2.9, and this ratio for lower diameter (DL/DT) is 1.16. The hole diameter ratio (DU/DL) is in the order of 2.7.

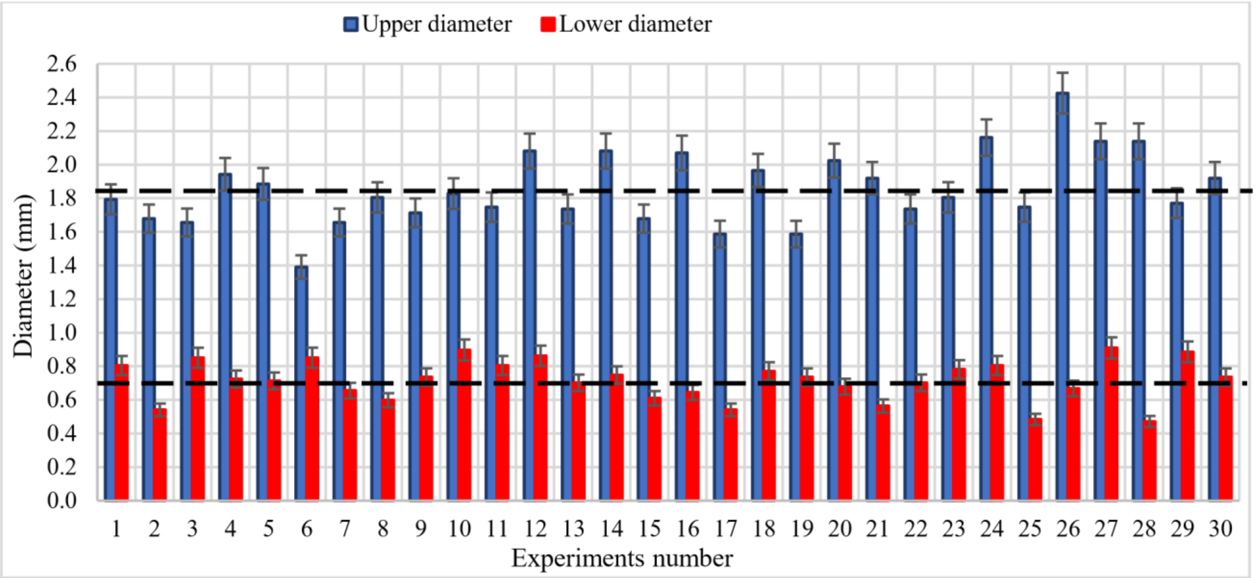


Figure 6. Showing the upper and lower diameter of hole. The x axis is the experiment number according to Table 1. Dashed lines show the average of diameter

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.

$$Diameter = 5050.895050.89 + (49.25 \times V) - (67.37 \times C) - (3336.8 \times P) - (708.5 \times F) - (3.63 \times V \times C) - (115.4 \times V \times P) - (7.6 \times V \times F) + (13.98 \times C \times P) + (8.57 \times C \times F) + (537.63 \times P \times F) + (5.3 \times V^2) + (0.8 \times C^2) - (505.055 \times P^2) + (20.1172 \times F^2) \qquad (1)$$

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

Figure 7 indicates the correlation between experiment and Equation 1. The minimum error percentage is 0.17% which happens in experiment number 14, and the maximum error percentage is 46% which occurs in experiment number 2. In experiment number 4, the error percentage is 40% whilst in experiment number 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 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.

