Journal of
Manufacturing and Materials Processing

MDPI

Article

Comprehensive Experimental Analysis of Electrochemical Jet Machining (ECJM) for Advanced Material Processing

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Abstract

This study examines the capabilities and optimisation of electrochemical jet machining (ECJM), a component of the electrochemical machining (ECM) production chain. A localised electrolyte jet helps remove material from selective areas; it is a suitable process for contoured parts and hard-to-machine material without inflicting thermal or mechanical stresses. In this regard, the study incorporates details of an experimental layout and variation in parameters in terms of voltage, electrolyte concentration, and jet velocity. The most striking findings indicate that the material removal rate and surface quality are susceptible to parameters such as applied voltage and stand-off distance, and electrolyte concentration and jet velocity (via electrolyte supply rate) fixed. Higher voltages and fixed electrolyte concentrations give higher removal rates, though this might impair the surface finish, thereby requiring a trade-off at best. These results provide insights into optimising process parameters for enhanced precision and efficiency in ECJM. Future research could focus on advanced electrolytes and improving scalability for industrial applications.

Keywords: Electro-Chemical Jet Machining (ECJM); Electro-Chemical Machining (ECM); electrolyte concentration; jet velocity; stand-off distance (SOD); dissolution rate; micromachining; surface integrity

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Academic Editor: Steven Y. Liang

Received: 10 June 2025
Revised: 7 July 2025
Accepted: 8 July 2025
Published: 16 July 2025

Citation: Shirguppikar, S.; Ašonja, A.; Desnica, E.; Ganachari, V.; Gavali, P.B.; Selvarajan, L.; Stojanović, B. Comprehensive Experimental Analysis of Electrochemical Jet Machining (ECJM) for Advanced Material Processing. *J. Manuf. Mater. Process.* **2025**, *9*, 240. https://doi.org/10.3390/jmmp9070240

1. Introduction

Extensive research has been conducted on electrochemical jet machining (ECJM) to improve its precise production capabilities, especially for difficult-to-machine, chemically inert materials, by Lu et al. [1]. This research aims to enhance machining performance by generating an electrolytic plasma at the jet-material contact zone. Dalabehera et al. [2] studied the cutting of thin metallic sheets utilising electro-jet machining with continuous and pulsed direct current application and ultrasonication to achieve accuracy and little overcut with pulsed DC power. Their assessment [2] of ECJM technology encompassed current advancements, process basics, and potential industrial applications. Bartolo has shown that rapid prediction techniques may be used to optimise machining settings by creating models to forecast material removal profiles in turbulent jet electrochemical machining. To develop a prediction model for machining results, Netprasert et al. [3] carried out parametric research on the ECJM of titanium alloy, concentrating on the effects of pulse frequency and duty cycle on cavity dimensions and material removal rate. Significant application potential was shown by Qu [4] when he optimised the flow field in the electrolytic jet electrochemical turning of TB6 titanium alloy to increase surface quality and machining efficiency. Converging hole nozzles enhanced the depth of cut, according to research by Kendall et al. [5] on the impact of nozzle design on material removal. Further research into specialised nozzle geometries, such as duckbill nozzles explored in Mask Electrolyte Jet Machining (MEJM) [6], could also yield improvements in ECJM performance. Converging hole nozzles can enhance the depth of cut by up to 9.7%, suggesting that innovative nozzle designs may be able to maximise jet stability and accuracy. Kyttä [7] provided a methodical description of ECM micromachining methods, including how they may be used to drill both macro- and micro-holes in complex metal manufacturing. Advanced electrolytes might be investigated in future studies to improve ECJM. For instance, utilising an acid electrolyte, Feng et al. [8] developed a novel jet electrochemical machining technique that produced stable machining with a Gaussian-distributed material removal rate and a decreased surface roughness (Ra) of 14.8 nm. This implies that sophisticated electrolytes tailored for different materials may be developed, thereby enhancing the efficiency and surface quality of ECJM. Furthermore, there are not many thorough investigations on novel nozzle designs and materials, such as nanostructured coatings, to improve performance and decrease wear.

While machine learning has shown promise in related areas like data-driven modelling and profile prediction in ECM [9], its application for real-time ECJM control remains less explored. With tiny inter-electrode gaps and high applied voltages, Ming Wu et al.'s [9] exploration of Jet-ECM for surface flattening in post-processing additively generated components demonstrated increased surface flatness and suggested the potential for machine learning models for real-time optimisation. Furthermore, a significant obstacle during machining is the development of a hydrogen layer at the anode–cathode contact. A model to forecast machined profiles and localised corrosion range was developed by Liu et al. [10] based on their analysis of the anodic behaviour of TB6 titanium alloy. Examining techniques to regulate the production of hydrogen layers may improve the dependability of ECJM.

