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A COMPARATIVE ANALYSIS OF THE TWO ELECTROLYTE FLOW CONFIGURATIONS IN ELECTRODE TOOL TO IMPROVE EFFICIENCY IN ELECTROCHEMICAL MACHINING

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Abstract:
Electrochemical machining (ECM) is defined as a non-conventional method of manufacturing that is greatly employed in processing of materials with complex geometry which are hard to be machined, providing high accuracy and excellent surface finish. ECM is influenced to higher extent by the configuration of the electrolyte flow and design of electrode tooling. In this work, two types of electrolyte flow configurations in electrode tooling are studied and compared: straight flow and side nozzle flushing flow. The effects of these configurations on material removal rate (MRR) and surface roughness were investigated both experimentally and numerically. The results emphasize the significance of the choice of electrolyte flow configuration in improving the uniformity of ion transport, flow turbulence during machining and quick heat dissipation. According to the findings, it is clear that the hollow electrode with straight flow has the best material removal rate with a percentage increase of 4.61 percent recording a rate of 0.4352 g/min, as compared to the rigid electrode with nozzle flushing flow which records 0.416 g/min. Also, the hollow electrode at straight flow showed the least extreme surface roughness, a percentage decrease of 28.52% with the least extreme of 2.030 µm and the robust electrode surface with the nozzle flow of 2.840 µm. These findings have fundamental implications for the improvement of ECM technologies with regards to productivity, energy consumption, and accuracy of machining processes. In regards to the finding, the research provides an insight into the impact customization of flow and tooling with regards to the processes in the electrochemical operation.

Key words: copper electrode, electrochemical machining, material removal rate, surface roughness, taguchi

INTRODUCTION

Electrochemical machining (ECM) is an un-conventional machining process, where the material removal occurs via anodic dissolution in an electrolysis operation [1]. A direct voltage is applied through the gap between the pre-fabricated cathode electrode and the anode workpiece. The electrolyte an aqueous solution of sodium chloride, for instance, flows at speeds of 10 to 60 meters per second through the space between the electrodes, which are 0.10 to 6 millimeters [2, 3]. The current density typically ranges from 20 to 200 Amperes per square centimeter. The rate of anodic dissolution, which is determined by Faraday's laws of electrolysis, is influenced by the electrochemical characteristics of the metal, the properties of the electrolyte, and the electric current and voltage applied [4]. Regardless of the mechanical characteristics of any electrically conductive material, ECM can machine it with high stock removal rates because it is a non-mechanical metal removal method. Specifically, the ECM clearance rate is unaffected by the material's toughness, hardness, and other characteristics [5]. The production of intricately formed pieces from materials that are difficult to machine using other mechanical techniques is where ECM is most justified. Using a tool composed of a material harder than the workpiece is not necessary, and tool wear is essentially nonexistent [6]. The ECM process does not eliminate material through thermal energy. Consequently, this negative effect can be mitigated within the ECM process [7]. Therefore, ECM can be applied efficiently for machining hard and brittle materials. According to Faraday's first law, the amount of material removal is directly proportional to the amount of charge that has flowed. Additionally, Faraday's second law states that the current that passes through anodic particles regulates their dissolution. as a result, the current density has much influence on ECM process [8, 9]. It is quite essential to study the ways to achieve the best machinability for current density control. This emphasis has made Electrochemical Machining one of the most commonly used and efficient machining techniques in commercial practices [10]. ECM is used in several industrial applications and is most significant within the aerospace and automotive markets [11].

