

# Analysis of influence of the parameters and sodium polyacrylate conductivity on the efficiency and geometry of micro-hole after electrochemical discharge machining in Inconel 718

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## ABSTRACT

The technology of making micro-holes in aircraft engine parts is one of the most demanding. This stems from the application of high technological requirements for micro-hole quality and the specialized superalloys from which aircraft engine parts are manufactured. This paper presents an analysis of the effects of electrical parameters and the effect of sodium polyacrylate conductivity (10; 200; 400; 900  $\mu\text{S}/\text{cm}$  – used as working fluid) on the efficiency of the electrochemical discharge machining (ECDM), as well as micro-hole geometry (radial overcut, conicity). The analysis of the results covers nearly 10,000 micro-holes drilled with a 0.3 mm diameter electrode in the Inconel 718 superalloy. The analysis of the results showed that fluid conductivity affects the efficiency and stability of the ECDM process. However, higher fluid conductivities (200, 400, 900  $\mu\text{S}/\text{cm}$ ) improved radial overcut and conicity. Analysis of the results showed that  $I_p$ , DC, and GAP have the greatest impact on MRR, while CAP has the greatest impact on LTW. However, the material removal rate was improved for conductivities of 200  $\mu\text{S}/\text{cm}$  and 400  $\mu\text{S}/\text{cm}$  (achieving approximately 0.35 mm/s). However, for the applied fluid conductivity of 200–400  $\mu\text{S}/\text{cm}$ : linear tool wear decreased to approximately 1 mm, radial overcut increased slightly to approximately 0.6 mm, and conicity decreased to within the range of 0.04–0.05 mm. Analysis of the results also showed how the range of electrical parameter values should be reduced for further drilling tests.

**Keywords:** micro-drilling technology, electrochemical discharge machining, difficult-to-cut material, Inconel 718.

## INTRODUCTION

Currently, micro-hole technology is particularly applicable in the aviation industry. It is used to create “cooling holes” in hot sections of aircraft engines. Cooling holes improve the performance of turbine blades by reducing their temperature through the coolant flowing through them [1,2]. Such a cooling system is crucial due to the high-temperature operating conditions of the turbine [3]. In fourth-generation aircraft engine turbines, whose thrust-to-weight ratio is approximately 10, the turbine inlet temperature has reached approximately 2000 K [4]. The inlet temperature of fifth-generation aircraft engine turbines can reach 2200 K. This

demonstrates the enormous challenges facing the design and production of turbine blades [5].

Cold gas flows through hundreds of holes, each with a diameter of 0.2–1.2 mm, distributed across the part, creating a cooling film that acts as a barrier between the hot gas and the part. This reduces the part's surface temperature [5].

Moreover, due to the high-temperature operating conditions of the turbine, its parts are manufactured from materials with high resistance to strong oxidation and corrosion, resistance to thermal fatigue, and excellent tensile strength at high and cryogenic temperatures. Turbine blades are most often made of nickel-based superalloys and titanium alloys [6–8].

The enormous challenges for cooling hole manufacturing technology stem from the difficult-to-machine materials from which turbine blades are made and the hole geometry. The diameter of these micro-holes is less than 1 mm, often reaching 0.3 mm [9]. Furthermore, micro-holes in selected parts of aircraft turbines are also made at an angle, or their outlet diameter is larger than the inlet diameter. Currently, one of the most effective methods for producing micro-holes is electrical discharge machining (EDM) [1,10]. However, EDM has its advantages and disadvantages. EDM enables effective machining of materials such as nickel-chromium superalloys or titanium alloys, and provides acceptable dimensional and shape accuracy [11]. However, defects such as heat-affected zones or microcracks in the protected surface layer necessitate additional machining technology. Moreover, EDM is characterized by high tool electrode wear and relatively lower efficiency compared to other unconventional machining methods (such as electrochemical or laser machining) [12,13].

To improve the performance of EDM technology, a hybrid technology combining EDM and electrochemical machining (ECM) has emerged, known as electrochemical discharge machining (ECDM). The main goal of ECDM is to reduce tool electrode wear and increase machining efficiency [14]. ECDM technology, using a tube electrode and a salt solution or deionized water, has good potential for micro-hole drilling. The ECDM process ensures machining accuracy and low cost. However, the material removal mechanism in this machining process is poorly understood due to its complex mechanism, which is difficult to study [15]. However, as reported by the authors in [1], the surface integrity of small holes machined by electrochemical discharge drilling is insufficient, and the effect of process parameters on micro-hardness, micromorphology, and residual stress is unclear. Therefore, further experimental testing of this hybrid process must be conducted to gain more knowledge about it. This would allow for faster determination of machining parameter values and accelerate the preparation of the micro-hole drilling technological process.

When combining EDM and ECM machining, a salt solution or deionized water is most often used as the working fluid. In this machining method, material is removed through phenomena associated with electrical discharges and electrochemical dissolution – these processes mutually

reinforce each other. The hybrid combination of these two treatments ensures high efficiency. The machined surface after the ECDM process is characterized by high integrity and the absence of a metamorphic layer. Furthermore, the taper of long micro-holes is small, and dimensional accuracy is controlled by applying appropriate parameter values. Furthermore, the tool electrode is subject to significantly less wear, and the entry hole has a smoother edge. Furthermore, additional advantages of the ECDM process include high quality, high efficiency, and high precision. This hybrid machining process eliminates the burrs and recast layer, reduces the tapering and roughness of micro-holes [16,17].

The results of electrochemical discharge drilling tests in [6,18] show that, compared to electrical discharge drilling (EDD), ECDM technology provides better drilling efficiency and better quality of drilled micro-holes. In [18] demonstrated that the surface inside holes drilled in nickel-based single-crystal superalloy is smoother, free of recast layers, cracks, and voids compared to the surface obtained after EDD. However, selecting machining parameters to ensure process stability and repeatability is challenging. Analysis of the results showed that increasing electrolyte conductivity increases the material removal rate to a certain value.

In [6], the efficiency of ECDM and EDM drilling and the accuracy of micro-hole geometry (overall hole circularity) were also compared. Micro-hole drilling was performed using the Inconel 718 superalloy. Analysis of the results showed that the machining rate was significantly higher for ECDM drilling. Overall hole circularity also gave similar values for the inlet and outlet diameters of the hole. The results of these drilling tests also showed a smoother surface inside the hole compared to the surface after EDM. The surface machined after ECDM was characterized by significantly fewer micro-pits and irregular attacks. Furthermore, ECDM drilling resulted in lower tool wear.

The applied salt solution conductivity value significantly influences the efficiency of ECDM drilling. In [19] reported that the material removal rate (MRR) decreases with increasing salt solution conductivity. To obtain a high MRR, a salt solution with low conductivity should be used. Also, for dimensional accuracy of the hole, a lower salt solution conductivity should be used. When the salt solution conductivity exceeds 6

mS/cm, dimensional accuracy deteriorates. This is due to excessive dissolution, which destroys the machined hole inlet shape. Therefore, the optimal salt solution conductivity value was 3 mS/cm. Similar conclusions were shown by the taper angle analysis. Furthermore, compared to EDM, after tube electrode high-speed electrochemical discharge drilling, the recast layer does not appear in the inlet and middle of hole areas. However, there are no signs of removal of the recast layer near the exit area. The test results showed that there is a certain value of the working fluid conductivity that ensures high MRR and good hole geometry accuracy. However, this conductivity value will be the specific effective value for a given electrochemical discharge drilling process for the machining of a given material. Finding this effective conductivity value for a salt solution must be determined experimentally to obtain its optimal value, due to the unpredictable nature of phenomena in the ECDM process.

Furthermore, the process of making micro-holes using electrochemical discharge drilling (ECDD) allows for obtaining better quality and accuracy of micro-hole geometry compared to EDM. In [1] demonstrated that only a few defects were observed on the smooth machined surface after ECDM. The machined surface had a roughness of  $R_a = 1.69 \mu\text{m}$ . Furthermore, the entrance to the ECDM drilling machined hole had a rounded corner with a radius of curvature of approximately  $150 \mu\text{m}$ . Furthermore, analysis of the results showed that the recast layer was removed in ECDM drilling when the working fluid conductivity increased from 0.005 to 3.6 mS/cm. Test results showed that electrochemical discharge drilling improved the surface integrity of micro-holes. In manufacturing technology, the quality of hole making (the accuracy of product, surface quality) plays a key role [20].

The ECDM process still requires refinement of optimal parameters to ensure its stability and efficiency, as well as acceptable micro-hole geometry when drilling in a given material. The process is ambiguous in nature, with many factors influencing its performance. There is still a gap in existing knowledge about the ECDM process, allowing for a better understanding of the process and defining, within a certain range, the parameters that provide the most efficient process (high material removal rate, low linear tool rate, high radial overcut accuracy, and conicity). One significant challenge is finding the most efficient

ECDM drilling for the working fluid used in the form of salt solutions, which have a certain conductivity. A new feature of this work is the analysis of various conductivity values of sodium polyacrylate used as the working fluid in the ECDM process. The study also analyzed the effect of sodium polyacrylate conductivity in values, such as 10, 200, 400, and 900  $\mu\text{S/cm}$ , which is also a novelty. Furthermore, it is worth emphasizing that the analysis of the results of drilled micro-holes was performed based on nearly 10,000 holes. In experimental tests, it is rare to analyze the results for such large data sets.