Crucial ECJM parameters that affect material removal rate, precision, and overall process efficiency include voltage and stand-off distance. The dissolving rate is accelerated by high voltage, but to preserve homogeneity, excessive material removal must be prevented. The distance between the nozzle and the workpiece, or stand-off distance, must be optimised to balance electrolyte flow while maintaining the required accuracy and surface quality. By optimising these parameters, the surface smoothness and dimensions of the machined feature are affected while also improving machining stability and localisation. In high-precision work, voltage control avoids problems like excessive heat generation, which can have undesirable thermal consequences, and a predetermined stand-off distance guarantees consistent material removal without changing the workpiece. These elements are crucial in sectors like semiconductor production, where even small changes may significantly impact performance. For ECJM's industrial uses, scaling up the technique for large-scale production is crucial. A multiphysics model for Jet-ECM was created by Hackert-Oschätzchen et al. [11], including fluid dynamics to mimic the electrolyte jet's dynamic behaviour during material removal. Examining the integration of ECJM into current industrial workflows, process consistency, and economic viability are all key considerations. Furthermore, there are few comprehensive studies on the efficiency and optimisation of ECJM for certain difficult-to-machine materials, including those used in biomedical and aerospace applications. Sen and Shan [12] examined current improvements in jet-electrochemical drilling and electrochemical macro-to-micro-hole drilling techniques, emphasising the possibility of achieving optimal outcomes by customising ECJM settings for various materials. Since they focus the electrolyte jet onto the workpiece, nozzles are essential to ECJM because they significantly impact accuracy and quality. The nozzle's geometry and design affect the electrolyte distribution, pressure, and flow rate, which involves the surface polish and precision of machined items. Nozzles with an inclined or duckbill design offer more consistent and enhanced machining performance. While duckbill-shaped nozzles guarantee consistent current density distribution, which improves machining consistency, inclined nozzles increase flow characteristics to improve machining precision. Nozzle types have a significant impact on the ECJM process's efficiency. For example, clean cuts are ensured by fine jet nozzles, which are ideal for applications like microelectronics that demand great accuracy. The production process may be made more flexible and adaptable by customising nozzle designs to fit certain materials and machining specifications, which is essential in custom manufacturing, research, and development. The non-contact method known as electrochemical jet machining (ECJM) is highly effective in producing intricate and accurate microstructures on various materials. By avoiding heat and mechanical stresses and attaining high accuracy and clean surface finishes, ECJM preserves material qualities in contrast to traditional procedures that entail direct touch. ECJM is very useful in industries like aerospace, medical, and electronics that need high precision and little material change because of this cleaner and more accurate material removal procedure. Aerospace components, for example, require precise features that are difficult to create using traditional processes. Because of how it operates, ECJM is perfect for cutting complex, brittle workpieces with the extreme accuracy needed in medical applications to create high-quality surgical equipment and implants [13]. Selvarajan et al. [14] studied a variety of approaches to improving surface quality and machining efficiency. This study examines how adding rutile nanoparticles into glass fibre-reinforced epoxy composites improves their mechanical and morphological attributes. The primary emphasis is on enhancing composite properties to boost performance. Srinivasa Perumal et al. [15], in comparison to 0 weight percent rutile, in their investigation discovered that 15 weight percent rutile produced tensile values of 228 MPa and flexural strengths of 317 MPa, indicating increases of 0.588% and 82.22%, respectively. Furthermore, compared to the pure sample, the impact strength with 5 weight percent TiO_2 was 72% higher. FESEM morphological evaluations showed that the composites had better filler dispersion and structural integrity. This research digs into optimising composite structure EDM parameters in additive manufacturing and their characterisation, ramifications, and applications. It talks about how titanium alloys are sensitive to changes in the flow field and how turbulent flow can cause substantial stray corrosion. This means that machining needs to have rigorous flow analysis and control. It also discusses the problems when setting up reasonable flow field limitations in macro-electrochemical jet machining [16]. Jet electrochemical cutting, also referred to as Jet-ECM, is the method the paper focused on for machining aluminium matrix composites with silicon carbide particles. This is especially attractive because, compared to conventional machining, there is a clear advantage to it. One of the main topics discussed is how machining is affected by voltage, electrolyte type, and concentration [17]. The technology known as electrochemical jet machining (ECJM) is becoming more and more relevant in advanced manufacturing sectors because it is especially beneficial for machining complex geometries and materials that are difficult to machine. Even though ECJM is becoming more and more popular, little is known about its operational parameters and how they affect machining performance. Notably, a systematic parametric analysis designed especially for stainless steel 304 (SS304), a material utilised extensively in many industrial applications because of its superior mechanical and corrosion resistance, has frequently been ignored in previous research. By examining the impact of particular factors, including the applied voltage and sodium dodecyl sulphate concentration, on the machining performance of SS304 in ECJM procedures, this work seeks to close this crucial gap. Focussing on these characteristics, the study aims to clarify how they affect geometrical precision and material removal rates, providing important information for improving ECJM methods. It is anticipated that the results of this study will contribute to the existing understanding of ECJM, laying the groundwork for enhanced process control and efficiency in advanced material machining applications. In addition to improving SS304′s machining capabilities, the findings will open the door for further research on other cutting-edge materials in the ECJM field.