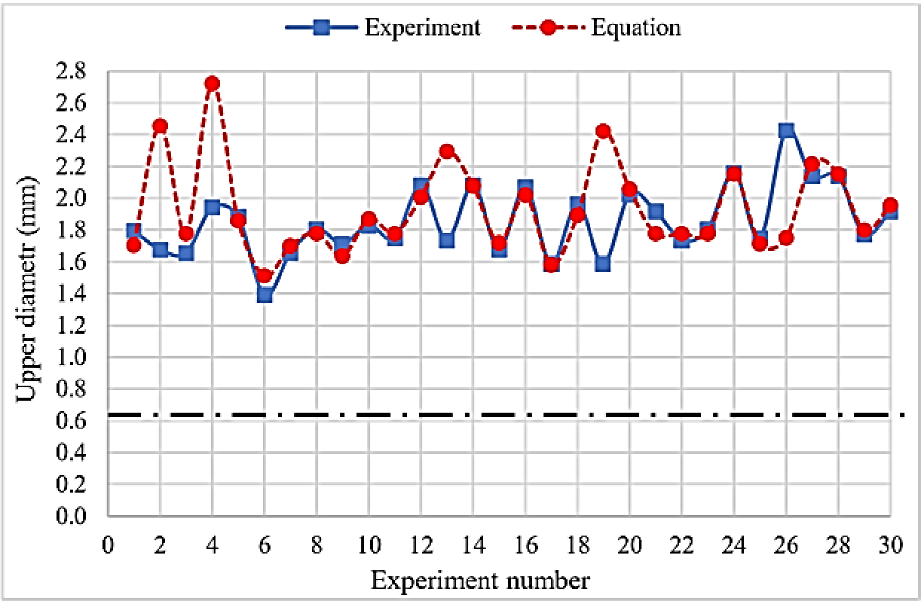


Figure 7. Showing the correlation between experiment and equation 1 for upper hole diameter. The tool diameter is 0.64 mm.

3.2 Feed rate efficiency (E_F)

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

$$EF = \frac{F}{PE} = \frac{F}{V.I} \left\{ \frac{mm^3/s}{V.A} = \frac{mm^3}{J} \right\} \qquad (2)$$

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 how much anodic dissolution penetration occurs for every Joule energy entered the depth of work workpiece, which can be considered as an approximate measure of feed rate efficiency during the ECM time. Figure 8 illustrates the ratio of F/PE or feed rate efficiency (EF) for every experiment done in this research. In the range of used ECM parameters, the minimum and maximum ratio of F/PE is 0.00079 and 0.00374 mm/J, which were obtained at experiments 19 and 2, respectively. As seen from Table 1, 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.

Figure 9 shows the ratio of F/PE versus the upper diameter of the hole. As seen, the upper diameter slightly reduces with an increase in the ratio of F/PE. In other words, by increasing the anodic dissolution penetration into the depth of the material for each Joule, the hole has slightly narrowed. An increase in the F/PE is caused either by decreasing the voltage, decreasing the current, or both, or by increasing the feed rate. In Figure 8 and in the range of applied experiment parameters, an increase in the F/PE is provided by a reduction in the voltage from 18 – 5.5 V.