Aezeden Mohamed and Noel Martin [12] reported an experimental study on the fabrication procedure of a hybrid composite, AA5052/TiB2/B4C, evaluating its ECM process variables on material removal rate (MRR). Optimum MRR is obtained using experimental design with Minitab-17 software, and the analysis of variance shows the individual effect of each parameter according to the Taguchi L16 orthogonal array. The analyzed characteristics of the Electrochemical Machining process were FR (feed rate), VE (voltage), and EC (electrolyte concentration), compared to the MRR responses. It is clear that the following conditions of FR4, VE1 and EC4, namely 0.40 mm/min, 25 V, and 50 g/L resulted in the maximum MRR, while the lowest MRR was obtained with FR1, VE3 and EC3, namely 0.25 mm/min, 45V, and 40 g/L. The data pointed out that the most influential factor for the augmentation in the MRR was the electrode feed rate that had a share of 73.12%, while the voltage together with 13.79% and 6.95% of the electrolyte concentration were the other main contributors.

A forward lead i.e., A. Giribabu et al. [13] have studied the machining parameters that are relevant to the Al/B4C composites anodic machining, through L27 orthogonal array method and genetic algorithms for optimization. The input machining parameters, such as applied voltage (an electrical parameter), tool feed rate (an electrode parameter), electrolyte concentration (an electrolyte parameter), and reinforcement content (a property of the workpiece), were introduced into the model. Different linear regression models were developed to address the estimation of Material Removal Rate, Radial Overcut, and Surface Roughness. MRR increased with an increase in voltage up to 20V, feed rate at 1 mm/min, an electrolyte concentration of 30 g/L, and reinforcement content at 2.5 wt % for maximum radial overcutting. At 13.4 V applied voltage, a feed rate at 1 mm/min, electrolyte concentration at 29.98 g/L, and reinforcement content at 2.5 wt %, minimum surface roughness was reported. Further lowest radial overcut was achieved by applying a voltage of 12 V, feed rate at 1 mm/min, electrolyte molecules of 10 g/L, with reinforcement content of 7.5 wt %.

Dhia Ahmed Alazawi [14] led research on the effects of applied voltage, electrolyte flow rate, and current density on weight loss, dissolving rate, and material removal rate (MRR) in low carbon AISI 1005 steel. It has been found that weight loss increases with voltage and flow rates, peaking at 9.23 g and 5.35 g, respectively. A maximum MRR of 0.248 g/min and a dissolution rate of 1.59 mm/min were obtained with an increase in current density. Additionally, the data indicated a 3.94% rise in the disintegration rate and a 66.8% increase in the MRR.

A study on the optimum machining parameters in AISI D2 tool steel drilling to improve the MRR was conducted by Galang Sandy Prayogo and Nuraini Lusi [15]. Among these parameters the factors selected for the ECM process were electrolyte concentration, voltage and gap width. The maximum MRR was 0.153 g/min, which was observed at a voltage of 48 V, an electrolyte concentration of 150 g/L, and a gap width of 1 mm. Among these parameters, electrolyte concentration emerged as the most significant factor affecting the MRR.

Suresh H. Surekar et al. [16] conducted a number of experiments in which three parameters, including electrolyte flow rate, voltage, and feed rate were varied. The electrolyte was (200 g/L) sodium nitrate ($NaNO_3$) aqueous solution. Optimal values for the parameters leading to maximum material removal rates (MRR) were found to be a feed rate of 1 mm/min, minimum electrolyte flow rate of 150 L/hr and a voltage of 16 V. Particularly, it was found that the most significant factor influencing the rate of material removal was the feed rate.

Nguyen Thi Bich Nhung et al. [17] researched for the effect of different process parameters on the ECM process. These parameters included the electrolyte concentration, applied voltage, feed rate going to the electrode, and the Inter-Electrode Gap (IEG) taken from the tool with the workpiece. The used workpiece was aluminum, while the tool was copper circular cross-section. ECM process had the optimal settings as seen from the results. Electrode (Inter-Electrode Gap) distance between the electrodes had a huge impact on MRR and surface roughness of both. the results showed that the highest MMR was for electrolyte concentration of 100 g/L, feed rate of 0.0375 mm/min and voltage as 15 V, gap between electrodes 0.5 mm. But for a smoother surface, 80 g/L electrolyte concentration; 0.0468 mm/min feed rate; voltage holding potential of 10 V and an electrode gap also 0.5mm employed.