As part of this work, ECDM drilling tests were performed in the superalloy Inconel 718 using different conductivities of sodium polyacrylate solution as the electrolyte. The influence of electrical parameters on the stability and efficiency of micro-discharge machining was first analyzed to verify the machining performance using the selected aqueous salt solution. For this analysis, tests with a fluid conductivity of 200  $\mu\text{S/cm}$  were selected. Next, the influence of four electrolytes conductivity values (10, 200, 400, and 900  $\mu\text{S/cm}$ ) on the stability and efficiency of the machining was examined. The primary focus was on analyzing the influence of electrical parameters and electrolyte conductivity on the machining process, as well as observing and explaining phenomena occurring during ECDM. This analysis provides valuable information on how further research could improve the efficiency of ECDM technology in difficult-to-machine materials.

## MATERIALS AND METHODS

The main objective of this work is to analyze the impact of electrical parameters and working fluid conductivity on the electrochemical discharge machining process. Determining the process parameters and effective working fluid conductivity is a challenge for this unconventional process. This is due to the fact that it is often difficult to predict the relationship between the drilling parameters and the resulting factors.

To verify the effect of ECDM process parameters on drilling efficiency, a test campaign was conducted. Circular holes were drilled perpendicularly to the surface using ECDM in 3.2 mm thick Inconel 718 flat plates. Belmont single-channel brass electrodes with an outer diameter of 0.3 mm and a nominal length of 400 mm were

used for the test. Sodium polyacrylate was used as the working fluid, what is a novelty in experimental tests. Furthermore, the novelty is the use of conductivity values for this working fluid, with values 10, 200; 400; 900  $\mu\text{S}/\text{cm}$ . Moreover, the work analyzes nearly 10,000 ECDM micro-hole drilling tests, which is rarely performed in experimental tests. Consistent with other test results, single-channel electrodes are the most efficient for drilling micro-holes [19]. Table 1 presents the most important thermophysical properties of the workpiece material and the tool electrode material. Table 2 provides the chemical composition of the Inconel 718 superalloy. The chemical composition of Inconel 718 was determined using an X-MET8000 X-ray spectrometer (Hitachi High-Tech, Tokyo, Japan).

Data from nearly 10.000 holes were analyzed, what is emphasizing. Due to the wide range of parameters tested during the EDM process, there were holes in the test campaign for which the breakout was not detected. This was largely due to the unstable EDM process. Such holes were removed from this analysis to avoid any distortion in the results.

The test campaign was conducted on a custom EDM machine for fast hole drilling (FHD). This EDM machine was adapted to automatically apply a sodium polyacrylate solution to enable ECDM drilling. The machine is equipped with a transistor-controlled generator controlled via \*.nc code. This machine is equipped with a breakout detection system. The machine monitors several conditions to determine whether a breakout has occurred. The primary condition is the Z-axis speed. During drilling, the electrode moves down at a constant feed rate. When a breakout occurs, the Z-axis slows down, primarily due to a loss of water pressure. The machine, using an algorithm, senses this slowdown and activates the breakout detection. During the process, the working electrode moved toward the workpiece at a feed rate primarily controlled by

the GAP voltage. This ensured a constant gap between the electrode and the workpiece. Flushing fluid, which flushed out vaporized material residue, was fed through the electrode channel using a constant fluid pressure. Additionally, the tool electrode has a constant rotary motion, which machining process makes easier and helps in flushing the machining area. Figure 1 shows a diagram of the test stand where ECDM machining was performed.

The following electrical parameter setting levels were used to perform the drilling tests:

- the pulse on time ( $T_{on}$ ): 10 – 20 – 40 – 70  $[\mu\text{s}]$ ,
- duty cycle (DC): 30 – 50 – 70 [%], calculated according to the formula Equation 1:

$$DC = \left( \frac{T_{on}}{T_{on} + T_{off}} \right) \cdot 100 [\%] \quad (1)$$

where:  $T_{on}$  – the pulse on time  $[\mu\text{s}]$ ,  $T_{off}$  – the pulse off time  $[\mu\text{s}]$ , capacitance (CAP): 200 – 950 – 1900 – 2850 – 4000 nF, voltage (GAP): 20 – 60 – 100 – 140 V, current amplitude ( $I_p$ ): 10 – 20 – 30 – 40 A.

The parameter range for testing with a 0.3 mm diameter electrode was selected based on experience with the machine used for EDM drilling tests. Care was taken to maintain a range of parameters that allowed for the EDM drilling process. Different levels were applied to individual input parameters, reflecting the range of individual parameters, using the principle that the larger the range, the more levels, and the ability to select the next parameter setting, as the machine adopts each setting in increments. An additional reason for operating within these ranges was safety considerations. Exceeding these settings could result in burnout of transistors or resistors in the power board.

Additionally, the influence of parameters on the outcome factors was analyzed, such as:

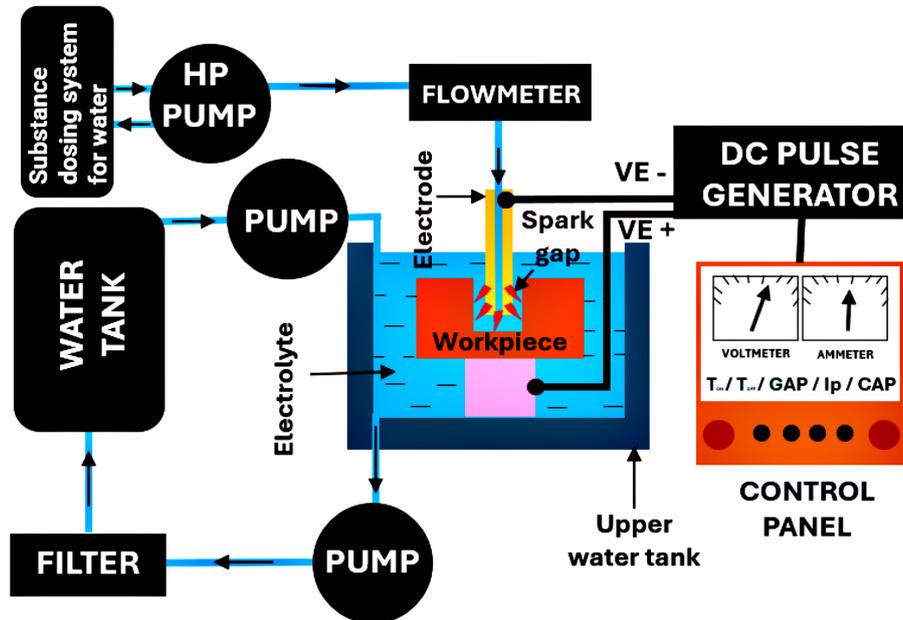
- feed rate (Fr): 76 – 102 – 128 – 152 mm/min,
- electrode length (EL) [mm],
- flushing medium flow rate (Flow) [g/min].

**Table 1.** Selected thermophysical properties of the superstop Inconel 718

Property [unit]	Workpiece material	Electrode material
	Inconel 718 [20,21]	Brass [22,23]
Density $[\text{g}/\text{cm}^3]$	8.19	8.55
Melting point [K]	1.533–1.609	1.263
Thermal conductivity $[\text{W}/(\text{m}\cdot\text{K})]$	11.4	159
Specific heat capacity $[\text{J}/\text{kg}\cdot\text{K}]$	435	385

**Table 2.** Chemical composition of Inconel 718

Element	Al	Co	Cr	Cu	Fe	Mo	Nb	Ni	Si	Ti	W
Value [%]	0.57	0.1	18.4	0.08	16.81	3.16	5.37	53.63	0.34	0.96	0.06



**Figure 1.** Scheme of the ECDM experimental test stand

The constant parameters and assumptions adopted were:

- liquid temperature: 21 °C,
- pressure of the supplied medium 11 MPa,
- water conductivity in the main tank: 10 μS/cm,
- electrode rotational speed: 750 rpm.
- The following outcome factors were analyzed in this study:
- process stability determined by the burning curve evaluation parameter (BCE):

To analyze the impact of electrical parameters and feed rate on the stability of the ECDM process, the BCE parameter was used. This parameter is determined by a custom-developed algorithm that captures electrode displacement over time, identifies burncurves, scales them, and normalizes them to just over 100 points via linear interpolation. The optimization model uses a binary classification of drilling (“good/bad”) as a penalty function. Input to this classifier is based on observations of anomalies and assessments of spindle position over time. These assessments were initially entered by the technologist to create training data for the ML model. The model is based on the DNN LSTM (Long-Short-Memory) time series classifier (Pytorch). To date, the tool

has been trained on approximately 8.000 runs, all performed using a 0.3 mm Inconel 718 electrode. A specially developed Machine Learning module, based on a previously trained data sample, assigns a rating parameter ranging from 1 for the most unstable process to 5 for the most stable EDM drilling process. Based on the burning curve evaluation parameter, it is possible to determine metrics for stable parameter sets:

- process efficiency – material removal rate (MRR), which was calculated from the equation Equation 2:

$$MRR = \frac{HD}{TB} [\text{mm/s}] \quad (2)$$

where: *HD* – hole depth [mm], *TB* – time to breakout [s],

- linear tool wear (LTW), which determines the amount of electrode used when drilling to a depth of 1 mm and is calculated on the basis of the formula Equation 3:

$$LTW = \frac{REF \cdot EU}{WT} [\text{mm}] \quad (3)$$

where: *REF* – reference value equal to 1 mm, *WT* – workpiece thickness [mm],

$EU$  – electrode used was calculated based on the formula Equation 4, for illustration, formula 4 is explained for the example hole A (Figure 2):

$$EU = Z_{point A} - Z_{point B}, [mm] \quad (4)$$

where:  $Z_{point A}$  – Z axis coordinate for hole A,  $Z_{point B}$  – Z axis coordinate of hole B readied before ECDM drilling.