A key finding from the research is that using sodium nitrate as the electrolyte improves the precision of the machining. They discovered that voltage plays an important role in shaping the dimples and affecting the surface roughness, highlighting Jet-ECM's capabilities when dealing with these advanced materials [18,19]. One of the sections of the article under focus, Jet-ECM, considers the silicon carbide concentration on aluminium matrix composites with neutral electrolytes. Just like other ECM techniques, Jet-ECM has features of micro-machining, such as negligible destruction to the microstructure of the material and low electrolyte consumption, which renders it effective for machining aluminium composites with different concentrations of silicon carbide. This study looks into the efficacy of the selected electrolytes and how they contribute to the material removal processes, thereby aiding in deepening the knowledge in advanced electrochemical processing. Going back to jet electrochemical machining, which is different from ECJM, they highlighted that there were some quite stunning experimental data regarding how the axial feed in EN 1.4301 stainless steel grooves changes with the application of varying current density during the machining process. It is one thing to set a working gap and voltage, but to be able to sculpt an artefact through the changes made to the initial design is an entirely different endeavour. Modifying the current density achieved the intended depth and surface quality owing to different levels of machining [20,21]. It discusses simulations of flow fields that are applied to optimise the machining parameters, achieving an impressive contour error of under 1% and a surface roughness of about Ra 2.414 µm. The findings also highlight the significance of voltage, feed rate, and rotational speed of the workpiece, confirming that ECT has significant potential for industrial applications related to advanced material processing [22]. Other pulsing techniques or Maglev methods, as referred to in the research, were said to enhance surface polish and quad estimation precision of aluminium alloy components using sequences of short, high-frequency pulses. The course of the studies was smooth. The limits of variation in size, with careful control of the flow and electric fields, were confined to under 0.05 mm with the surface roughness ranging from 0.1 to 0.2 µm [5]. The paper also explores Jet-ECM, focusing on how different nozzle shapes impact material removal. The findings indicate that converging hole nozzles can boost cutting depth by nearly 9.7% compared to standard cylindrical nozzles. It points out that elements like flow speed, pressure, and electric current distribution are crucial for maintaining stable machining processes. This information aids in understanding the Jet-ECM techniques relevant to the production process. This research focuses on reducing the machining area while minimising overcutting and determines how electrolyte pressure and pulse duty cycle influence the quality of machining [23]. This section examines how the voltage, the concentration of the electrolyte, and the distance from the nozzle to the working piece affect the depth of the craters in silicon wafers. The results showed that increasing voltage and electrolyte concentration lead to deeper craters, while a greater distance between the nozzle and workpiece results in shallower craters, with polarity having little to no effect [24]. The paper gives a detailed experimental analysis focused on the ECJM process, examining how various factors, including voltage, electrolyte pressure, and machining time, can alter the rate of material removal. The findings back the model by correlating performance with machining aspects. It highlights the control of electrolyte temperature and conductivity due to their influence on dissolution rate and efficiency of ECJM in advanced material processing [25]. The study discusses the influence of the inter-electrode gap (IEG) as a considerable parameter and chooses an optimal IEG of 0.6 mm for TB6 titanium alloy Jet-ECM. The research is based on other parameters like the composition of the electrolyte, voltage, and flow rate in order to achieve better performance of machining [26,27].

One important factor affecting the efficiency and reliability of ion transport in electrodialysis systems is the distribution of current density. By boosting local current density and producing shadowing effects, the shape of the system and the presence of insulators can alter the distribution and increase ohmic losses [28]. Multi-ion transport in electrolytes is complex due to interactions between different ions and the solvent. There are claims that the presence of supporting electrolytes can alter concentration gradients and enhance conductivity, both of which have an effect on the limiting current density [29].

By filling these gaps, future studies can significantly enhance the effectiveness, accuracy, and applicability of ECJM in various high-precision sectors.

2. Materials and Methods

Stand-off distance (SOD) and machining voltage have a great impact on the material removal rate (MRR) and the depth achieved on the workpiece. The ECJM process is the advanced form of ECM, which operates on the same principle as Faraday's law of electrolysis. The material removal occurs on the workpiece through the anodic dissolution. The amount of material removal can be determined using Equation (1),

$$MRR = \frac{M}{z \cdot F} Q \tag{1}$$

Here, M is the molar mass of dissolved material, Q is the amount of charge that was supplied during the machining process, z is the valance of ion of ablated material, and F is Faraday's constant value (96,485.3329 C/mol).

Setting up and preparing all the required equipment (Figure 1) is the first stage in any machining operation. The operation's electrical power has to be supplied first by connecting to the DC power source. After that, make sure the nozzle is firmly fastened so it can guide the electrolyte flow when milling. To prevent movement when working, it is essential to secure the workpiece firmly in place. The installation and configuration of the electrolyte pump is also necessary to provide a constant supply of electrolyte to the work area. Finally, a Computer Numerical Control (CNC) system has to be set up and put into action so that machining may be automated and operations can be controlled precisely.

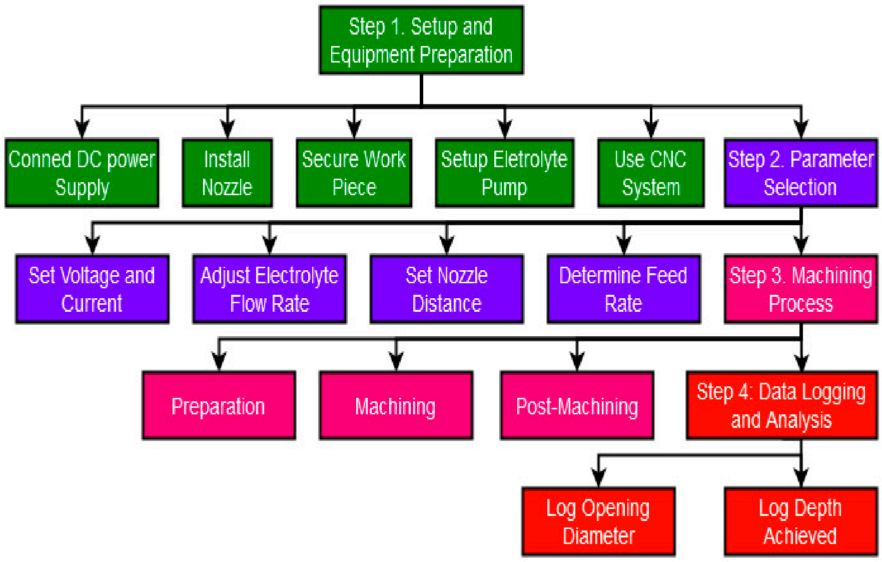


Figure 1. Flow chart of the ECJM process.