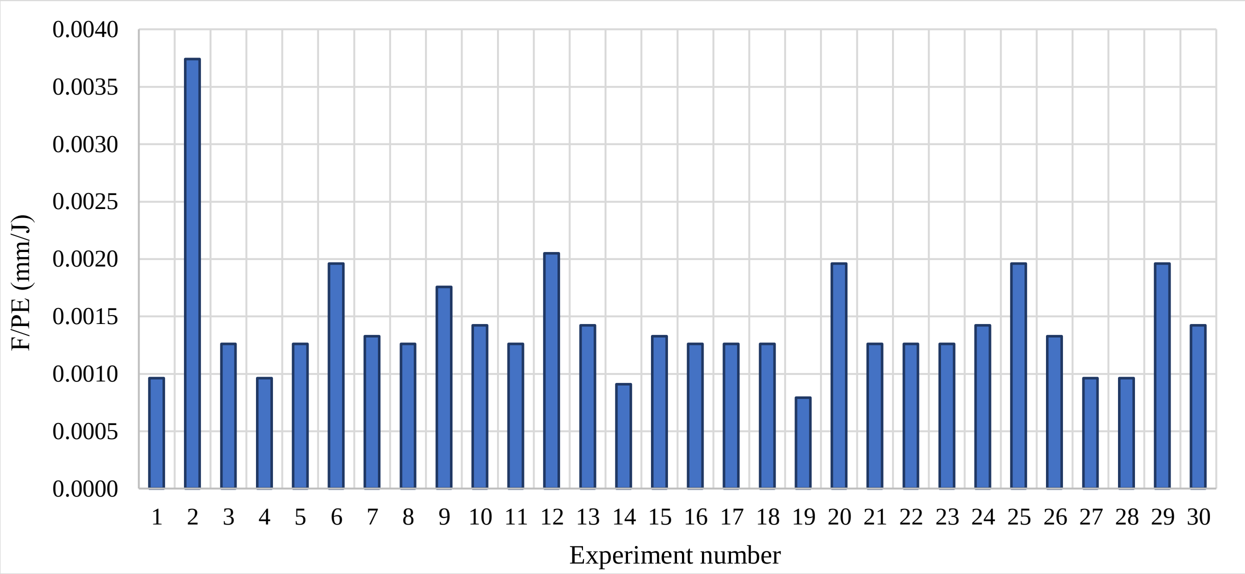


Figure 8. The ratio of F/P_E or feed rate efficiency for every experiment

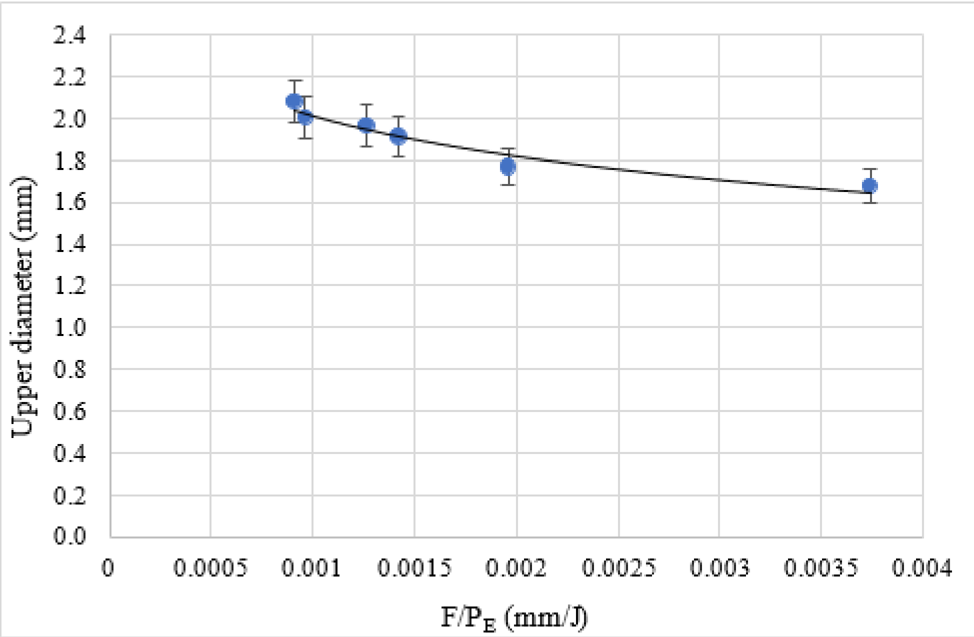


Figure 9. Upper diameter versus the ratio of P_E/F

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:

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

Where MRR stands for the material removal rate (mm^3/s), V_h denotes the volume of hole (mm3), t is the ECM time (s), T is the sheet thickness, and F is the tool feed rate. The removed volume is the volume of material to be electrochemically machined, which is transformed from the solid state into metal dissolution. In order to study the MRR, at first, the volume of holes must be obtained. Figure

10 indicates the volume of the holes for every experiment done in this research. In the range of used ECM parameters, the minimum and maximum volumes of the hole are 2.7 mm^3 and 9.2 mm^3, which were obtained at experiments 2 and 28, respectively. Considering all experiments, the average volume of holes in this research is in the order of 5.7 mm^3.