- micro-hole geometry – radial overcut (ROC).  
ROC is the gap distance between the electrode and the workpiece (inter-electrode gap). The hole diameter measurements were used to calculate the radial overcut parameter according to Formula 5:

$$ROC = \frac{(IHD-ED)}{2} [mm] \quad (5)$$

where:  $IHD$  – inlet hole diameter [mm],  
 $ED$  – nominal electrode diameter [mm],

- conicity.  
The conicity measurement was based on data from hole diameters measured with a 5-axis Alicona microscope. This parameter indicates the degree of hole deformation in terms of the diameters at the electrode’s entry and exit from the material. The analyzed holes have the same distance after breakout. The formula Equation 6 was used to determine the conicity:

$$Conicity = \text{atan} \left( \frac{\frac{IHD-OHD}{2}}{WT} \right), [^\circ] \quad (6)$$

where:  $IHD$  – inlet hole diameter [mm],  $OHD$  – outlet hole diameter [mm],  $WT$  – workpiece thickness [mm].

The hole geometry was scanned and measured using an Alicona C200 optical microscope (Alicona Imaging GmbH, Raaba/Graz, Austria). A special lens with an extended focal length and high resolution was used for scanning. Figure 3 shows an example of a hole measurement.

The measuring a hole diameter along its depth was considered indirectly through the conicity measurement. In this work, we analyze the conicity parameter, which contains information about the inlet and outlet diameters of the hole. This parameter provides information about the shape of the hole at its beginning and end, and indirectly, throughout its entire depth. In the presented results, the difference between the entry and exit diameters was in average 0.004 mm, with a tendency to increasing the hole as the electrode exits the material. This means that the hole at the electrode exits the material has a larger diameter than at the entrance. This indicated that the diameter varied little along the hole’s depth.

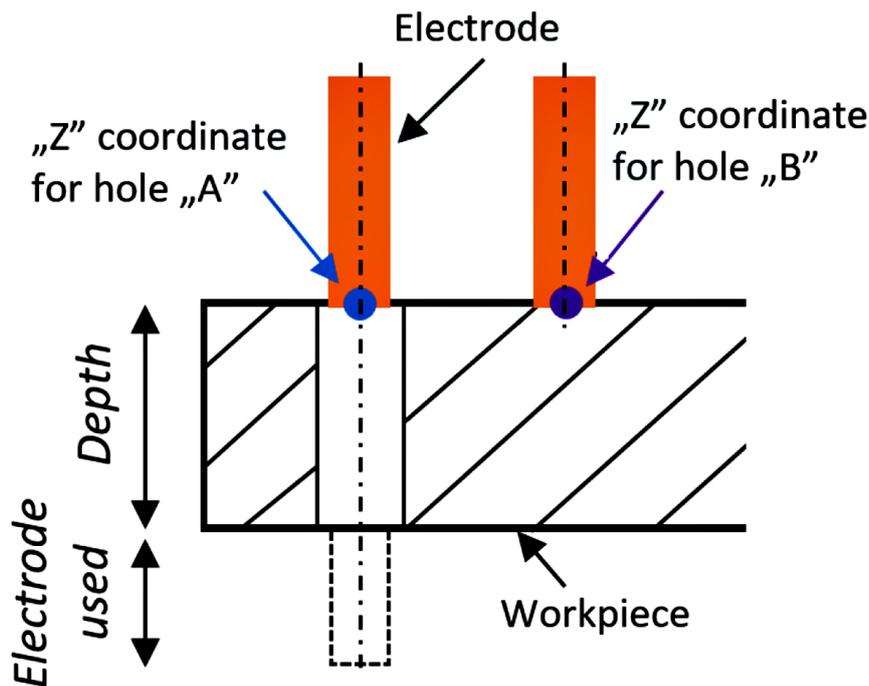


Figure 2. Schematic diagram of determining electrode used

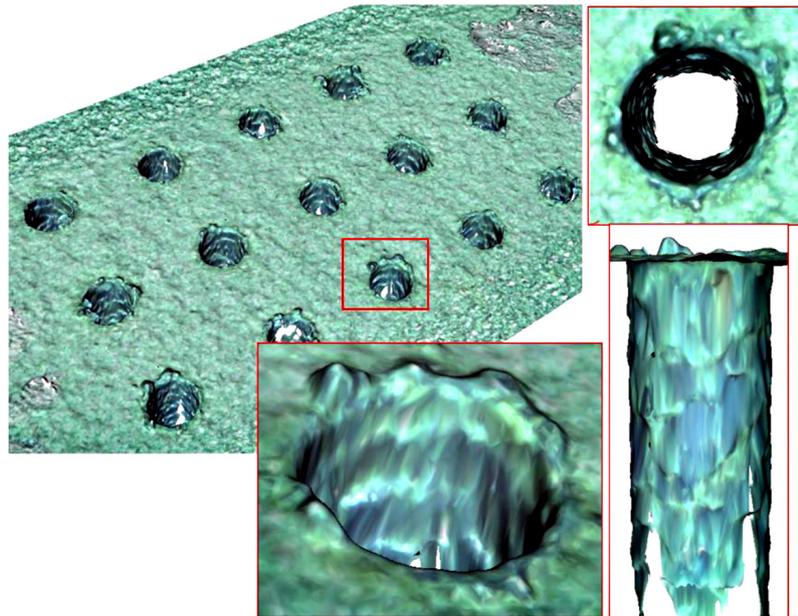


Figure 3. Example of micro-hole measurement using the Alicona C200 optical microscope

As part of the work, the following analysis was carried out:

- the influence of electrical parameters, feed rate, and fluid flow on the stability and efficiency of the machining process. For this analysis, the conductivity of the electrolyte fluid flowing through the electrode channel was assumed to be 200  $\mu\text{S}/\text{cm}$  to avoid distortion of the results due to the conductivity of the electrolyte fluid,
- the effect of electrolyte conductivity on machining stability and efficiency. For this analysis, the effect of the conductivity of the electrolyte flowing through the electrode channel was assumed, with the following values analyzed: 10, 200, 400, and 900  $\mu\text{S}/\text{cm}$ . The same set of parameters was adopted for each fluid conductivity used. This approach enabled a better analysis of the effect of fluid conductivity on the process.

## RESULTS

Minitab Statistical Software 22 was used to prepare parameter sets for test. The tested parameters were combined and shuffled according to the full factorial design of experiments (DoE). This resulted in 3840 parameter sets, which were repeated four times. This eliminated the influence of electrode length on process performance and stability at this stage of the analysis.

In Minitab, CART Regression was used to create decision trees for continuous response variables such as burning curve evaluation (BCE), material removal rate (MRR), linear tool wear (LTW), radial overcut (ROC), and conicity. The continuous predictor variables were: pulse-on time ( $T_{on}$ ), duty cycle (DC), feed rate (Fr), electrode length (EL), flushing medium flow (Flow), pulse-off time ( $T_{off}$ ), current (IP), electrical voltage (GAP), and electrical capacitance (CAP). CART Regression illustrates important patterns and relationships between continuous responses (outcome factors) and important predictors within the data, without the use of parametric methods.

Based on the experimental data, approximating functions were generated using Minitab. The statistical significance of the obtained function coefficients was analyzed based on the p-value. All function coefficients were found to be significant with a p-value less than 0.05. Below are the obtained approximating functions for the individual outcome indicators:

- burning curve evaluation (BCE) (Equation 7):

$$\begin{aligned}
 BCE = & 2.249 - 0.425 \cdot Flow - 0.01779 \cdot \\
 & \cdot EL - 0.014063 \cdot Fr + 0.06508 \cdot Ton + \\
 & + 0.4621 \cdot Ip + 0.001693 \cdot CAP + 0.05477 \cdot \\
 & \cdot GAP + 7.802 \cdot DC - 0.001326 \cdot Ton^2 - 0.008271 \cdot \\
 & \cdot Ip^2 - 0.000468 \cdot GAP^2 - 4.708 \cdot DC^2 + 0.001601 \cdot \\
 & \cdot Flow \cdot EL - 0.000211 \cdot EL \cdot IP - 0.3498 \cdot Ip \cdot DC
 \end{aligned} \quad (7)$$

- material removal rate (MRR) (Equation 8):

$$\begin{aligned}
 MRR = & -0.2616 - 0.000356 \cdot EL - 0.001828 \cdot Fr + 0.006459 \cdot Ton + 0.04849 \cdot Ip + \\
 & + 0.000174 \cdot CAP + 0.008483 \cdot GAP + 0.3978 \cdot DC - 0.000041 \cdot Fr^2 - 0.000179 \cdot Ton^2 - \\
 & - 0.001176 \cdot Ip^2 - 0.00012 \cdot GAP^2 - 0.4562 \cdot DC^2 + 0.000382 \cdot Fr \cdot Ip + 0.006869 \cdot Fr \cdot DC - 0.00016 \cdot Ton \cdot Ip - 0.000068 \cdot Ton \cdot GAP + \\
 & + 0.00594 \cdot Ton \cdot DC - 0.000217 \cdot Ip \cdot GAP - 0.01371 \cdot Ip \cdot DC - 0.000107 \cdot CAP \cdot DC + 0.003966 \cdot GAP \cdot DC
 \end{aligned} \tag{8}$$