2.1. Parameter Selection

Selecting and fine-tuning the machining process's important parameters listed in Table 1 is the focus of this stage. To obtain the necessary amount of material removal, the applied voltage was carefully adjusted. For efficient, precise, and high-quality machining, it is important to specify the distance between the nozzle and the workpiece. In order to manage the machining speed and surface smoothness, it is also necessary to set the feed rate, which dictates the velocity of the nozzle or workpiece.

Table 1. Process parameters of machining.

Parameters	Value
Workpiece	SS304 (304 Stainless Steel) Chromium 17.5–19.5% Nickel 8.0–10.5%
Electrolyte	2 M NaCl
Nozzle inner diameter	300 μm
Electrolyte supply rate	20 mL/min
SOD	400 μm, 600 μm, 800 μm
Voltage	50 V, 60 V, 70 V

2.2. Machining Process

As a whole, machining consists of three stages. As a last step in getting ready, you should double-check that everything is set up properly by making any necessary modifications. During the machining step, the setup and settings are carefully followed to remove material using electrochemical or other techniques as indicated. Last but not least, after machining, everything is rinsed with deionised water and checked to make sure it turned out the way it should.

2.3. Data Logging and Analysis

Finally, the performance of the machining operation is assessed by recording and analysing data. The dimensional correctness is evaluated by measuring and recording the diameter of the opening that is formed during the machining process. In order to further assess the success of the material removal procedure, it also measures and records the depth obtained. This information is critical for assessing the operation's performance and fine-tuning it for the future.

3. Results

In Figure 2, you can see the experimental setup. An electrolyte tank with a pump for electrolyte circulation is part of the ECJM setup, which also comprises a DC power supply (rated 160 V, 2 A) used to apply the desired voltages for constant electrical conditions and an axis controller for accurate nozzle movement in the Z axis. To keep the nozzle steady as it sprays the workpiece with the electrolyte, a nozzle holder is required. The electrolyte is fed to the nozzle via the input pipe, and the wasted electrolyte is removed through the output pipe. Checking the electrolyte pressure using a pressure gauge is important. This setup is ideal for machining materials that are difficult to cut because it allows for precise material removal by controlling the flow of electrolyte, electrical conditions, and the placement of the nozzle. The experimental results (the input/output parameters) are listed in Table 2 for the experimentation.

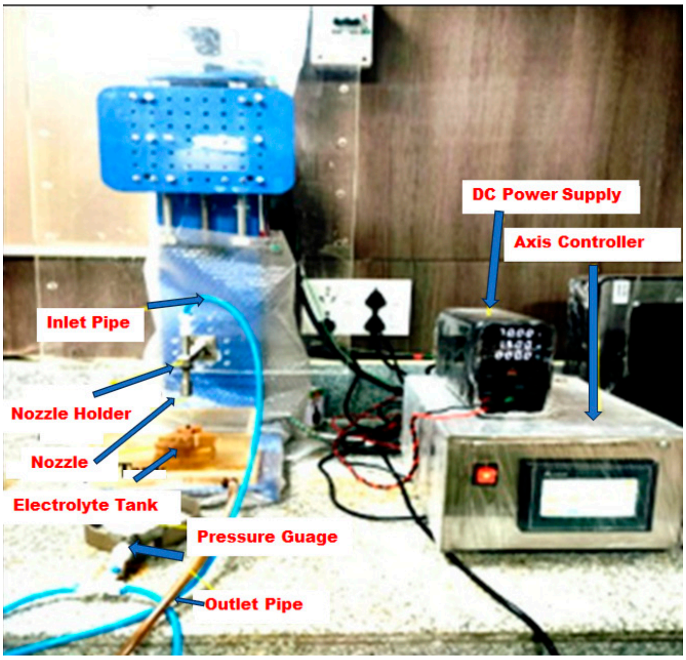


Figure 2. Experimental setup of ECJM at IIT Bombay.

Table 2. Experimental results.

Input Parameters			Output		
SN	Voltage (V)	SOD (µm)	Depth Achieved (µm)		
1	50	800	378	362	383
2	50	600	572	582	668
3	50	400	655	668	665
4	60	800	477	484	487
5	60	600	640	628	630
6	60	400	780	756	762
7	70	800	650	657	665
8	70	600	702	703	698
9	70	400	840	834	843

4. Discussion

The depth of the hole on the SS304 workpiece increased as the voltage was increased. For this experiment, the voltage was adjusted, the SOD constant was kept, and the feed was adjusted.

4.1. Constant SOD = 800 µm

With a constant stand-off distance of 800 µm, Figure 3 and Table 3 show the applied voltage plotted against the depth of machining in SS304 workpieces. Its direct proportionality is seen in the graph. As the voltage was raised from 50 V to 70 V, the machined hole became deeper. Since the material is deeper into the workpiece, this pattern indicates that greater voltages would remove it quicker. The same results can be compared with the J. Kozak et al. [25], where the voltage plays an essential role for the out parameters. The image below emphasises this idea by demonstrating the significance of this voltage in relation to the crucial parameter for electrochemical jet machining depth control. If the goal of this research is to optimise machining conditions for a specific application, then these findings have substantial optimisation implications.