Zhenghui Ge et al. [18] studied the static and dynamic pressure energy transition of electrolyte liquid as a whole on the performance of electrochemical machining (ECM). With experimental results, the improvement of high surface quality and material removed rate (MRR) are emphasized that effective energy conversion of the electrolyte plays a critical role. On the other hand, a substantial reduction in the fluid's dynamic pressure energy will effect on ECM functionality. It was also identified in their study that for optimal machining performance the ratio of MRR and surface roughness (Ra) had an optimum value of fluid energy conversion ranging between 50% to 70%. The results also showed that there are optimized energy conversions of electrolyte fluid for efficient electrical power to work conversion during ECM.

Based on previous research, the primary objective of this study was to improve the impact of three important parameters of electrochemical machining, namely voltage, inter-electrode gap, and the electrolyte concentration on the ECM surface quality and material removal rate when using a rigid and hollow copper electrode under different electrolyte flow conditions. This study goals to determine the ideal mix of these attributes in order to improve ECM performance and material removal efficiency.

EXPERIMENTAL WORK

A 40 x 40 mm square plate with a thickness of 6 mm made from AISI stainless steel 304L was selected as the workpiece. Two copper rods, diameter measuring of 16 mm and the length 85 mm were selected as the tool for this work. The first electrode is rigid, and the second electrode has a hollow drilled by drilling machine into it with added of side nozzle to allow the electrolyte to cycle inside of electrode and remove the debris away from the machining zone. Figure 1 A, B, and C compares the two electrodes with design of hollow electrode.

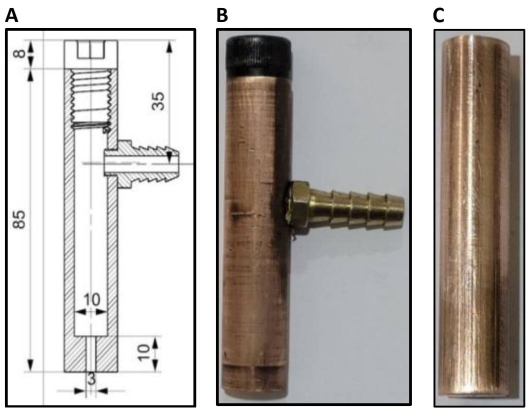

Fig. 1 A – Electrode designed, B – Hollow electrode, and C – Rigid electrode

The chemical composition of the stainless steel 304L workpiece and the copper tool has been analyzed at the State Company for Engineering Rehabilitation, as detailed in Table 1 and Table 2 respectively.

Table 1
Chemical composition of the workpiece (AISI 304 L stainless steel)

Material	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**
Weight %	0.0249	0.452	1.174	0.0287	< 0.0005	18.75	< 0.002	8.670
Material	**Al**	**Cu**	**Co**	**Ti**	**V**	**W**	**Fe**	
Weight %	0.001	0.0258	0.272	0.0046	0.135	0.0233	Balance	

Table 2
Chemical composition of electrode (pure copper)

Material	Fe%	Sn%	P%	S%	Al%	Si%	Sb%
Weight %	0.0458	0.0073	0.0013	0.0038	0.0017	0.016	0.005
Material	Pb%	Ag%	Ni%	Cr%	Ti%	Cu%	
Weight %	0.0155	0.0019	0.0032	0.0007	0.0002	99.9	

All the considered specimens were cleaned using a metal brush attached to the scouring pad to remove oxidation and grease from the metal.

Figure 2 shows the workpiece before and after the machining.