- linear tool wear (LTW) (Equation 9):

$$\begin{aligned}
 TW = & 0.2272 - 0.000471 \cdot EL + 0.000761 \cdot Fr + 0.005084 \cdot Ton + 0.02509 \cdot Ip + 0.000273 \cdot CAP + 0.00582 \cdot GAP + 0.0087 \cdot DC - 0.000113 \cdot DC
 \end{aligned} \tag{9}$$

- radial overcut (ROC) (Equation 10):

$$\begin{aligned}
 ROC = & 0.01227 + 0.000018 \cdot CAP + 0.000103 \cdot Ip + 0.000151 \cdot Ton + 0.000256 \cdot GAP + 0.00139 \cdot Flow - 0.000119 \cdot Fr - \\
 & - 0.02438 \cdot DC + 0.000025 \cdot Ip \cdot Ton - 0.00001 \cdot Ip \cdot GAP + 0.001457 \cdot Ip \cdot DC - 0.000238 \cdot GAP \cdot DC
 \end{aligned} \tag{10}$$

- conicity (Equation 11):

$$\begin{aligned}
 Conicity = & 0.13937 - 0.00007 \cdot CAP - 0.006024 \cdot Ip - 0.001194 \cdot Ton
 \end{aligned} \tag{11}$$

Table 3 summarizes the values of the obtained R-squared (R-sq) and adjusted R-squared (Adj R-sq). The R-sq and Adj R-sq values were used for statistical verification of the obtained approximating functions. The results of this statistical analysis showed that the R-sq and Adj R-sq values were above 50%, except for the conicity parameter. It was assumed that all the determined functions provide an acceptable fit of the actual parameter values to those calculated from the functions. In case of conicity, R-sq, and Adj R-sq, the model’s fit to the measurements is poor. Therefore, it can be concluded that conicity cannot be controlled through electrical parameters. During the ECDM drilling process of a single hole, the set values of the electrical parameters were constant. However, the influence of the electrical parameters on the resulting factors was analyzed in this work, and these parameters are also included in the approximation function. However, the results showed slight differences between the diameter values for the

given set electrical parameters. Furthermore, the R<sup>2</sup> parameter (approx. 27%) also indicated that the fit of the function model to the taper results was poor. Based on this information, it can be concluded that the taper of micro-holes is controlled by factors other than electrical parameters. Furthermore, it is worth noting that the conicity value for the 0.3 mm electrode is very small. This is indicated by small differences in the values between the diameters at the inlet and outlet of the holes. However, for larger electrode diameters (greater than 1 mm), where we are dealing with larger differences in the diameters of the holes at the inlet and outlet of the electrode, relationships most likely exist describing the influence of electrical parameters on conicity. So far, a relationship between the electrode distance after breakout detection and the outlet diameter has been observed. Therefore, this parameter, which is also adjustable but not treated as an electrical parameter, has a significant impact on conicity, and it is not analyzed in this article.

## DISCUSSION

Analysis of the influence of electrical parameters on the stability, efficiency of ECDM drilling and hole geometry

In this study, the influence of individual parameters on the outcome factors was first examined. This influence was verified based on the relative variable importance analysis. It was assumed that parameters with the greatest influence on the outcome factor had a relative variable importance parameter value above 50%. The analysis demonstrated a sufficient level of model validity. It is important to properly classify the importance of input parameters, which were achieved using CART Regression analysis.

In the ECDM process of micro-hole drilling, the stability of the drilling process throughout the entire hole depth is crucial. In this study, we analyzed drilling stability using the burning curve evaluation (BCE) parameter. Therefore, based on nearly 10.000 drilled holes, it turns out that the

**Table 3.** Model summary for R-sq i Adj R-sq

Parameter	BCE	MRR	LTW	ROC	Conicity
R-sq [%]	51.94	81.57	84.79	85.48%	27.04%
Adj R-sq [%]	51.82	81.50	84.75	85.30%	26.96%

following drilling parameters had the most significant impact on the stability of ECDM drilling (Figure 4): Flow, EL, CAP, GAP, and Ip.

For the stability of micro-hole drilling, the flow rate of liquid flowing through the electrode channel (Flow) is a crucial [24]. The Flow parameter ensures effective flushing of the machining area. This allows for the effective removal of erosion products, air bubbles, and other contaminants from the inter-electrode gap. During ECDM drilling, due to the size of the inter-electrode gap and the size of the hole, it is often difficult to effectively flush debris or heat accumulation from the inter-electrode gap. Accumulation of debris or heat in the inter-electrode gap can lead to the appearance of short circuits. Short circuits cause instability in this process. This allows for the effective removal of erosion products, air bubbles, and other contaminants from the inter-electrode gap. However, changing the electrode length affects the fluid flow rate through the electrode channel, which is why this parameter was also

found to be one of the most influential parameters on BCE. Generally, these Flow and EL parameters are interdependent, as it can be seen that the shorter the electrode and the more flushing medium flows through the electrode, the more stable the process. This information has a significant impact on experiment planning, as a given set of parameters can behave in two ways in terms of stability. Therefore, determining process trends and designing tests is crucial to preparing data that will give reliable results. Therefore, it is crucial to ensure that a given set of parameters is performed with different electrode lengths and with a large number of repetitions.

However, analysis of the Main Effects Plot for BCE revealed multiple inflection points for the influence of parameters on stability (Figure 5, along with a Table 4 showing the standard deviation values). The BCE parameter begins to decrease for the following dependencies: for CAP above 1900 nF BCE, for GAP above 140 V BCE, for IP above 30 A BCE, and for Ton above 40  $\mu$ s.

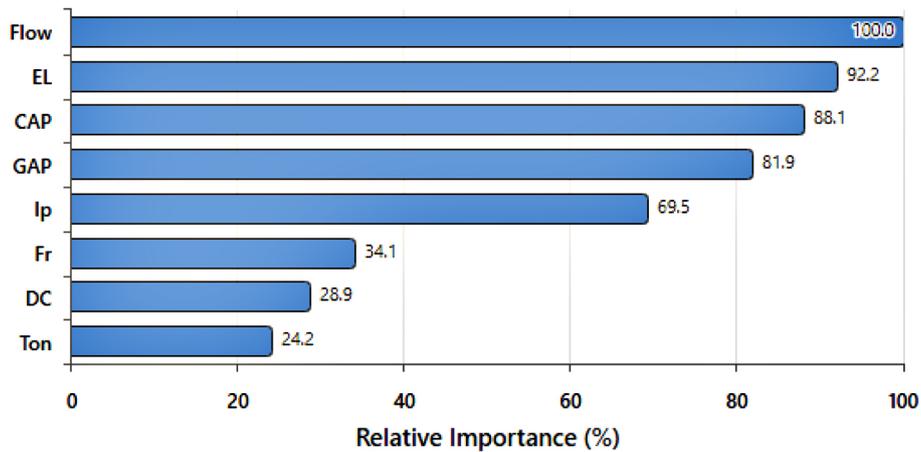


Figure 4. Relative variable importance for the burning curve evaluation

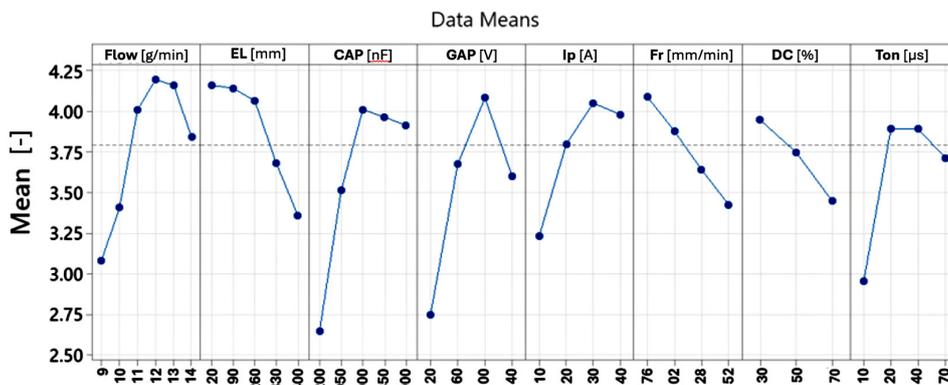


Figure 5. The results of main effects plot for the burning curve evaluation (BCE)

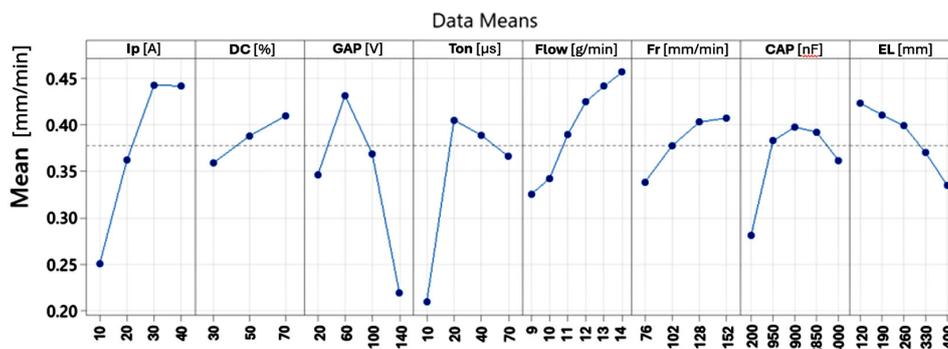
**Table 4.** Standard deviation values (Stdev) for process parameter values in the BCE analysis

BCE [-]															
Flow [g/min]	StDev [g/min]	EL [mm]	Stdev [mm]	CAP [nF]	Stdev [nF]	GAP [V]	Stdev [V]	Ip [A]	Stdev [A]	Fr $\left[\frac{mm}{min}\right]$	Stdev $\left[\frac{mm}{min}\right]$	DC [-]	Stdev [-]	Ton [μs]	Stdev [μs]
9	0.764	120	1.027	200	0.954	20	0.879	10	0.878	38	1.039	30	0.989	10	0.907
10	0.962	190	0.991	950	1.029	60	0.972	20	1.022	51	1.011	50	1.036	20	1.008
11	0.998	260	0.994	1900	0.954	100	0.953	30	0.990	64	1.011	70	1.062	40	1.049
12	0.976	330	0.995	2850	0.946	140	1.083	40	1.051	76	0.933			70	0.989
13	0.936	400	0.937	4000	0.974										
14	1.068														

An interesting result is the decrease in BCE stability for Flow > 12 g/mm. While the MRR (Figure 6, along with a Table 5 showing the standard deviation values) and LTW (Figure 7, along with a Table 6 showing the standard deviation values) parameters continue to increase with increasing Flow. Typically, increasing Flow improves conditions in the inter-electrode gap region. This may be the result of material removal primarily by electrical discharges.