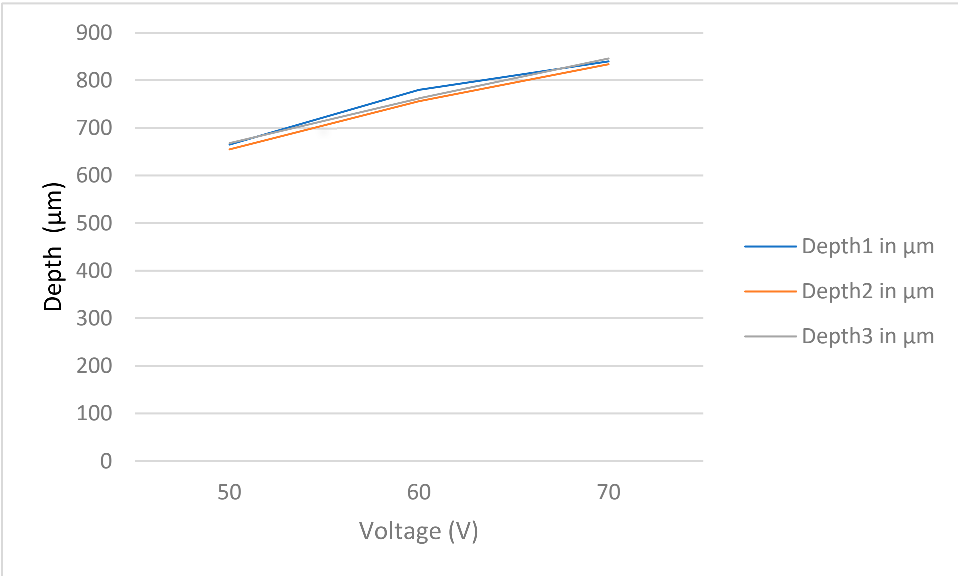


Figure 3. Effect of voltage on machining depth at constant SOD (800 µm).

Table 3. Results of voltage on machining depth at Constant SOD (800 µm).

Depth 1 (µm)	Depth 2 (µm)	Depth 3 (µm)	Voltage (V)
383	378	362	50
477	484	487	60
657	665	650	70

Figure 4 shows the opening size and depth profile at 800 µm SOD. At voltages of 50 V, 60 V, and 70 V, with an SOD of 800 µm, it displays three sub-images that depict the opening widths and depth profiles of the machined holes.

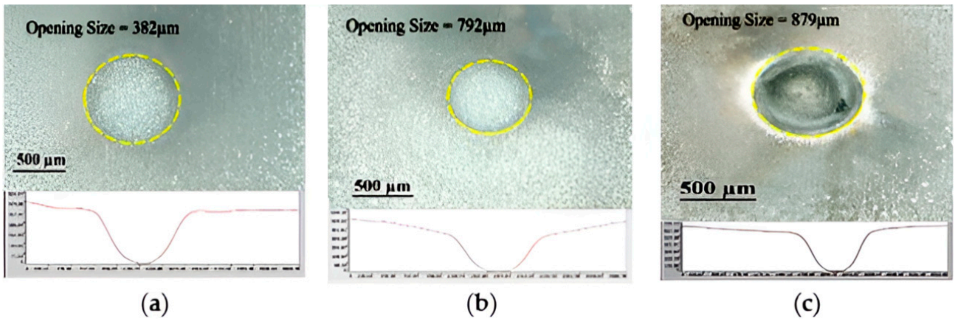


Figure 4. Opening Size and Depth Profile at 800 µm SOD (**a**) at 50 V, (**b**) at 60 V, (**c**) at 70 V.

(a) 50 V: It shows that the material removal is modest since the machined aperture is shallow and wide.
(b) At 60 V, the aperture is much broader and deeper than at 50 V. This symbolises superior machining performance.
(c) 70 V: This voltage level affects maximum material removal since it has the broadest and deepest opening of all the possibilities.

This provides visual evidence that, concerning depth and lateral diameters, there is a direct correlation between rising voltage and machining efficiency.

4.2. Constant SOD = 600 µm

Figure 5 and Table 4 shows the depth of machining versus voltage for an SOD of 600 µm. The trend remains the same as shown in Figure 3. That is, increasing voltage increases machining depth. It may be noted that the depths obtained at this SOD are higher than the same set of voltages for 800 µm SOD values. This means that as the SOD is reduced, the material removal rate continues to increase for deeper machining [27], even at lower voltages. It must be gathered from these data that the machining parameters in which a controlled depth requirement can be achieved are optimised by taking both voltage and SOD as adjustable input parameters.

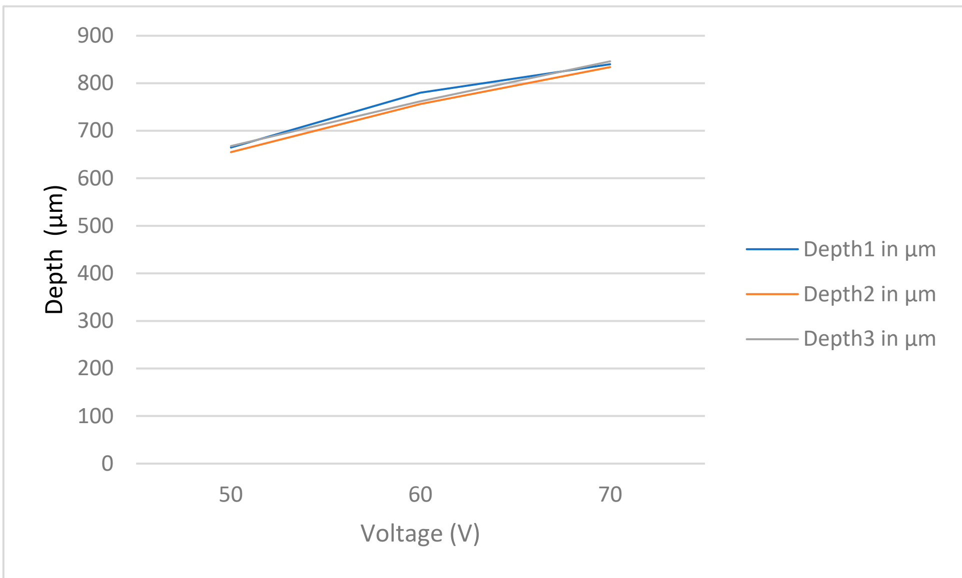


Figure 5. Effect of voltage on machining depth at constant SOD (600 µm).

