

## INVESTIGATION OF THE EFFECT OF MACHINING PARAMETERS IN EDM MICRO-DRILLING USING DEIONIZED WATER ON DIFFICULT-TO-CUT MATERIALS

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In recent years, efforts have been made to adapt electrical discharge machining (EDM) for micro-hole production in turbine blades to safer and more environmentally friendly conditions. The use of deionized water as a working fluid in EDM represents one such solution. The study investigates the effect of EDM parameters on two difficult-to-cut materials, Inconel 718 and Ti-6Al-4V. The results are considered preliminary findings, highlighting both the advantages and limitations of the process. They indicate that electrical discharge drilling (EDD) using deionized water is a promising solution. In this process, the use of deionized water enables additional electrochemical dissolution, thereby accelerating material removal. The analysis shows that the adopted parameter values are more suitable for drilling the titanium alloy; however, the accuracy of the resulting hole geometry requires further improvement.

**Keywords:** difficult-to-cut materials, electrical discharge machining/drilling, micro-hole, deionized water

### 1. Introduction

Electro-erosion micro-hole production in difficult-to-cut materials is widely used in the aviation industry, particularly for manufacturing cooling holes in turbine blades [1]. There is still a need to improve this technology. This demand arises from the increasing use of advanced alloys and superalloys for turbine blades manufacturing, such as nickel-chromium superalloys or titanium alloys [2]-[4]. In addition, there is an growing demand for micro-holes with diameters below 0.1 mm, which additionally causes new challenges for this technology.

Electrical discharge drilling (EDD) is one of the most commonly used manufacturing technologies for producing micro-holes. This is due to the removal of material by means of phenomena accompanying electrical discharges [5]. As a result, materials exhibiting high hardness and strength can be effectively machined. However, the thermophysical nature of the process causes that the thermal properties of the materials make this treatment difficult [6].

Initially, the dielectrics used in EDM were mainly kerosene or oil-based fluids. Deionized water (characterized by a certain low electrical conductivity) was mainly used for wire electrical discharge machining to avoid possible ignition in the machining area.

However, the use of EDM for micro-hole drilling in the aerospace industry, where 20,000–40,000 holes are made in turbine blades, requires a more environmentally sustainable approach [7]-[9].

The efficiency of machining using deionized water as a working fluid is higher than in the case of using oil dielectrics, and the wear of the working electrode is also reduced. This was demonstrated by the research results presented in [10]-[12]. The research results presented in [13]-[15], showed that during hole making using EDM with deionized water, there was a smaller linear wear of the working electrode, with simultaneous increased machining efficiency. Deionized water used as a working fluid also provides dielectric strength enabling the occurrence of electrical discharges, as well as appropriate electrical conductivity for electrochemical reactions.

However, the electroerosion process is individual for each EDM machine and the set electrical parameters. The length of the working electrode or the flow rate of the dielectric through the electrode channel also have an impact on the efficiency and stability of the process. Therefore, each subsequent experimental test brings new information that can be implemented to improve this process. Continuous improvement of the EDD process is important for the aerospace industry, where the technology of making micro-holes is very much needed. So far, EDM is one of the most effective treatments used to make micro-holes.

Table 1: Thermophysical properties of the analyzed material

Property	Inconel 718 [16]-[18]	Ti-6Al-4V [19]
Density (g/cm <sup>3</sup> )	8.19	4.43
Melting point (K)	1,533-1,609	1,933
Thermal conductivity (W/(mK))	11.4	6.7

This paper analyses the influence of EDM parameters on micro-hole drilling in Inconel 718 and Ti-6Al-4V. The drilling results in these two materials were compared. In particular, the influence of deionized water on the drilling efficiency (average drilling velocity and linear tool wear) and the hole geometry (side gap thickness) were analyzed.