In addition to identifying the parameters with the greatest impact on drilling stability, it is worth noting the specific impact of input parameters on ECDM drilling stability. Generally, to achieve high drilling stability (burning curve evaluation) of ECDM, high parameters of electrical capacitance (CAP), electrical voltage (GAP), and current (IP) should be used. These electrical parameters were found to primarily influence the ECDM drilling process. Parameters for which low settings should be used include duty cycle (DC) and feed rate (Fr). We also observe that high values of the CAP, GAP, and Ip parameters improve stability up to a certain value, after which the burning curve evaluation begins to decrease. This is due to the inherent ambiguity of the ECDM process.

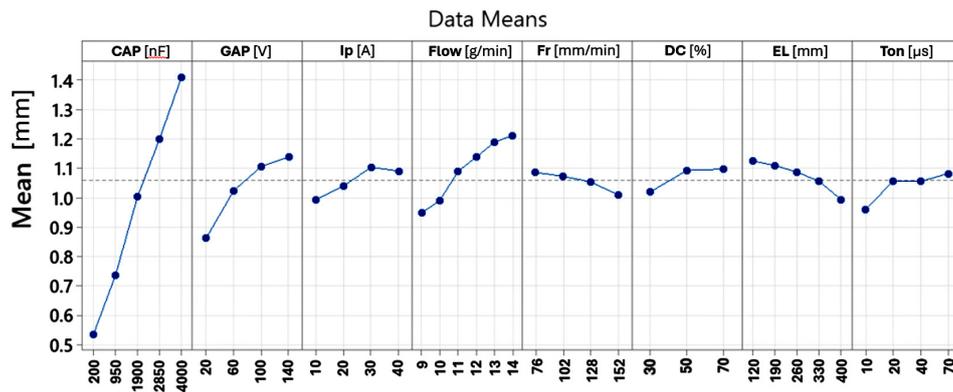
Excessively high values of electrical parameters can cause short circuits. Comparing the burning curve evaluation results with the drilling efficiency – material removal rate (MRR) we observe similar trends. For electrical parameters, their inflection points are the same or similar for BCE and MRR (CAP is 1900 nF, Ip is 30 A, GAP is 100 V for BCE and 60 V for MRR, Ton is 20–10 μs for BCE and 20 μs for MRR). Values of these electrical parameters above the inflection points result in a reduction in BCE and a deterioration in MRR. This analysis shows that there are parameter values that ensure a stable process with acceptable performance. It is worth emphasizing that for Ip and GAP, the highest parameters used were not necessarily optimal. This shows that up to certain high values of electrical parameters, the drilling MRR increases. Characteristic breaks are visible in the Main Effects of BCE and MRR, indicating that to achieve the most stable process, a selected parameter value should be used, and this value should not be extreme. Furthermore, it is worth noting that the analysis of the results revealed values of the extreme parameters that are technologically too low or too high to achieve process stability and acceptable performance. For



**Figure 6.** The results of main effects plot for the material removal rate (MRR).

**Table 5.** Standard deviation values (Stdev) for process parameter values in the MRR analysis

MRR [mm/min]															
Ip [A]	StDev [A]	DC [%]	Stdev [%]	GAP [V]	Stdev [V]	Ton [us]	Stdev [us]	Flow [g/min]	Stdev [g/min]	Fr [mm/min]	Stdev [mm/min]	CAP [nF]	Stdev [nF]	EL [mm]	Stdev [mm]
10	0.102	30	0.128	20	0.169	10	0.121	9	0.122	38	0.087	200	0.133	120	0.148
20	0.113	50	0.143	60	0.140	20	0.140	10	0.127	51	0.124	950	0.141	190	0.140
30	0.120	70	0.141	100	0.110	40	0.126	11	0.137	64	0.157	1900	0.127	260	0.139
40	0.126			140	0.094	70	0.129	12	0.136	76	0.169	2850	0.137	330	0.131
								13	0.143			4000	0.133	400	0.121
								14	0.153						



**Figure 7.** The main effects plot for the linear tool wear (LTW)

**Table 6.** Standard deviation values (Stdev) for process parameter values in the LTW analysis

LTW [mm]															
CAP [nF]	StDev [nF]	GAP [V]	Stdev [V]	Ip [A]	Stdev [A]	Flow [g/min]	Stdev [g/min]	Fr [mm/min]	Stdev [mm/min]	DC [%]	Stdev [%]	EL [mm]	Stdev [mm]	Ton [us]	Stdev [us]
200	0.147	20	0.315	10	0.341	9	0.381	38	0.341	30	0.298	120	0.328	10	0.391
950	0.106	60	0.298	20	0.326	10	0.310	51	0.348	50	0.343	190	0.338	20	0.318
1900	0.137	100	0.323	30	0.319	11	0.338	64	0.317	70	0.391	260	0.330	40	0.330
2850	0.192	140	0.456	40	0.349	12	0.327	76	0.315			330	0.334	70	0.339
4000	0.324					13	0.276					400	0.324		
						14	0.569								

example, for Ton, 10  $\mu$ s is too low, and for GAP, 140 V is too high. Excessively high GAP values can lead to short circuits, which reduce the efficiency of the process and increase electrode wear. For GAP values of 100 V or 140 V, an increase in LTW is observed (Figure 7). The analysis of the results also showed how the ranges of drilling parameter values should be narrowed in further experimental tests.

By reducing the Ip current setting from 30 A to 10 A, a 44.4% reduction in MRR is observed, while in the case of LTW, this change reduces electrode wear by 9%. It turns out that, on the one

hand, trying to improve MRR by increasing the Ip current, which is beneficial, simultaneously increases electrode wear, which is disadvantageous. However, these results show that material is also removed by electrical discharges during the EDM process (because the electrode wears, and the MRR increases). In the analysis of the GAP Voltage on MRR, it can be concluded that the lowest setting in the test (20 V) is too low and makes the ECDM process significantly unstable due to the large number of short circuits, as indicated by the characteristic break in the Main Effect Plot for MRR. Further, it was observed that in the stable

GAP Voltage parameter range, as the setting increases from 60 to 140V, the MRR decreases by 49%, which is unfavorable, while the LTW decreases by 24%, which is definitely favorable. A reduction in MRR in this case may also indicate poor material removal through electrochemical dissolution. In summary, to set up a batch process, depending on the electrode changeover time, optimal parameters should be calculated. This allows for a relatively short and efficient process time, while also ensuring low electrode wear and, consequently, less frequent electrode changeovers.

When analyzing the effect of parameters on the MRR and LTW of ECDM (Figure 8, Figure 9), the electrical parameters, i.e.,  $I_p$ , DC, GAP, and CAP, have the greatest impact. This is an accurate result, as the ECDM process involves material removal through electrical discharges. In the case of EDM, it is the electrical parameters that most significantly influence the material removal rate and electrode used. In the case of electrochemistry in ECDM, the  $I_p$  and GAP parameters have the greatest impact on the MRR, which could also indicate the significant impact of these parameters on the process. It's worth emphasizing that the change in the Flow parameter is more a factor resulting from the shortening of the tool electrode along its length. As the tool electrode shortens along its length, the flow increases, consistent with the laws of flow through a tube.

We also examined how the analyzed electrical parameters affected the hole geometry analyzed by radial overcut (ROC) (Figure 10) and conicity (Figure 11). Analysis of the relative variable importance for ROC and conicity showed that

the capacitance CAP parameter had the greatest impact on the hole geometry and next important parameter is  $I_p$ .