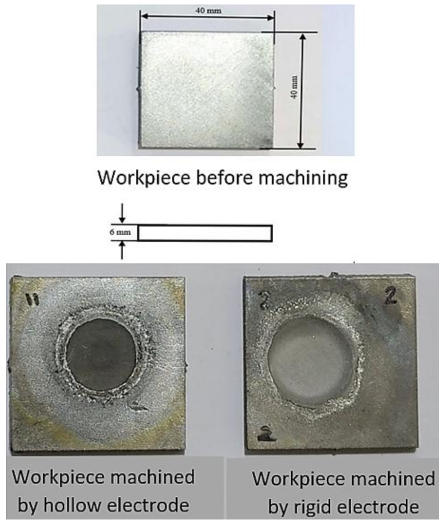

Fig. 2 Workpiece before and after machining

The electrolyte solution, which is made up of water and salt NaCl in different amounts, has been selected because it has no influence on passivation on the workpiece surface.

A water pump that was undersized and had a pressure of about 0.18 bar was selected. According to the Eq. (1), the Material Removal Rate (MRR) is calculated by dividing of the difference of the workpiece weight before and after the machining operation by the machining length of time [19, 20]. A digital gauge (A&D HF-400 Scale.001 G) is used to determine the workpiece's weight both before and after the ECM operation. To assess the roughness of the machined surface, three measurements are obtained from the surface, followed by the calculation of the average surface roughness (Ra) across the sampling length utilizing the (Mahr Pocket Surf IV) device.

$$\mathrm{MRR} = \frac{\text{W before} - \text{W afer}}{\text{Machining time}} \tag{1}$$

The workpiece was placed in the cell using a fixture to prevent it from vibrating while the electrochemical process was underway. A drilling machine is used to fix the cylindrical tool in the tool holder. Manual control is used to regulate the distance between the tool and the workpiece. The tool and the workpiece are then linked to the power supply's negative and positive poles, respectively, using a (Hewlett-Packard 6434B DC Power Supply 0-40 V). After adding the electrolyte solution, which is a mixture of salt and water, to the tank, the salt (NaCl) is weighed using a sensitive balance according to the experiment's proportions, and a small water pump is used to circulate the electrolyte solution to the rigid and hollow electrodes. as seen in Figures 3A and B, which depicted machining using two different electrolyte flow types.

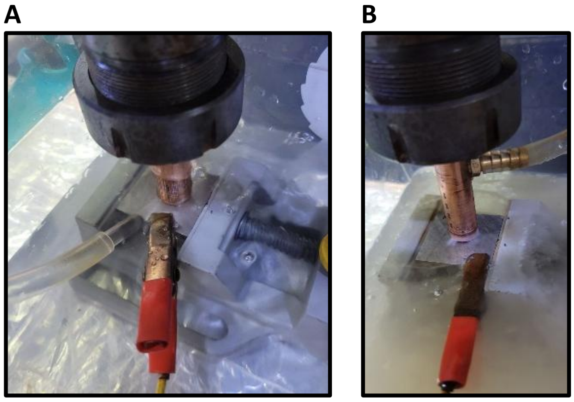

Fig. 3 ECM machining by two types of electrodes (A – rigid electrode, B – hollow electrode)

The Taguchi method was employed to evaluate the results, representing a statistical technique aimed at enhancing the quality of manufactured products and engineering systems. This method emphasizes robust design while minimizing the impact of variations and external influences [21]. It serves as a means to identify the optimal process variables and parameters that yield a desired process response or output. The primary goal is to produce high-quality products at a lower cost [22]. This approach facilitates the detection of interactions among variables, leading to more accurate results compared to alternative methods [23]. In this research, three parameters were selected, each with three levels, as detailed in Table 3. Utilizing Minitab-17 software, nine experiments were conducted by combining the parameter levels for both rigid and hollow electrodes.

Table 3
ECM parameters with levels

Parameters	Level 1	Level 2	Level 3
Voltage (Volt)	10	20	30
Electrolyte concentration (g/L)	50	75	100
Inter-electrode gap (mm)	0.3	0.5	0.8

RESULT AND DISCUSSION

The Taguchi method was used in this study to identify three factors, each characterized by three different levels. A design matrix was developed utilizing Minitab-17. The machining parameters and response parameters identified during the execution of nine experiments with the rigid and hollow copper electrode are presented in Table 4.