## 2. Experimental procedure

Electrical discharge machining (EDM) tests were conducted on a prototype EDM machine at the Cracow University of Technology. The experimental studies were carried out in accordance with the principles of experiment planning, for a complete rotary-uniform five-factor five-level plan with six repetitions in the center of the plan. The plan is a multifactor plan, which influenced its selection (the number of input factors used  $n = 5$ ). Moreover, the ranges of input factor value were significantly varied in order to obtain a broader analysis of the effect of process parameters on performance factors.

The investigated process factors were:

- average working voltage (U): 60; 80; 100; 120 (V),
- time of the impulse (ti): 100; 550; 1000 ( $\mu$ s),
- current amplitude (I): 2; 2.66; 3.33; 4.00; 4.65 (A),
- initial supply pressure of the working fluid (p): p = 5; 6; 8; 9 (MPa),
- working electrode rotation speed: 100; 200; 300; 400; 500 (rpm).

The constant factors adopted were:

- thickness of the initial inter-electrode gap: 50  $\mu$ m,
- processing time: 45 min (or shorter if a through hole was produced),
- material and type of working electrode – single-channel copper electrode with an outer diameter 0.4 mm (the electrode was used until it reached its limit of wear along its length),
- working fluid: deionized water (electrical conductivity in the range 1 – 8.5  $\mu$ S/cm),
- thickness of the processed material: 10 mm.

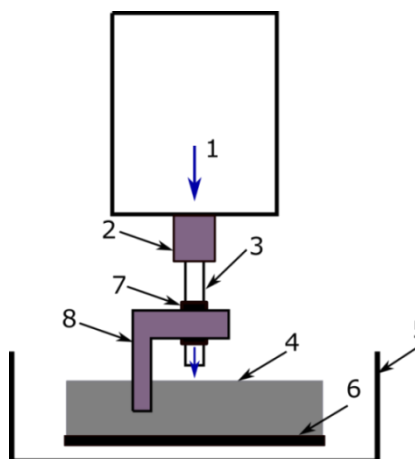


Figure 1: Schematic diagram of the electro-erosion drilling of holes; symbols: 1 – inflow of pressurized fluid into the working electrode channel, 2 – sleeve for mounting the working electrode, 3 – working electrode, 4 – workpiece, 5 – tank for collecting the working fluid, 6 – pad, 7 – guide, 8 – guide mounting holder.

The outcome factors were calculated as follows:

- average drilling velocity, ADV:

$$ADV = \frac{\text{hole depth}}{\text{drilling time}}, (\mu\text{s}/\text{mm}) \quad (1)$$

- linear tool wear, LTW:

$$LTW = \left( \frac{\text{electrode shortening}}{\text{hole depth}} \right) \cdot 100 (\%), \quad (2)$$

- side gap thickness, SGT:

$$SGT = \left( \frac{\text{entrance diameter of the hole}}{\text{electrode diameter}} \right) / 2, (\mu\text{m}). \quad (3)$$

The initial test series involved rotary drilling of holes in a rectangular specimen made of Inconel 718 superalloy. This test series resulted in relatively large side gap thicknesses. Therefore, a ceramic guide was used in the final test series. The guide was used to minimize the lateral run-out of the working electrode. The use of the guide required the design and fabrication of a mounting fixture (Figure 1).

48 through holes were produced in Inconel 718 and 32 in Ti-6Al-4V (all within 45 min). The materials in which micro-holes were drilled have different chemical compositions [5],[15] and different thermo-physical properties (Table 1). Thermo-physical properties significantly affect the efficiency of electrical discharge machining. Both analyzed materials have specific properties, which results from their use in parts in the aviation industry in jet engines.

The experimental tests were aimed at checking the machinability of two difficult-to-machine materials, the superalloy Inconel 718 and the titanium alloy Ti-6Al-4V, by electrical discharge machining using deionized water. For this purpose, the influence of the machining parameters on the process efficiency and the accuracy of the micro-hole geometry was analyzed.