When analyzing the electrical parameters on ROC (Figure 12 along with a Table 7 showing the standard deviation values), it turns out that the parameters CAP,  $I_p$ , Ton, and GAP have the greatest impact, respectively. However the electrical parameters CAP and  $I_p$  have the greatest impact on ROC (Figure 10) and conicity (Figure 11). Figure 12 shows that from CAP above 950 nF, it increases strongly ROC, and for 4000 nF ROC is about 0.06 mm. These parameters significantly determine the heat generated in the inter-electrode gap and the amount of energy required to remove material via electrical discharge. As capacitance increases, more charge accumulates in the capacitor. This means that more energy impacts the workpiece during discharge. As a result, more material is removed with each discharge, which causes a larger ROC. High capacitance can lead to the formation of larger discharge craters on the workpiece. These craters can cause dimensional inaccuracies, especially when creating very small and precise components. In the analyzed tests, we have micro-holes, so a significant effect of capacitance on hole geometry is normal. Furthermore, high energy release can also cause thermal stresses in the workpiece, which can also lead to deformation. However, lower capacitance allows for more precise control of the machining process. Smaller discharges create smaller craters, which makes better dimensional control. Reduced thermal effects also help minimize distortion, resulting in a more accurate final product. Changing the hole diameter solely using the CAP

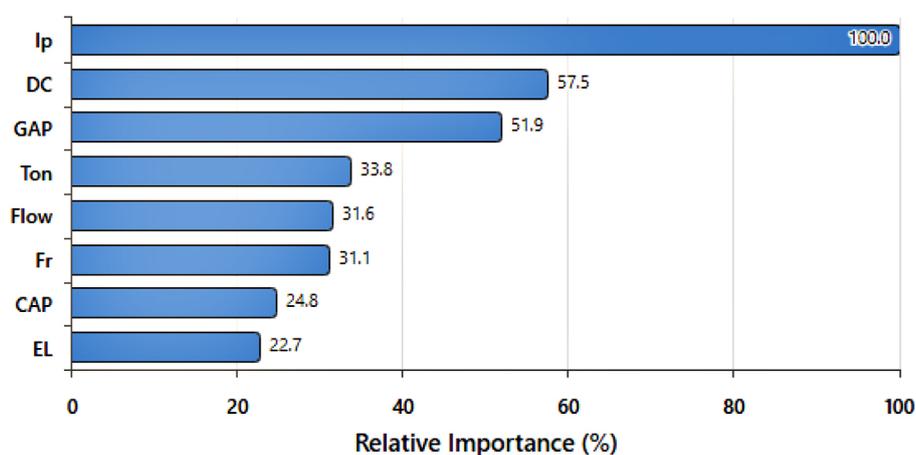


Figure 8. Relative variable importance for MRR

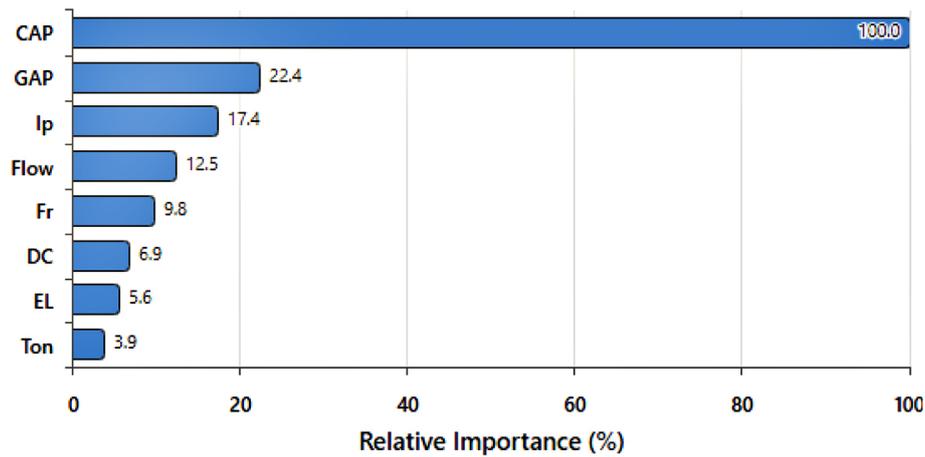


Figure 9. Relative variable importance for LTW

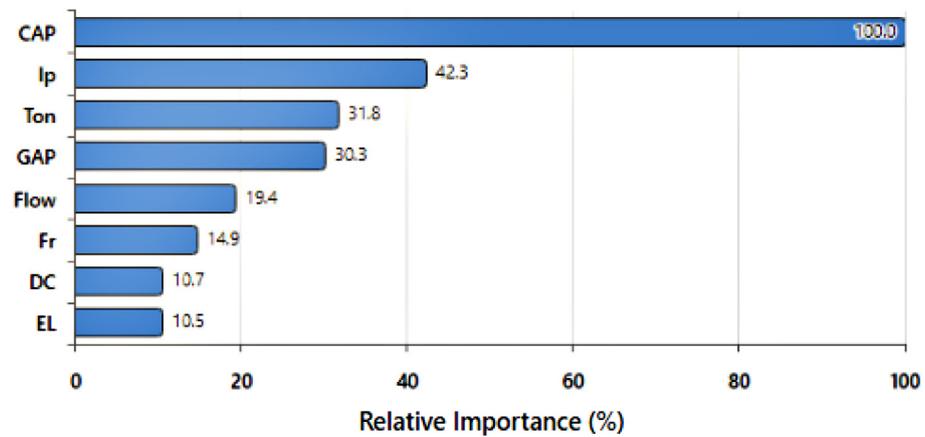


Figure 10. Relative variable importance for ROC

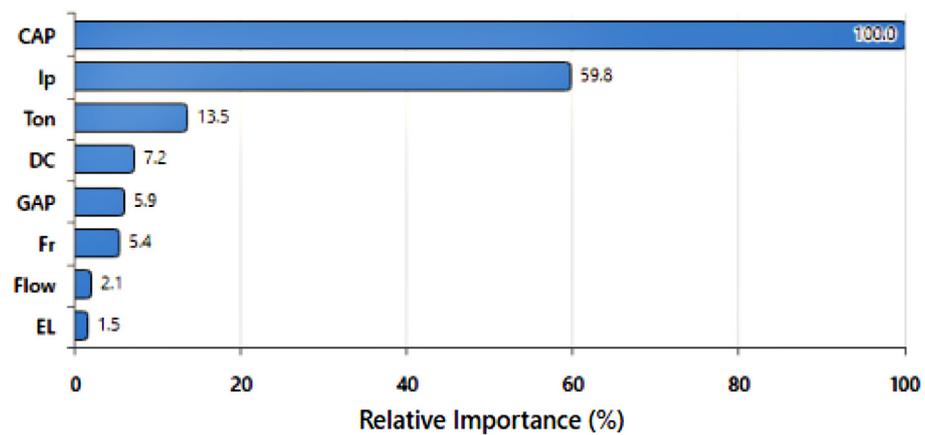


Figure 11. Relative variable importance for conicity

parameter, looking at both extreme settings (200–4000 nF) (Figure 12), this allows for a change in the inter-electrode gap within a range of 0.017 mm. However, considering all possible adjustable parameters, the inter-electrode gap can vary within a range of 0.035 mm (+/- 0.0175 mm),

resulting in holes with diameters ranging from 0.365 mm to 0.435 mm.

The issue of selecting parameters for a stable ECDCM drilling process goes beyond the simple conclusions above, but can provide a basis for efficient process improvement when detecting

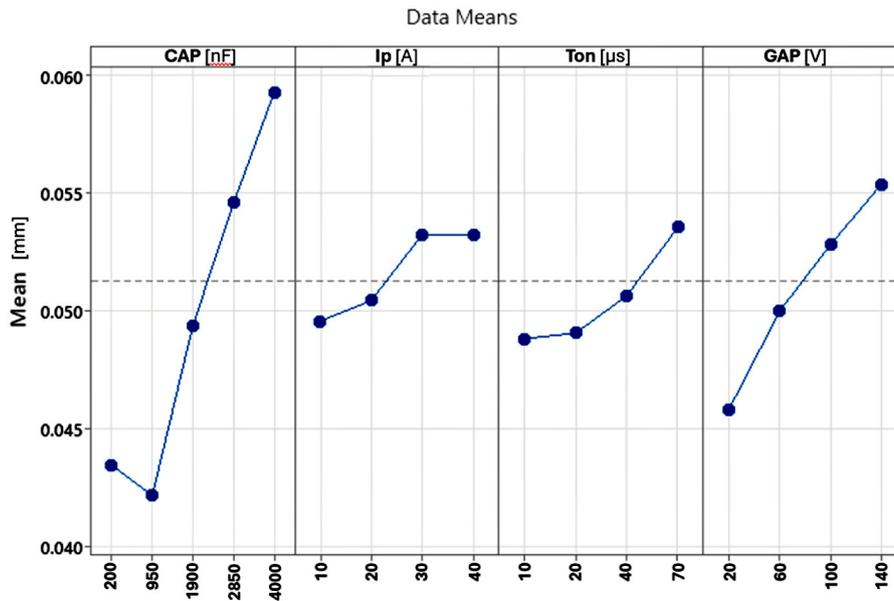


Figure 12. The main effects plot for the radial overcut (ROC)

Table 7. Standard deviation values (Stdev) for process parameter values in the ROC analysis