Figure 4 presents the primary effects graph that illustrates the factors influencing the Material Removal Rate (MRR) when employing a rigid copper electrode with side nozzle flushing. Figure 4 presents the primary effects graph that illustrates the factors influencing the Material Removal Rate (MRR) when employing a rigid copper electrode with side nozzle flushing.

Table 4
Machining parameters and Response factors using of rigid copper and hollow cooper electrode

No. of experiments	Voltage (V)	Electrolyte Concentration (g/L)	Enter-electrode Gap (mm)	Rigid copper electrode		Hollow copper electrode	
				Material Removal Rate (MRR) (g/min)	Surface Roughness (µm)	Material Removal Rate (MRR) (g/min)	Surface Roughness (µm)
1	10	50	0.3	0.1048	2.840	0.147	2.030
2	10	75	0.5	0.1533	3.260	0.1564	3.027
3	10	100	0.8	0.1342	4.860	0.1437	4.647
4	20	50	0.5	0.2827	5.757	0.2834	4.290
5	20	75	0.8	0.3514	5.973	0.3051	4.797
6	20	100	0.3	0.3806	4.017	0.3335	5.323
7	30	50	0.8	0.3811	5.593	0.3717	4.820
8	30	75	0.3	0.3935	5.467	0.4352	5.380
9	30	100	0.5	0.416	5.227	0.4227	5.183

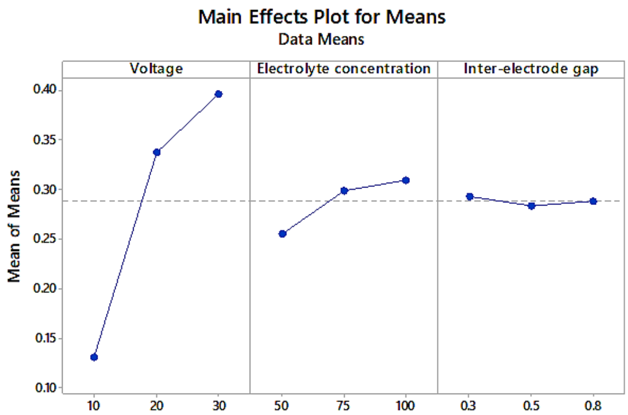

Fig. 4 Main effects plot of MRR machined by rigid copper electrode

The analysis indicates that voltage has the most substantial effect, as detailed in Table 4. The results demonstrate that MRR increases proportionally with both voltage and electrolyte concentration, while an inverse relationship is observed between MRR and inter-electrode gap. The average MRR was measured at 0.1307 g/min with a voltage of 10 volts. As the voltage was increased to 20 volts, the MRR rose to 0.3382 g/min, and further increased to 0.3968 g/min at 30 volts. This trend can be attributed to the enhancement of electric field strength, which accelerates ion migration and improves the rate of dissolution for the workpiece material, thereby resulting in a higher MRR. These observations are consistent with findings from a prior study [24]. In Figure 4, the MRR was initially recorded at 0.2562 g/min with an electrolyte concentration (EC) of 50 g/L. An increase in EC to 75 g/L led to an MRR of 0.2994 g/min, and further increasing the EC to 100 g/L resulted in an MRR of 0.3102 g/min. This increase is due to the reduction in electrolyte resistance, which facilitates a stronger ionic current, thereby promoting faster material dissolution and a higher MRR. Conversely, the increasing in the electrode gap was related with a decreasing in the average of MRR. At a gap of 0.3 mm, the mean MRR was 0.2929 g/min, which decreased to 0.284 g/min at 0.5 mm, and then slightly increased to 0.2889 g/min at an inter-electrode gap of 0.8 mm. A reduction in the gap results in a stronger electric field, higher current density, and an increased MRR [25, 26].