Table 4. Effect of voltage on machining depth at constant SOD (600 µm).

Depth 1 (µm)	Depth 2 (µm)	Depth 3 (µm)	Voltage (V)
562	582	575	50
640	630	634	60
698	704	701	70

Figure 6 illustrates the opening sizes and depth profiles at 50 V, 60 V, and 70 V voltages with an electrode separation of 600 µm. For the case of the following:

(a) 50 V: It can be seen that the machined opening was more profound and broader compared to the same voltage for an 800 µm SOD, which meant better material removal.

(b) 60 V: The application of a subsequent increase to 60 V shows that more depths and widths have been obtained with improved machining efficiency.

(c) 70 V: The broadest and most profound of the three, proving to have the highest material removal rate.

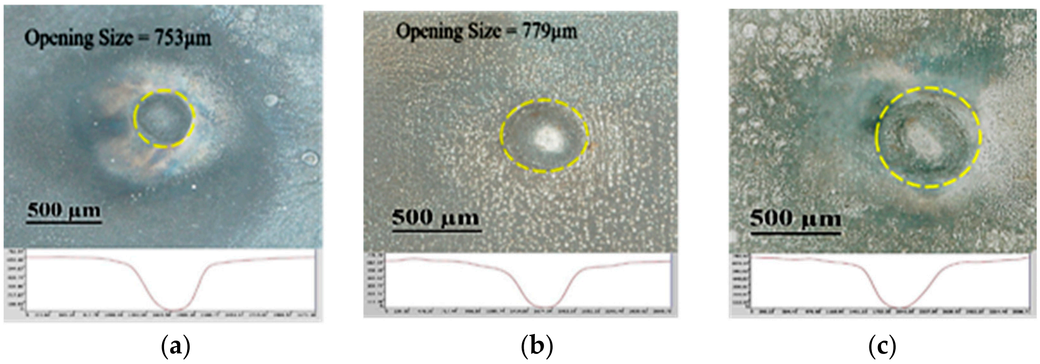


Figure 6. Opening size and depth profile images at 600 µm SOD (**a**) at 50 V, (**b**) at 60 V, (**c**) at 70 V.

These images further justify what is being demonstrated by Figure 6, which illustrates greater depths and sizes of a hole or opening if a smaller SOD is used there.

4.3. Constant SOD = 400 µm

In Figure 7 and Table 5 the influence of the different voltage on the depth is validated under the constraint where the size of the SOD is kept at 400 µm. The trend of increasing depth with voltage is almost continuous, where the depths are way more significant than those achieved at 600 µm and 800 µm SOD for the same voltages. Stand-off distance is essential for both economy and machining speed [28]. This point in the figure works to underline the fact that a low SOD significantly helps in improving the machining depth. An SOD of 400 µm instead appears quite optimal for achieving deep machining parameters even for the smaller voltages, therefore showing its pleasant prospect for high-precision applications.

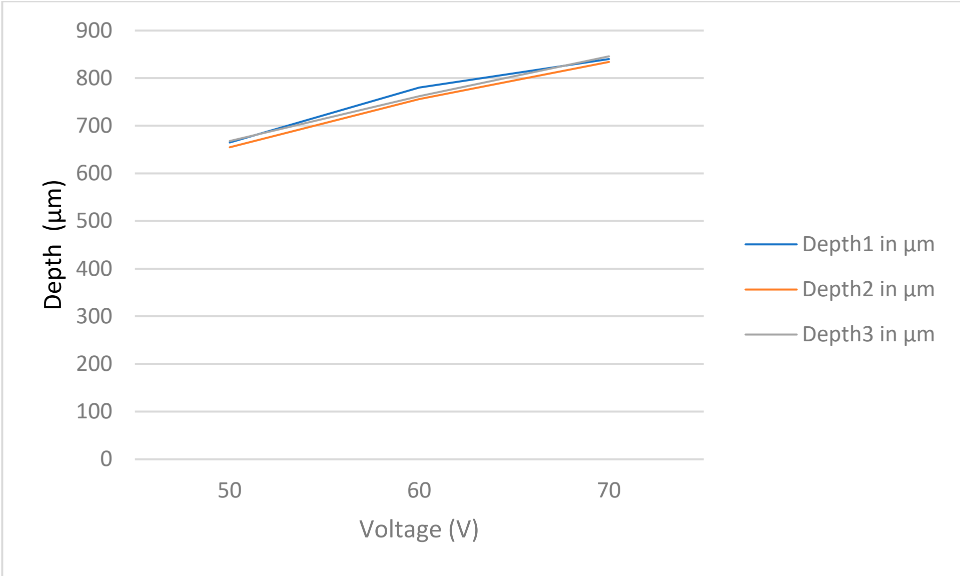
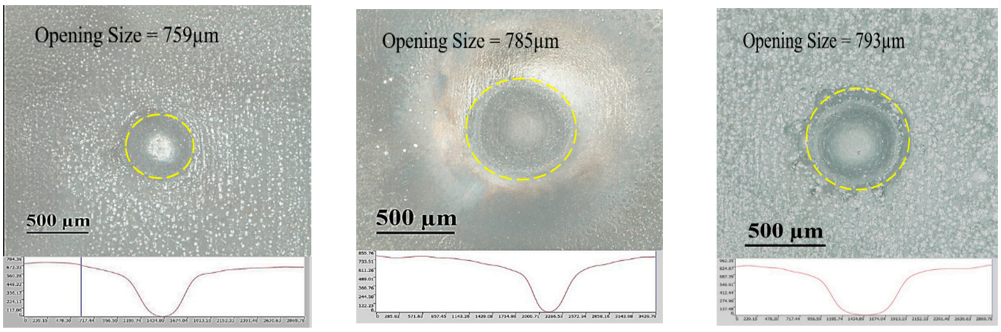