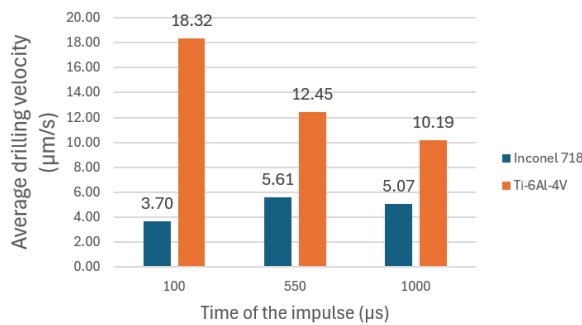


Figure 2: Relationship between the average drilling velocity and time of the impulse for the analyzed materials.

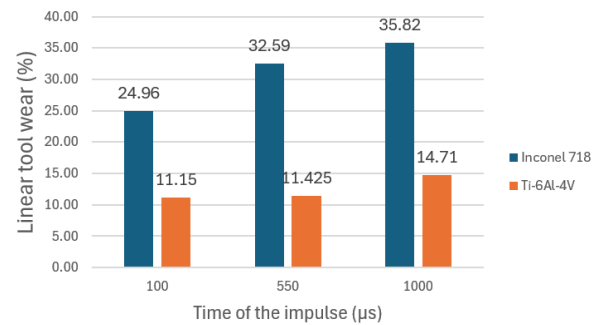


Figure 3: Relationship between the linear tool wear and time of the impulse for the analyzed materials.

### 3. Results and analysis

#### 3.1. The effect of impulse time on output

The analysis examines the influence of drilling parameters on the performance indicators of EDD, namely average drilling velocity, linear tool wear and side gap thickness. The statistical analysis showed that drilling parameters such as working electrode revolutions and initial pressure of liquid supply to the electrode channel have a slight influence on the result variables. Therefore these parameters were excluded from further analysis due to the statistically insignificant effect on the response variables. However, for higher applied values of working electrode revolutions, the drilling process exhibited improved stability and higher values of average drilling velocity were obtained.

First, the influence of the time of the impulse parameter on the result factors was analyzed. This parameter is crucial during EDM machining using deionized water as the working fluid. In this process, thanks to the deionized water used, electrochemical dissolution contributes to stock removal. The analysis of the results for the EDM drilling tests in Inconel 718 and Ti-6Al-4V showed that better drilling efficiency was obtained when making holes in the titanium alloy Ti-6Al-4V (Figures 2 and 3).

The average drilling velocity for the titanium alloy is more than twice as high as compared to those obtained for drilling in Inconel 718. During the drilling tests in the titanium alloy, the tool electrode also wore less (linear tool wear values were less than half of those observed during drilling in Inconel 718).

Analyzing the influence of parameters for minimum, maximum and average values of drilling parameters, the following can be observed:

- more efficient machining for the assumed parameter values when drilling micro-holes in a titanium alloy,
- the effect on more efficient drilling of micro-holes in titanium alloy can be related to the thermophysical properties of this alloy: its lower density and lower thermal conductivity (compared to the corresponding properties of Inconel 718),

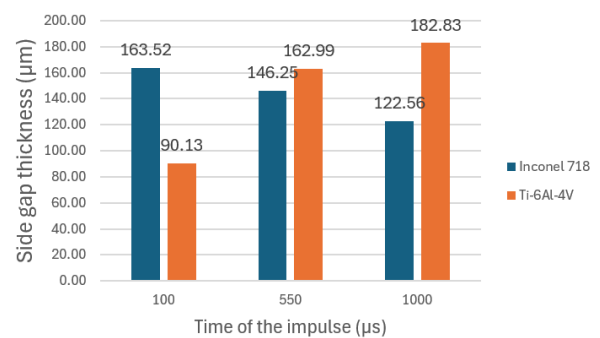


Figure 4: Relationship between the side gap thickness and time of the impulse for the analyzed materials.