The parameters influencing surface roughness (SR) are illustrated in Figure 5 when using rigid electrode with side nozzle flushing, with a summary of the analysis results provided in Table 4.

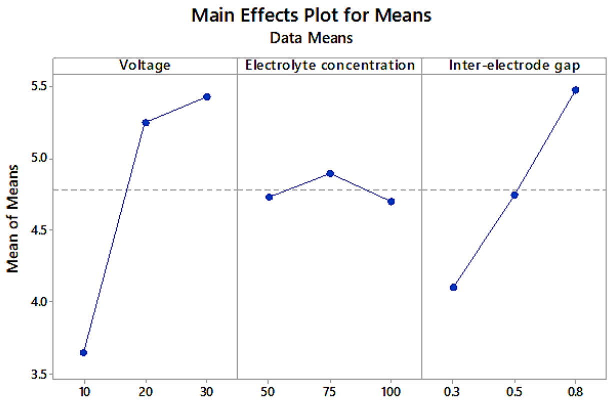

Fig. 5 Main effects plot of Surface roughness using rigid copper electrode

The findings indicate that Voltage is the predominant factor affecting SR. It has been observed that SR correlates directly with electrode gap, voltage, and electrolyte concentration. Specifically, the average SR values recorded were 3.653 µm at 10 volts, 5.248 µm at 20 volts, and 5.428 µm at 30 volts. An increase in Voltage enhances the material dissolution rate, potentially leading to uneven surface removal. Additionally, excessive voltage may result in localized heating and gas bubble formation, which can create pits and diminish surface quality [27, 28]. At an electrolyte concentration of 50 g/L, the SR was measured at 4.73 µm, while at an electrolyte concentration of 75 g/L the SR reached to 4.9 µm, it was 4.701 µm when increased to 100 g/L. High concentrations can provoke aggressive dissolution, localized corrosion, or precipitation, thereby increasing surface roughness [29]. Moreover, a rise in the inter-electrode gap was linked to an increase in the mean SR. The average SR was recorded at 4.107 µm with a gap of 0.3 mm, which slightly increased to 4.747 µm at 0.5 mm, and further to 5.475 µm at a gap of 0.8 mm. A larger gap weakens the electric field, leading to non-uniform material removal and heightened SR [30].

Figure 6 illustrates the primary effects graph that depicts the factors affecting the Material Removal Rate (MRR) when utilizing a hollow copper electrode with a straight electrolyte flow from the electrode core. The analysis reveals that voltage exerts the most significant influence, as outlined in Table 4. The findings indicate that MRR increases in direct proportion to both electrolyte concentration and voltage, while an inverse correlation is noted between MRR and the electrode gap.

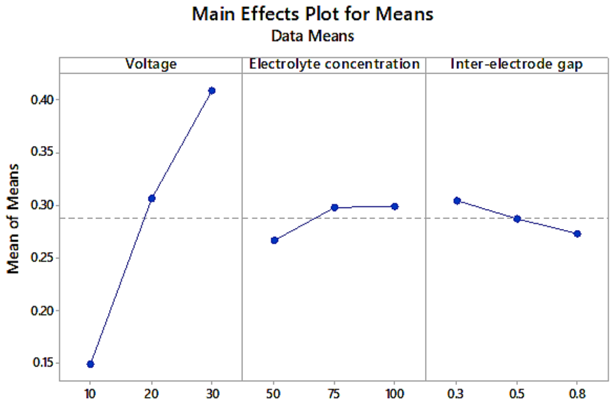

Fig. 6 Main effects plot of material removal rate using hollow copper electrode

The average MRR was recorded at 0.1490 g/min with a voltage of 10 volts. When the voltage was raised to 20 volts, the MRR increased to 0.3973 g/min, and further increased to 0.4098 g/min at 30 volts. In the same Figure 6, the MRR was initially measured at 0.2673 g/min with an electrolyte concentration (EC) of 50 g/L. An increase in EC to 75 g/L resulted in an MRR of 0.2989 g/min, and a further increase to 100 g/L yielded an MRR of 0.2999 g/min. Conversely, an increasing in the electrode gap was linked to a reduction in the average MRR. At a gap of 0.3 mm, the mean MRR was 0.3052 g/min, which decreased to 0.2875 g/min at 0.5 mm, and then slightly declined to 0.2735 g/min at an inter-electrode gap of 0.8 mm.