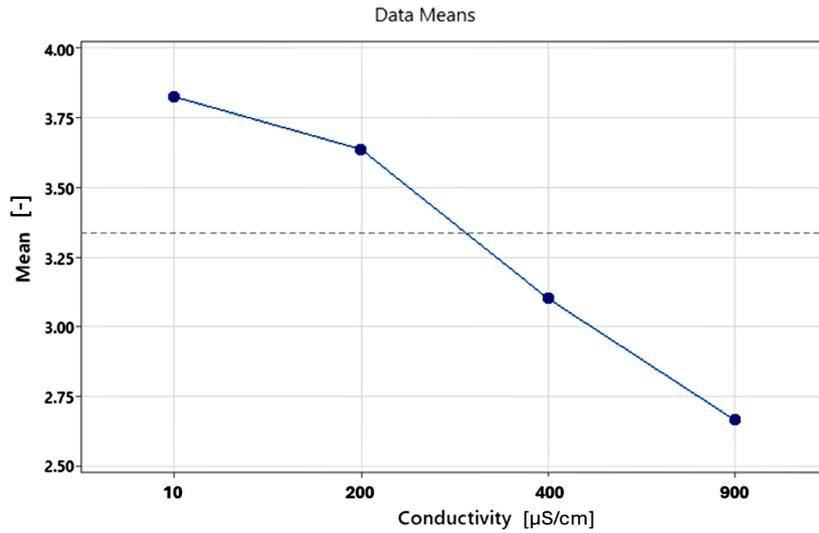
ROC [mm]							
CAP [nF]	StDev [nF]	GAP [V]	Stdev [V]	Ip [A]	Stdev [A]	Ton [us]]	Stdev [us]
200	0.00959	20	0.0086	10	0.00927	10	0.0111
950	0.00715	60	0.0081	20	0.00814	20	0.0091
1900	0.00619	100	0.0088	30	0.00877	40	0.0089
2850	0.00589	140	0.0097	40	0.00899	70	0.0078
4000	0.00540					10	

a significant number of electrical shorts. While the simplest conclusions can be drawn from the above, the matter becomes more complex when it comes to selecting the optimal set of parameters for ECDM drilling stability and efficiency. Therefore, it is necessary to calculate which is more favorable from a production perspective by calculating the optimal parameters, resulting in relatively low LTW and high MRR (depending on electrode costs, changeover time, machine-hour cost, etc.).

**Analysis of the effect of conductivity on the stability and efficiency of the ECDM process and the geometry of micro-holes**

To investigate the effect of electrolyte conductivity on the stability, efficiency, and geometry of holes, a single set of parameters was selected, which was used to drill nearly 3500 holes. Because several dozen electrodes were used in the test, the effect of electrode length was omitted.

First, we examined how changing the conductivity of the working fluid affected the stability of EDCM drilling (BCE parameter analysis). It turned out that increasing the conductivity (from 10 μS/cm to 400 μS/cm and further to 900 μS/cm) of sodium polyacrylate reduced the process stability (Figure 13). The BCE reduction with a change in the conductivity of the working fluid from 10 μS/cm to 200 μS/cm was small, approximately 5%. However, increasing the conductivity of the fluid from 200 μS/cm to 900 μS/cm reduced the BCE parameter by approximately 27%. A significant reduction in the stability of ECDM drilling with an increase in the conductivity of the working fluid to 400 μS/cm or 900 μS/cm may indicate that these conductivities are too high for an effective drilling process. The ECDM process, according to test results from other researchers, works effectively when using low conductivity working fluids. In this process, conditions for electrical discharges and electrochemical dissolution must be



Conductivity [μS/cm]	10	200	400	900
Mean	3.828	3.639	3.103	2.667
Standard deviation	1.2408	0.8374	0.8673	0.8549

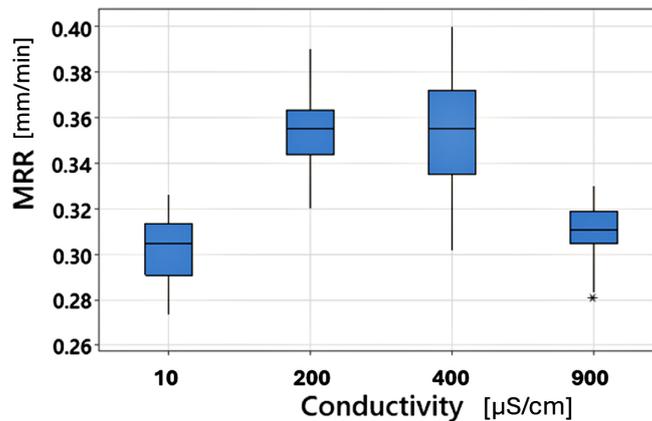
Figure 13. Main effects plot for BCE

achieved in a single pulse. When the conductivity of the working fluid is too high, short circuits often form in the interelectrode space, which leads to process instability and a decrease in the material removal rate.

Based on BCE which indicates how the gap between the electrodes changed during the process, it can be concluded that as conductivity increases above 400 μS/cm, the efficiency of the EDM process decreases (Figure 14). This does not mean that higher conductivities should be

avoided, but it should be taken into account that the same sets of electrical parameters may give stable results for one conductivity setting but not for another. This means that the parameters should be selected individually for each conductivity setting. Additionally, it should be emphasized that the process was stable across the entire range of conductivities tested in the test.

Analysis of the results of the effect of electrolyte conductivity on material removal rate showed that the conductivity range of 200 μS/cm



Conductivity [μS/cm]	10	200	400	900
Mean [mm/s]	0.301	0.353	0.351	0.311
Standard deviation	0.0149	0.0148	0.0263	0.0106

Figure 14. Results of the analyzed conductivity values of sodium polyacrylate on the material removal rate (MRR)

(from 10 to 200  $\mu\text{S}/\text{cm}$ ) allowed for the highest material removal rate (Figure 14). The MRR for these electrolyte conductivities is approximately 17% higher than for the another electrolyte conductivity settings analyzed. Higher conductivity improves the material removal rate by supporting it with electrochemical dissolution. Regarding the linear tool wear analysis, significantly lower linear tool wear was observed for the higher conductivities used (200, 400, 900  $\mu\text{S}/\text{cm}$ ). This indicates the presence of material removal beyond electrical discharges, also through electrochemical dissolution. For comparison, using a conductivity of 10  $\mu\text{S}/\text{cm}$  gave similar efficiency as for a conductivity of 900  $\mu\text{S}/\text{cm}$ , but in this case the LTW was approximately 40% higher (Figure 15). This indicates the presence of a significant number of electrical discharges in a single pulse, hence the increase in LTW for the applied liquid conductivity of 10  $\mu\text{S}/\text{cm}$  – the EDM process is mainly involved here. Similar results were obtained in [19], where the MRR also increased with a certain increased value of the conductivity of the salt solution used as the working fluid.

Particular attention should be paid to LTW at different conductivity values. It turns out that changing the conductivity value from 10 to 200  $\mu\text{S}/\text{cm}$  can reduce electrode wear by 33%. It should be noted that the increase in conductivity from 10  $\mu\text{S}/\text{cm}$  to 200  $\mu\text{S}/\text{cm}$  is as much as ten-fold. When a conductivity of 10  $\mu\text{S}/\text{cm}$  was used, the main contribution to material removal was probably made by electrical discharges (the main

EDM process), which is why the electrode wore out more. Further increases in conductivity from 200  $\mu\text{S}/\text{cm}$  to 400  $\mu\text{S}/\text{cm}$  and from 400  $\mu\text{S}/\text{cm}$  to 900  $\mu\text{S}/\text{cm}$  result 6% reductions in electrode used, respectively. We can conclude that increasing the conductivity of the electrolyte fluid makes sense up to a certain value to improve the MRR and LTW for the ECDM process. As indicated by the research results in [19], very high conductivity of the salt solution is no longer suitable for material removal because it increases the likelihood of electric arc and short circuits. This results in very poor processing stability and a reduction in MRR. It's worth emphasizing that in the ECDM process, it's crucial that material is removed simultaneously by electrical discharge and electrochemical dissolution. This allows for the benefits of both processes to be utilized while minimizing their drawbacks.

In the simplest case, the efficiency of an ECDM drilling process can be determined by material removal rate. However, considering the different electrode used for different conductivities, the need for tool changes, and the tool cost, it may turn out that process efficiency is the result of many things, including the cost per machine hour of machine operation, tool change time, and electrolyte cost. In the case of relatively low electrode cost and wear (e.g., electrodes with diameters greater than 0.3 mm), it can be assumed that the contribution of electrode cost and machine hour cost will not significantly impact process efficiency.

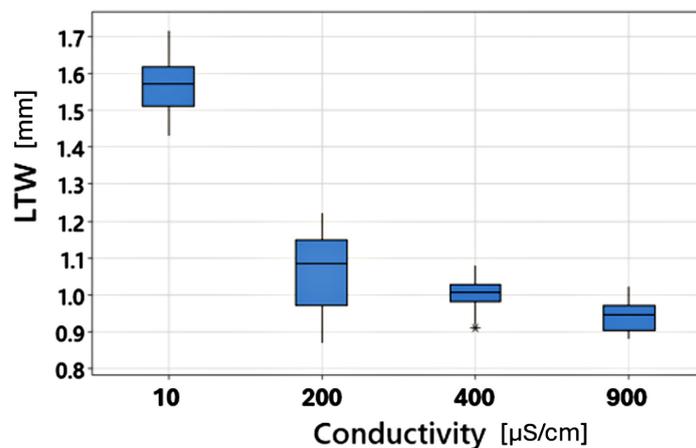


Figure 15. Results of the analyzed conductivity values of sodium polyacrylate on the linear tool wear (LTW)

The above analysis demonstrates that it's worthwhile to investigate the values to which increasing electrolyte conductivity improves machining efficiency for the adopted electrical parameters. These results also demonstrate that the ECDM process is ambiguous. Using a high-conductivity electrolyte fluid (which generates increased salt costs) may not necessarily provide the most efficient machining.