- in the case of LTW, the influence of the pulse duration on this parameter is smaller during drilling in both materials. It can be concluded that the selected electrode material (copper electrode, single-channel) had a smaller influence on the drilling process,
- the results show that for the superalloy Inconel 718 probably different values of the machining parameters should be used to obtain better machining performance.

For different values of pulse duration, the SGT results are less predictable when drilling the two materials (Figure 4). This shows that this parameter influences the side gap thickness results in an ambiguous way.

As shown in Figure 4 we also observe that the SGT increases with increasing time of the pulse for titanium alloy and decreases for Inconel 718. Moreover, the side gap thickness has similar values for both analyzed materials when using time of the pulse of 550 µs.

#### 3.2. Linear regression of all input

In the next section, the influence of other significant EDM parameters (current amplitude and voltage) on the performance factors was analyzed (Figures 5-8). Using the Matlab software, the obtained data were approximated. Below is the assumed function of the research object:

$$f(U, ti, I, p, VER) = \exp(b_0 + b_1 \cdot U + b_2 \cdot ti + b_3 \cdot I + b_4 \cdot p + b_5 \cdot VER + b_{12} \cdot U \cdot ti + b_{13} \cdot U \cdot I + b_{14} \cdot U \cdot p + b_{15} \cdot U \cdot VER + b_{23} \cdot ti \cdot I + b_{24} \cdot ti \cdot p + b_{25} \cdot ti \cdot VER + b_{34} \cdot I \cdot p + b_{35} \cdot I \cdot VER + b_{45} \cdot p \cdot VER + b_{11} \cdot U^2 + b_{22} \cdot ti^2 + b_{33} \cdot I^2 + b_{44} \cdot p^2 + b_{55} \cdot VER^2). \quad (4)$$

*Table 2* presents the beta coefficients obtained from the approximation.

The data obtained from the drilling tests were very diverse, which resulted from the wider range of drilling parameter values used in the research plan. Moreover, the EDM process is characterized by ambiguous behavior of the influence of the process parameters on the tested result factors. For example, further increase of the current amplitude does not necessarily guarantee an increase in the speed of stock removal. Therefore, finding the proper function of the research object is very difficult.

Data regression included determination of the regression coefficients, assessment of their significance using the t-Student test, and evaluation of model adequacy using the F test. The adequacy verification showed that the determined functions are adequate at the significance level of 0.05.

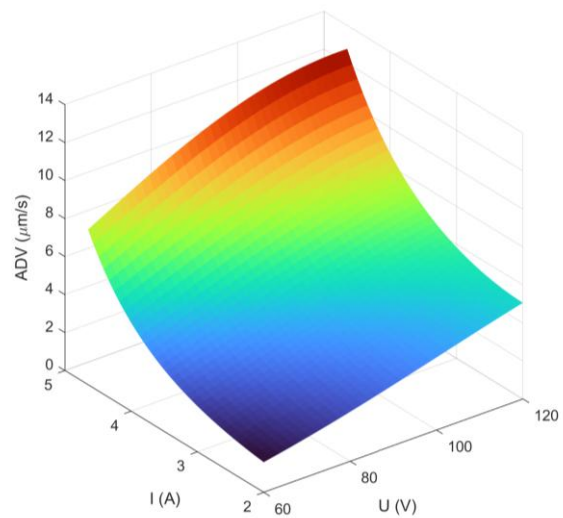
The following relations (*Figures 5 and 6*) show that the working voltage slightly affects the average drilling velocity. This may be attributed to the limited range applied in the tests. However, the EDM machine allowed

only this range of values for the working voltage to be used. Whereas for drilling in Inconel 718, the highest ADV values were obtained when using voltage 120 V. Superalloy Inconel 718 was processed less efficiently for the adopted parameters, perhaps the maximum applied values of the current amplitude and voltage parameters could provide more efficient drilling. On the other hand, the influence of current amplitude turned out to be specific to the EDM process. Higher values of this parameter gave higher drilling efficiency.