The factors influencing surface roughness (SR) are illustrated in Figure 7, which corresponds to the use of a hollow copper electrode with a straight electrolyte flow, serving as a detailed summary of the analytical findings outlined in Table 4.

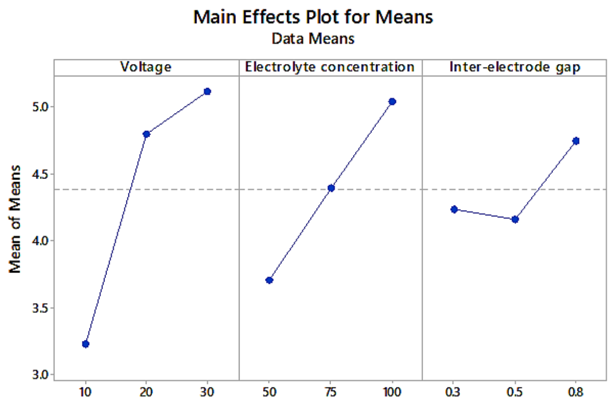

Fig. 7 Main effects plot of Surface roughness using hollow copper electrode

The examination indicates that Voltage is the foremost factor affecting SR. It has been noted that SR exhibits a direct correlation with voltage, electrode gap, and the electrolyte concentration. Specifically, the average SR values recorded were 3.234 µm at 10 volts, 4.803 µm at 20 volts, and 5.127 µm at 30 volts. At an electrolyte concentration of 50 g/L, the SR was measured at 3.713 µm, while at 75 g/L, it increased to 4.401 µm, and further rose to

5.051 µm at 100 g/L. Additionally, an increase in the inter-electrode gap was associated with a rise in the average SR. The average SR was noted at 4.244 µm with a gap of 0.3 mm, which slightly decreased to 4.166 µm at 0.5 mm, and then increased to 4.754 µm at a gap of 0.8 mm. Furthermore, it has been observed that the use of a hollow electrode resulted in a more uniform operation, a higher MRR and reduced surface roughness of the machined surface, as illustrated in Fig. 2. This improvement is attributed to the consistent flow and distribution of the electrolyte solution from the center of the electrode to the operational area, leading to a more stable performance compared to the use of side nozzle flushing.

Electrochemical machining advances the aerospace sector, enabling the more efficient and precise fabrication of intricate turbine blades, cooling channels, and other high-performance components with optimized flow configurations and material consumption as well as surface quality. Better control of electrolyte flow can increase production speed without sacrificing the necessary tight tolerances and smooth surfaces that are essential in aerospace applications. In the automotive industry, where the use of advanced alloys and titanium as lightweight yet durable materials is steadily increasing, employing optimized ECM configurations would ease the production processes of complex fuel injector, engine component, and heat exchanger parts. These findings will greatly benefit the medical device industry as well.

CONCLUSION

The results of the experiments allow for an explanation of the following important conclusions:

- The direct flow through a hollow electrode exhibited a higher material removal rate (MRR), achieving an increase of 4.61%, compared to the rigid electrode with a nozzle flushing flow, which reached a maximum of 0.4352 g/mm. In contrast, the rigid copper electrode recorded a lower MRR of only 0.416 g/mm.
- The hollow electrode demonstrated the least surface roughness (SR) at 2.030 µm, while the rigid copper electrode had a SR of 2.840 µm, indicating a reduction of 28.52%.
- The interplay of voltage, inter-electrode gap and electrolyte concentration had a significant effect on both the MRR and surface roughness for the hollow and rigid copper electrodes.

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