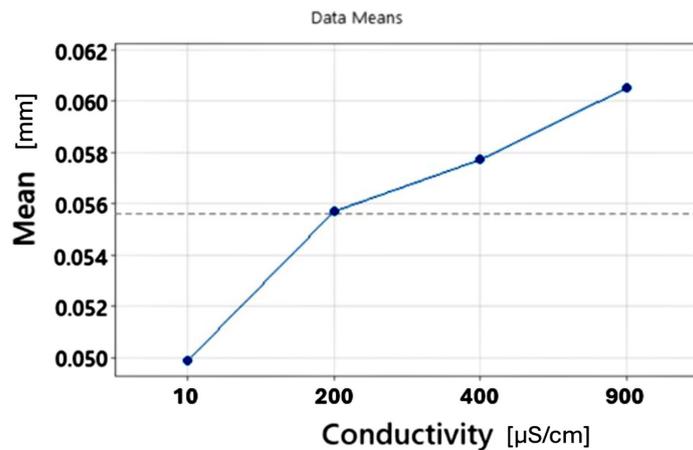
It is worth noting, however, that the paper assumes the analysis of the same sets of parameters in order to compare only the effect of conductivity on the drilling process. To increase drilling efficiency with higher electrolyte conductivities, the values of the electrical parameters and the feed rate would need to be adjusted.

Changing the conductivity level of the electrolyte flowing from the electrode for the tested conductivity values of the liquid resulted in a radial overcut (ROC) range of 0.05–0.06 mm (Figure 16). This means that the hole geometry in the tested experiments changed slightly due to changes in the liquid conductivity. From Figure 16, we observe that the ROC parameter increases for increasingly higher liquid conductivities. However, between successive higher sodium polyacrylate solution conductivity values, the ROC increase was approximately 20%. It is worth emphasizing that the ROC parameter for all applied liquid conductivities has a technologically acceptable value (the inlet diameter is approximately 0.1 mm larger than the nominal electrode diameter). For these sodium polyacrylate conductivity values, we can

conclude that the contribution of electrochemical dissolution to material removal was achieved to improve the MRR and simultaneously ensure acceptable hole geometry accuracy.

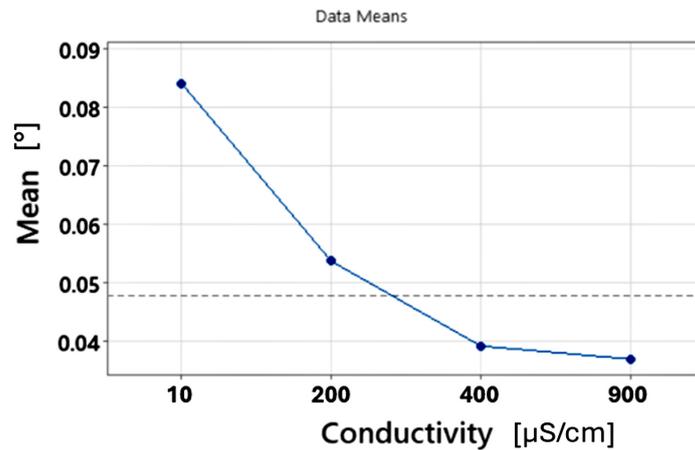
However, hole conicity analysis showed that the greatest hole conicity was achieved with a conductivity of 10  $\mu\text{S/cm}$  (Figure 17). However, for conductivities of 200  $\mu\text{S/cm}$ , 400  $\mu\text{S/cm}$ , and 900  $\mu\text{S/cm}$ , the change in hole conicity was insignificant, falling within the range of  $0.035^\circ$ – $0.055^\circ$ . This demonstrates that the fluid conductivity used during ECDM drilling affects the hole geometry and shape. For the tests performed, higher conductivities resulted in better hole geometry. However, we observed that using 200  $\mu\text{S/cm}$  and higher conductivities resulted in small improvements in hole geometry. Technologically, this is good news, as the cost of salt used in the ECDM process is high, so using lower conductivities reduced the overall process costs. This also demonstrates the ambiguous nature of the ECDM process and the challenges in determining trends in changes in process parameter values or fluid conductivity.

Analysis of the geometry of the holes made in the Inconel 718 superalloy (radial overcut and conicity parameters) showed that the ECDM test campaign for various fluid conductivities produced acceptable shape geometry. In the work [6] it was also shown that the ECDM process using a salt solution as a working fluid provides better dimensional and shape accuracy of holes than the EDM process using deionized water. For example, Figure 18 shows one of the micro-holes made.



Conductivity [ $\mu\text{S/cm}$ ]	10	200	400	900
Mean [mm]	0.050	0.0557	0.0578	0.0601
Standard deviation	0.0021	0.0029	0.0027	0.0029

Figure 16. Results of the analyzed conductivity values of sodium polyacrylate on the radial overcut (ROC)



Conductivity [ $\mu\text{S/cm}$ ]	10	200	400	900
Mean [mm]	0.084	0.054	0.039	0.037
Standard deviation	0.0484	0.04628	0.06335	0.03649

Figure 17. Results of the analyzed conductivity values of sodium polyacrylate on conicity

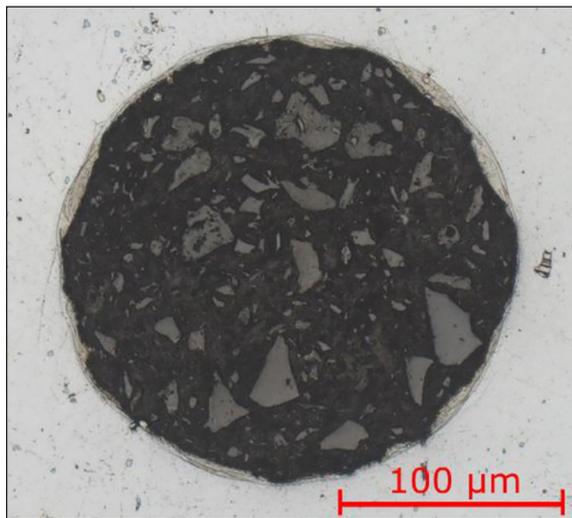


Figure 18. Photo of a micro-hole made with ECDM technology in Inconel 718 (drilling parameters: Ton – 20  $\mu\text{s}$ ; Toff – 46  $\mu\text{s}$ ; Ip – 40 A; CAP – 950 nF; Spindle speed – 750RPM; GAP – 100 V; Fr – 76 mm/min)

## CONCLUSIONS

This paper presents the results of electrochemical discharge drilling tests of micro-holes in the Inconel 718 superalloy, using sodium polyacrylate as the electrolyte fluid. Analysis of the influence of electrical parameters and the conductivity of the electrolyte allowed for the formulation of the following key conclusions:

It can be concluded that the greatest impact on this process stability is electrode length, flow, and

CAP. A short electrode, higher flow and CAP, and low FR and DC values result in higher ECDM process stability.

The Ip, DC, and GAP parameters have the greatest impact on MRR, while CAP has the greatest impact on LTW. In general, it can be concluded that the higher the Ip, DC, flow, and FR, the higher the MRR, while the higher the CAP, and the lower the GAP, Ip, flow, DC, and Ton, the lower the LTW. For example, by reducing the Ip current setting from 30 A to 10A, a 44.4% reduction in MRR is observed, while in the case of LTW, this change reduces LTW by 9%. For example, as the setting increases from 60 to 140V, the MRR decreases by 49%, which is unfavorable, while the LTW decreases by 24%, which is definitely favorable.

The hole diameter has the greatest impact has a CAP. The higher the values of these parameters, the greater the ROC. Operating with the full CAP range, ROC control is within 0.017 mm, while using extreme values of the remaining parameters, such as high Ip, Ton, and GAP, ROC control is possible within 0.035 mm.

For a chosen set of parameters for different conductivities, the higher the conductivity, the drilling stability systematically decreases. A given set of parameters for a conductivity of 200  $\mu\text{S/cm}$  allows for the highest MRR. The MRR for these electrolyte conductivities is approximately 17% higher than for the next extreme values of electrolyte conductivity.

Changing the conductivity value from 10 to 200  $\mu\text{S}/\text{cm}$  can reduce electrode wear by 33%. Further increases in conductivity from 200  $\mu\text{S}/\text{cm}$  to 400  $\mu\text{S}/\text{cm}$  and from 400  $\mu\text{S}/\text{cm}$  to 900  $\mu\text{S}/\text{cm}$  resulted in 6% reductions in the electrode used, respectively. An increase in ROC was observed from 0.05 mm to 0.06 mm with increasing conductivity within the tested range.

The greatest hole conicity was achieved with a conductivity of 10  $\mu\text{S}/\text{cm}$ . However, the change in conicity was insignificant, ranging from 0.035°–0.055°.

However, considering the different electrode used for different conductivities, the need for tool changes, and the tool cost, it may turn out that process efficiency is the result of many things, including the cost per machine hour of machine operation, tool change time, and electrolyte cost. Technologically, this is good news, as the cost of salt used in the ECDM process is high, so using lower conductivities reduced the overall process costs.

The ECDM process for micro-hole drilling is increasingly used in the aerospace industry to produce micro-holes in turbine blades. This process could successfully replace EDM using deionized water. ECDM using salt solutions produces better micro-hole geometry and improves process efficiency compared to EDM. EDM machines could be adapted to dose salt solutions to achieve ECDM.

The current test results could be expanded in the future with metallographic studies. Analysis of the thickness of the thermally modified layer could provide valuable information about the characteristics of the drilled holes, as well as the influence of electrical parameters. Such an analysis, performed along the entire depth of the hole, could provide important information. It would be worthwhile to verify the thermally modified layer with a scanning electron microscope. Furthermore, to determine the conditions of coolant flow through the micro-holes, it would be worthwhile to analyze the surface roughness (Ra and Rz parameters) of the micro-holes along their entire depth.

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