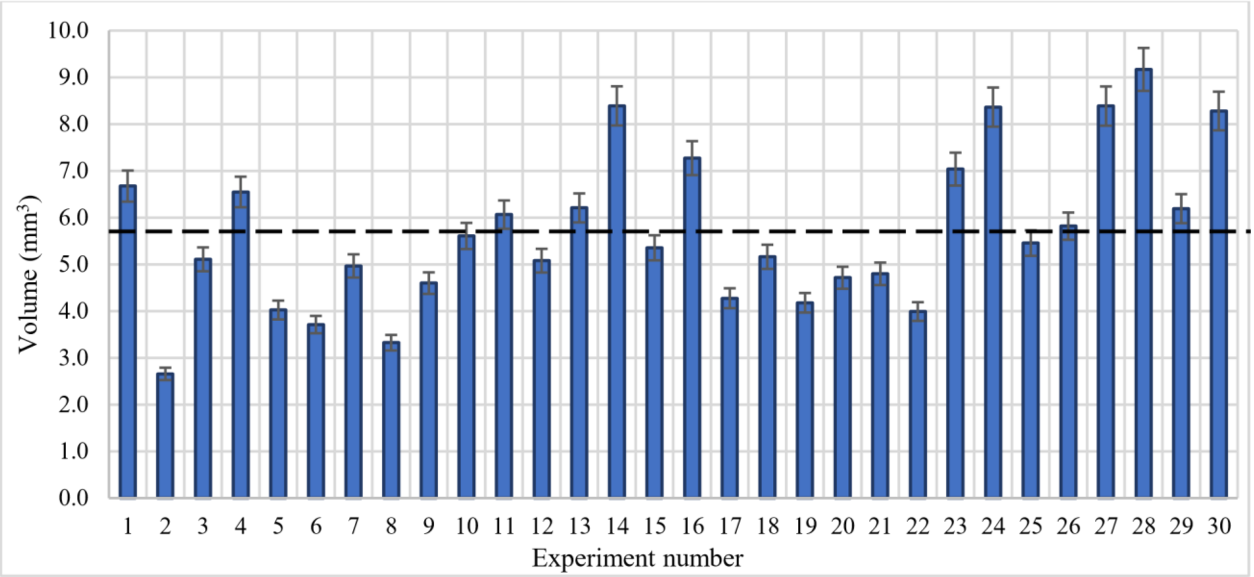


Figure 10. Volume of hole for every experiment. Dashed line shows the average of volume

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

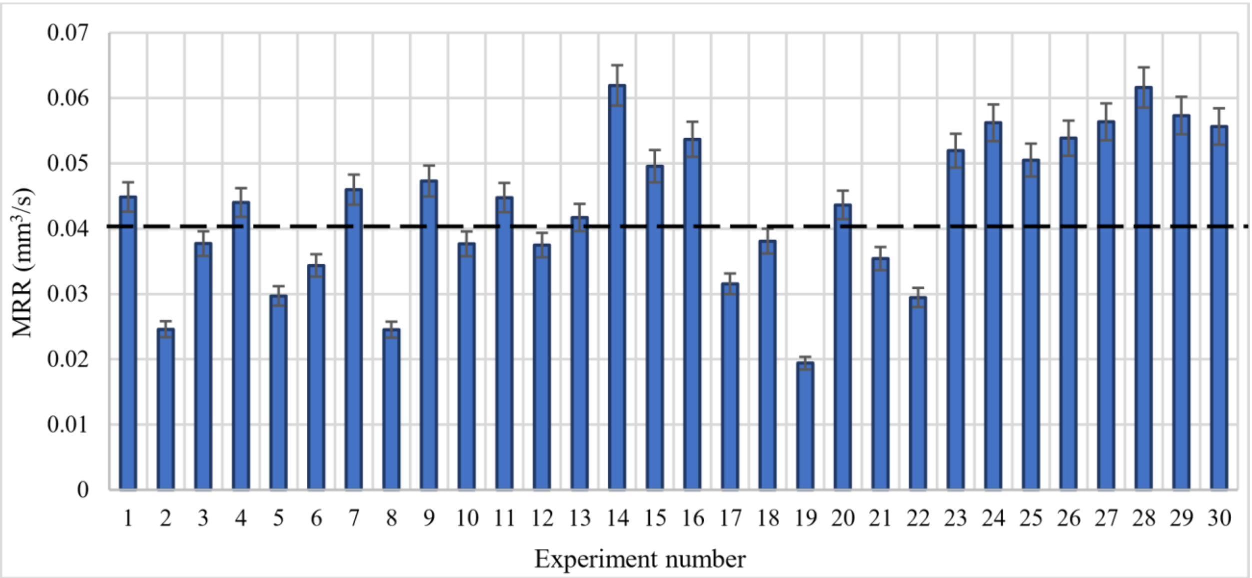
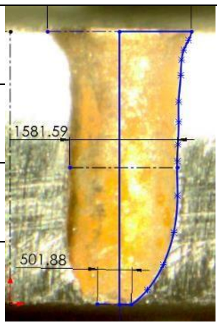
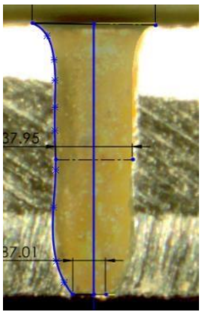