Figure 7. Effect of voltage on machining depth at constant SOD (400 µm).

Table 5. Effect of voltage on machining depth at constant SOD (400 µm).

Depth 1 (µm)	Depth 2 (µm)	Depth 3 (µm)	Voltage (V)
665	655	668	50
780	756	762	60
840	834	846	70

The effects of the voltages 50 V, 60 V, and 70 V on the opening size and depth profile at an SOD of 400 µm are shown in Figure 8.



(**a**) (**b**) (**c**)

Figure 8. Opening size and depth profile at 400 µm SOD (**a**) at 50 V, (**b**) at 60 V, and (**c**) at 70V.

(a) 50 V: The depth and width are significantly high compared to higher SODs, which could be indicative of the material removal efficiency.
(b) 60 V: Continuous increments in depth and size can suggest better machining performance.
(c) 70 V: This is the deepest and largest opening, indicating the best performance within this voltage and SOD combination.

These photographs confirm that a lower SOD of 400 µm can perform not only maximum machining depth but also opening size very well in deep and precise machining-demanding applications.

It was verified through the experiment that the depth which was achieved in the SS304 workpiece is directly proportional to the voltage applied and inversely proportional to the SOD Equation (2).

Mathematically it can be expressed as

$$Depth \propto \frac{voltage\ Applied}{SOD} \tag{2}$$

In Figure 9, the voltage versus depth data of multiple SODs (400 µm, 600 µm, 800 µm) are superimposed on each other in one graph. It is clear from the graph that for each level of voltage, the machining depth increases as the SOD decreases. This comparison highlights the inverse relationship between smaller SODs and machining depth for the same given voltage. Figure 10 demonstrates the significant influence of SOD in optimising machining, therefore clearly pointing out which SOD and voltage combinations are adequate to achieve a given machining depth.

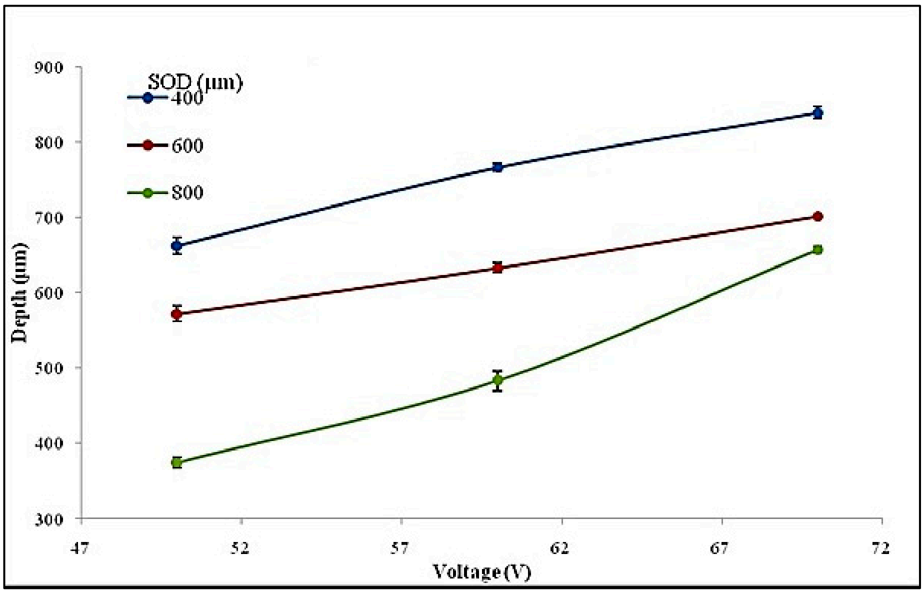


Figure 9. Comparison of machining depths at various SODs (400 µm, 600 µm, 800 µm).