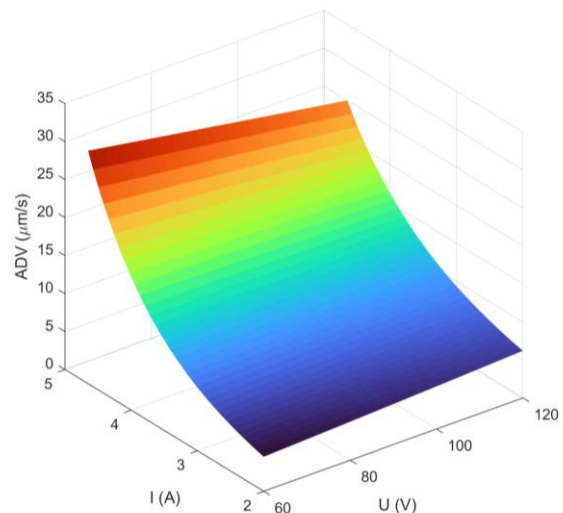
However, it turned out that the linear tool wear decreased for the applied current amplitude (*Figure 7*) when drilling Inconel 718. An increase in the drilling speed was observed for the increase in the applied current amplitude. We can conclude that, since the material was processed, electrochemical dissolution could contribute to the process. In the case of using deionized water, the

*Table 2:* Summary of beta coefficients of the research object function

Beta coefficient	ADV	LTW
$b_0$	-4.77	1.0508
$b_1$	-0.0025	0.048
$b_2$	0.0025	0.00057
$b_3$	1.39	-0.726
$b_4$	0.12	-0.069
$b_5$	0.0058	0.0016
$b_{12}$	-0.000004	0.000012
$b_{13}$	0.0023	-0.0045
$b_{14}$	-0.00016	-0.00017
$b_{15}$	0.0000015	0.000072
$b_{23}$	-0.00055	0.00061
$b_{24}$	0.000009	-0.0000007
$b_{25}$	0.000003	-0.0000007
$b_{34}$	-0.0068	0.0018
$b_{35}$	-0.00046	0.00109
$b_{45}$	-0.000025	-0.0005
$b_{11}$	0.000055	-0.00013
$b_{22}$	-0.0000012	-0.0000008
$b_{33}$	-0.105	0.124
$b_{44}$	-0.00059	0.00071
$b_{55}$	-0.000008	-0.0000042



*Figure 5:* Relationship between the average drilling velocity (ADV) and current amplitude (I) and voltage (U); workpiece material: Inconel 718.



*Figure 6:* Relationship between the average drilling velocity (ADV) and current amplitude (I) and voltage (U); workpiece material: Ti-6Al-4V.

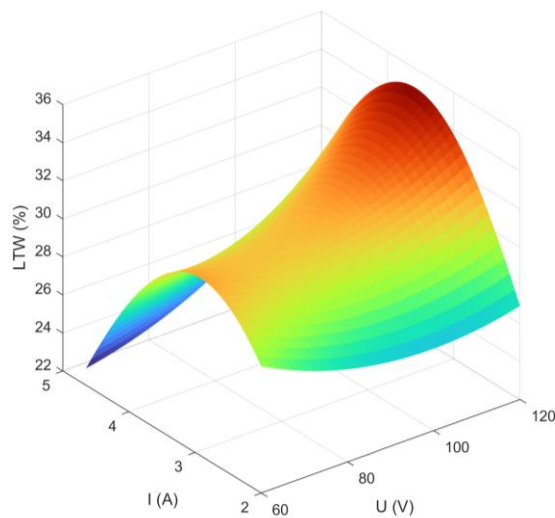


Figure 7: Relationship between the linear tool wear (LTW) and the current amplitude (I) and voltage (U); machined material: Inconel 718.