Figure 11. Material removal rate (MRR) for every experiment. Dashed line shows the average of MRR

The ECM parameters for experiments 14 and 19 (from Table 1) are rewritten in Table 4 to compare. As seen, while the electrolyte concentration and pressure are the same for both experiments, the voltage and tool feed rate for experiment 14 are more than those for experiment 19.

Table 4. Comparison the experiment 14 and 19

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

With a certain current, when the voltage increases, the amount of energy entering the anodic dissolution front rises. In this case, when other parameters contribute to this dissolution process, the material removal rate increases.

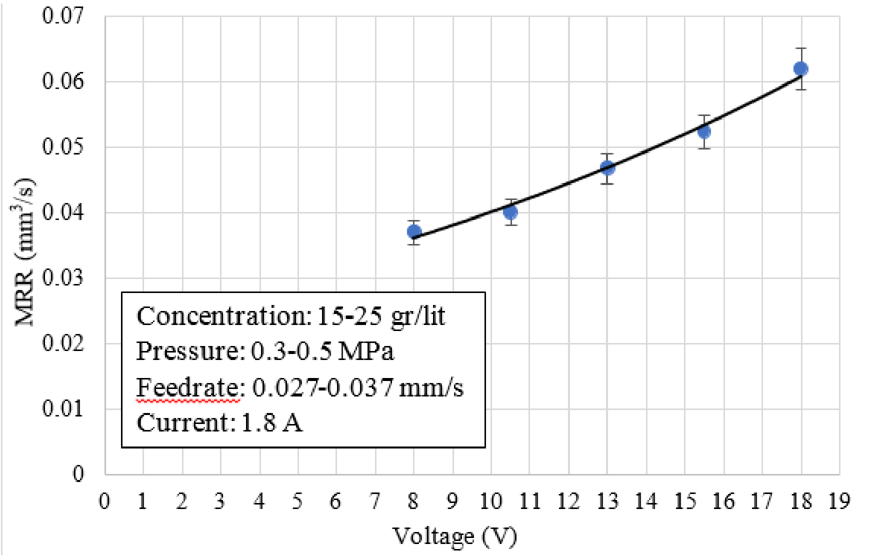


Figure 12. Material removal rate versus voltage

3.3 Volume Efficiency (E_V)

ECM volume efficiency (EV) means that for 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 a lower ECM cost. The ECM volume efficiency can be described by the following equation.

$$EV = \frac{V_h}{PE.t} = \frac{V_h.F}{PE.T} = \frac{V_h.F}{V.I.T} = \frac{MRR}{V.I}\left\{\frac{mm^3}{J}\right\}$$

Where, EV is volume efficiency (mm^3/J), V_h is volume of hole (mm^3), PE 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 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 is 0.00083 mm^3/J and 0.00303 mm^3/J, respectively.