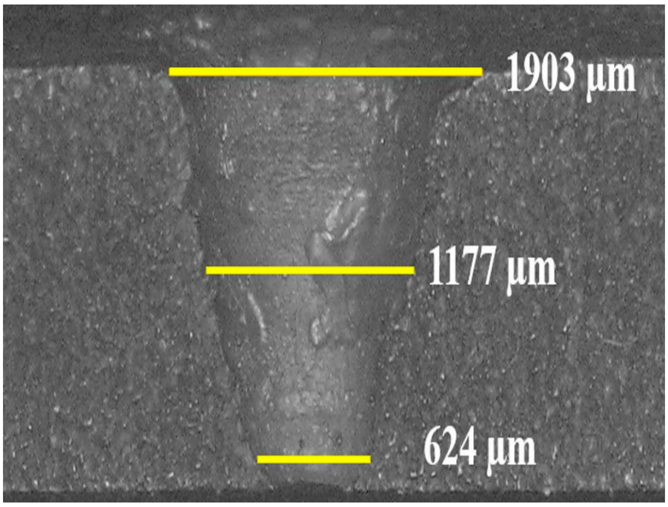
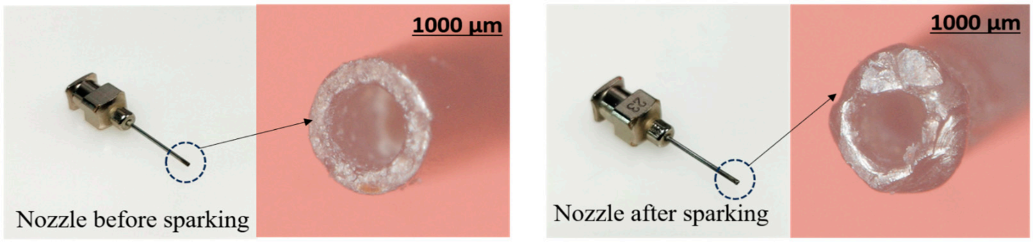


Figure 10. Through hole cross-section image at 60 V, 600 µm SOD.

A spark was observed during the machining process at 70 V and 400 µm SOD. The spark was generated because the electric field of the hydrogen layer formed between the anode and the cathode was less than the electric field in the system, resulting in the breakdown of the hydrogen layer into H+ and OH− ions. The spark image is shown in

Figure 11. Due to sparking, nozzle damage was observed. The nozzle was deformed into a shape, resulting in improper flow of the electrolyte, thereby reducing repeatability.



(a) (b)

Figure 11. (**a**) Nozzle before sparking. (**b**) Nozzle after sparking.

5. Conclusions

Results from extensive studies indicate that ECJM may be a viable alternative to conventional precision machining methods, particularly for producing components with complex features or cutting materials that are notoriously difficult to work with. This research investigated the effects of various machining parameters on material removal rate and surface quality. These factors included voltage, stand-off distance (SOD), and electrolyte concentration.

These experiments have established that voltage is one of the critical parameters in the ECJM process. As applied voltage increases, a greater material removal rate is generally attained. However, this is again at the expense of surface quality, as higher voltages may cause surface irregularities. Hence, a balance should be achieved to allow for the efficient removal of materials while maintaining high-quality finishes on the surface. It was noted that the machining depth is directly proportional to the voltage applied during the machining process.

The stand-off distance between the nozzle and the workpiece highly influences the precision and depth of the machined features. A shorter SOD enhances better machining precision, but in the process, it may cause the electrolyte flow to become less stable, disturbing the workpiece and resulting in damage. In contrast, a larger SOD will lead to a broader electrolyte jet and lower machining precision and feature definition. Optimal SOD values are thereby crucial for balancing depth, accuracy, and stability in the machining process.

The paper delves deep into advanced techniques and innovations boosting ECJM capabilities. Machining performance can be significantly enhanced with pulsed power supplies as the heat generation rate is lowered and the material removal rate improves. Nanostructured coatings, whether applied to a workpiece or a nozzle, can significantly reduce tool wear and enhance the precision of machining. Further integration of machine learning algorithms, building on prior work in ECM modelling and prediction [6], can improve the accuracy and consistency of real-time monitoring and control of machining parameters, making the process more reliably performed.

A hydrogen layer is formed at the interface of the anode and cathode during machining. Additionally, this material may ignite and spark, potentially damaging the nozzle and affecting repeatability and reliability during the process. The solution to such a problem relies on further research to optimise the machining parameters and develop more robust nozzles that can withstand these deleterious effects during sparking. Further research directions are therefore suggested to overcome the current challenges and enhance the scalability and efficiency of ECJM to realise its industrial potential. These include the search for advanced electrolytes that function correctly, innovative designs for nozzles to enhance jet stability and precision, and further investigation into the applicability of ECJM to a wider range of materials, particularly those used in the aerospace and biomedical high-precision industries.

This research has successfully demonstrated that ECJM is an advanced and versatile machining technique. Through detailed experimental investigations, it has identified key parameters that influence the process and proposed strategies for their optimisation. The current work is, therefore, a crucial step in expanding knowledge in the area of ECJM, particularly in its applied prospects for precision manufacturing, which cannot be overlooked. In the future, research should focus on addressing recognised problems and exploring innovative solutions to enhance efficiency and scalability for the application of ECJM in industrial environments. These findings will substantially contribute to the development of even more efficient, precise, and reliable ECJM processes, setting further standards for precision machining.

Author Contributions: Conceptualization, S.S. and P.B.G.; methodology, V.G.; investigation, P.B.G.; resources, S.S.; data curation, S.S. and A.A.; writing—original draft preparation, P.B.G.; writing—review and editing, S.S., E.D., and AA; visualisation, S.S., E.D., and A.A.; supervision, L.S. and B.S.; project administration, L.S., E.D., and B.S.; funding acquisition, P.B.G. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported through the project "Creating laboratory conditions for research, development, and education in the field of the use of solar resources in the Internet of Things", at the Technical Faculty "Mihajlo Pupin" Zrenjanin, financed by the Provincial Secretariat for Higher Education and Scientific Research, Republic of Serbia, Autonomous Province of Vojvodina, Project number 003101190 2024 09418 003 000 000 001.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ECJM	Electrochemical Jet Machining
ECM	Electrochemical Machining
SOD	Stand-off distance
Jet-EPM	Jet-Electrolytic Plasma Micromachining
MRR	Material Removal Rate
CNC	Computer Numerical Control

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