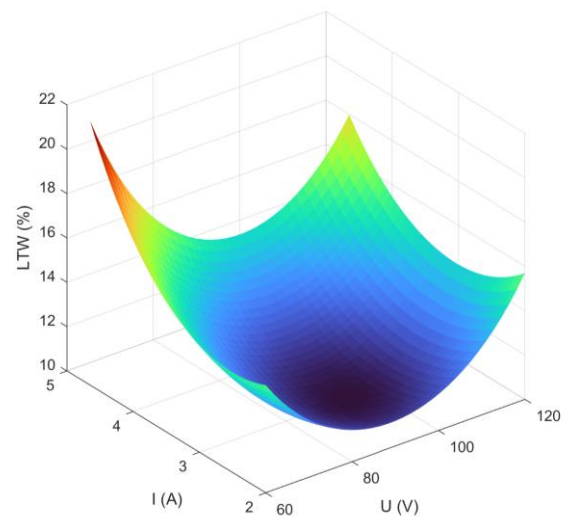


Figure 8: Relationship between the linear tool wear (LTW) and current amplitude (I) and voltage (U); workpiece material: Ti-6Al-4V.

material is additionally processed in a single pulse as a result of electrochemical dissolution [20].

For the drilling of titanium alloy we observe an increase in LTW with the increase of current amplitude (Figure 8) and also an increase in drilling speed (Figure 6). We can conclude that in this case the material could be removed to a similar extent by EDM and electrochemical dissolution. This behavior can be attributed to other properties of the titanium alloy. In particular, the lower thermal conductivity by about half compared to Inconel 718.

#### 4. Discussion

The results revealed distinct differences in the micro-hole drilling behavior of Inconel 718 and Ti-6Al-4V. These differences can be attributed primarily to the distinct thermophysical properties of the two materials. The analysis shows that the material's thermophysical properties significantly influence EDM machining. A strong focus on the impact of these material properties on machining could be crucial in further research. However, this process on the applied electrical discharge machine requires the development of appropriate parameter values for machining both materials. The test results show that EDM represents a viable machining process materials with such specific thermophysical properties. The analysis of the results showed that the machining of each material should be treated individually. The applied values of the discharge parameters must be specified individually for the machining of a given material. Furthermore, drilling in titanium alloy resulted in higher ADV and lower LTW values compared to Inconel 718. Because the experiments were exploratory, identical electrical parameter values were applied to both materials. Further research should focus on identifying optimized, material-specific parameter sets for EDM drilling of Inconel 718.

Moreover, the use of a guide when drilling in a titanium alloy shows that the influence of another factor should be sought to explain the obtained values of the side gap thickness greater than achieved with this technological solution.

The adopted parameter values were found to be more appropriate for drilling in titanium alloy, but they did not provide acceptable values of hole diameters. Dimensional and shape accuracy is an important parameter of geometry, therefore these results require refinement.

#### 5. Conclusion

This study examined the effect of EDM electrical parameters using deionized water on the machining of difficult-to-cut materials, namely Inconel 718 and Ti-6Al-4V.

The test results showed that the applied drilling parameter values were more suitable for effective drilling of micro-hole drilling in the titanium alloy. However, this material exhibited poorer the hole geometry accuracy manifested by higher side gap thickness compared to Inconel 718. In future studies, the accuracy of the micro-hole geometry should be further improved by optimizing the drilling parameters.

In addition, the most influential process parameters were pulse duration, current amplitude and voltage. The length of the impulse time was also important here due to the use of deionized water as the working fluid. An important advantage of the EDM process with this working fluid is its certain electrical conductivity, which supports the efficiency of stock removal through the presence of electrochemical dissolution. Furthermore, analysis of the results showed that thermophysical properties significantly influence the machining of these materials. Despite using the same values of the electrical parameters of the EDM, significant differences in the

resulting factors were obtained. The influence of the thermophysical properties of such machined materials should certainly be considered in future studies.

Future work should include more extensive EDM drilling experiments aimed at identifying parameters sets, that simultaneously ensure high productivity and high micro-hole geometry accuracy.

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