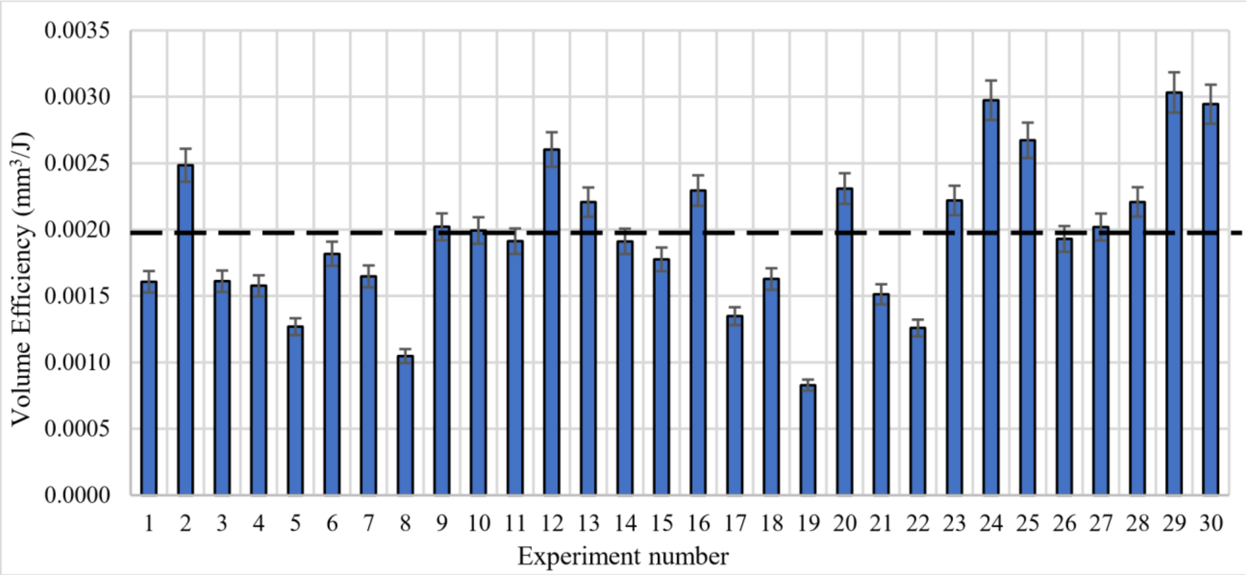


Figure 13. Volume efficiency (E_V) for every experiment. Dashed line shows the average of E_V

Table 5 indicates the ECM parameters for four experiments with the lowest efficiency and four experiments with the highest efficiency. Considering all the effective parameters, it seems that when the capacity of dissolving the workpiece material by the combination of parameters is sufficient, the use of a high feed rate, to some extent, can prevent short circuit from occurring, and can increase the machining efficiency.

Table 5. Different combination of ECM parameters for lowest and highest 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

The Volume efficiency in ECM drilling is lower than that for laser piercing. In an experimental laser piercing study [17], a hole with a volume of 0.4 mm^3 was pierced using a power of 1000 W on a 2 mm thick St37 sheet in an 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 using the same power, the volume is 0.8 mm^3, and the irradiation time is 0.06 s; the volume efficiency becomes 0.013 mm^3/J. In this case, the volume efficiency in laser piercing is about 5 times more than that for the highest ECM drilling efficiency (i.e., 0.00303 mm^3/J).

4. Conclusion

In this study, the influence of voltage, electrolyte concentration, pressure, and tool feed rate on the diameter of the hole, hole volume, material removal rate (MRR), and volume efficiency (EV) during drilling with the ECM process was 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 became approximately 2-3 times wider than the tool diameter (i.e. 0.64 mm).

- The ratio of tool feed rate to electricity power (F/PE) in some way assesses the efficiency for anodic dissolution penetration of the tool into the depth of the 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/PE.
- The ratio of upper diameter to lower diameter (DU/DL) is in the order of 2.7, which indicates that the hole shape generally is conical.
- The material removal rate (MRR) was obtained from 0.02 mm^3/s to 0.062 mm^3/s in this research. For a given electrolyte concentration, pressure, feed rate, and current, the MRR increases with increasing voltage.
- ECM volume efficiency (EV) means that for any combination of ECM parameters in an anodic dissolution, how much material can be dissolved with each joule of electrical energy. The volume efficiency in this research is 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). In order to commercialize this process, it is suggested that, in addition to research on surface quality and machining accuracy, the priority of studies should be focused on increasing the efficiency of this process.

5. References

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