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Experimental Investigations of Cutting Rates and Surface Integrity in Wire Electrochemical Machining with Rotating Electrode

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Abstract

The advantages of ECM regarding productivity and best surface qualities are always challenged by high costs for process development and complex electrolyte flow devices. Combining the working principle of electrochemical machining (ECM) with a universal tool, like a wire, could meet these challenges. Such a wire ECM process might be able to machine flexible and efficient 2.5-dimensional geometries like fir tree slots in turbine discs. Nowadays, established manufacturing technologies for such geometries are broaching and wire electrical discharge machining (wire EDM). Nevertheless, high requirements on surface integrity of turbine parts need an intensive process development and – in case of wire EDM – trim cuts to reduce the heat affected rim zone. In the past, few studies dealt with the development of a wire ECM process to meet these challenges. However, previous concepts of wire ECM were only suitable for micro machining applications. Due to insufficient flushing concepts, the application of the process for machining macro geometries with higher cutting rates failed. Therefore, this paper presents experimental investigations on wire electrochemical machining of macro geometries. An axial flushing approach with a rotating tool electrode is used in order to optimize electrolyte flushing and thus, to increase cutting rates. The influences of different machining parameters on cutting kerf, surface integrity and cutting rate will be presented.

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1. Introduction

Wire electrochemical machining (wire ECM) combines well-known advantages of the working principle of classical ECM with the kinematic of wire electrical discharge machining (wire EDM). Thus, the costly construction of a special machining device does not need to be conducted. Furthermore, the classical sinking ECM requires a time consuming and heuristic, iterative process for the cathode design for each machining task. Using a universal tool for wire ECM, 2.5-dimensional geometries can be cut without the complex process design. Possible applications for wire ECM could be the production of fir tree slots in a turbine disc. In this case, the process has to be evaluated with the main manufacturing processes broaching and wire EDM, similarly to Klocke et al. for Blisks [1].

In the last years, few studies about wire ECM have been published. An overview about the state of the art is given in [2]. In summary, the realization of a wire ECM process with high cutting rates was limited by an effective electrolyte flushing concept. Zeng et al. did an empirical investigation of different flushing concepts [3]. They analyzed an electrolyte flushing realized by a nozzle with different flushing angles and by a draining wire in an electrolyte bath. An axial nozzle provided the best machining results regarding the nozzle angle and the concept with the draining wire lead to highest aspect ratios of 50 that could be machined. However, the maximum reachable cutting rate was only $V_w = 1.2 \text{ mm}^2/\text{min}$ respectively a feed rate of $v_f = 0.06 \text{ mm}/\text{min}$. In latest research Fang et al. achieved the highest cutting rate of $V_w = 2.16 \text{ mm}^2/\text{min}$ respectively $v_f = 0.54 \text{ mm}/\text{min}$ in a workpiece with 4 mm height [4].

Nomenclature

d_{kerf}	Cutting kerf width / mm
d_{Nozzle}	Nozzle diameter / mm
d_{Wire}	Wire diameter / μm
h	Workpiece height / mm
p	Electrolyte pressure / bar
R_a	Average arithmetic roughness / μm
R_z	Average peak-to-valley (ptv) roughness / μm
s_L	Lateral gap width / μm
t	Machining time / s
U	Voltage / V
v_f	Feed rate / mm/min
V_w	Cutting rate / mm^2/min
wire ECM	Wire electrochemical machining
wire EDM	Wire electrical discharge machining

The flushing was realized by a rotating helical electrode in an electrolyte bath. In further investigations, Fang et al. used a process assisted with large-amplitude vibrations of wires [5]. The workpiece height was 5 mm and it was machined with a feed rate of $v_f = 0.09$ mm/min (smooth wire) and $v_f = 0.11$ mm/min (ribbed wire).

The short review showed that different approaches to increase the electrolyte flushing were already investigated. The previous focus of research in wire ECM was mainly on micro machining and up to date it was not possible to reach cutting rates comparable to wire EDM. Welling showed for a specific fir tree, that one slot is machined in $t = 80.3$ min using a standard brass wire [6]. Including one main cut and two trim cuts results in an equilibrium average cutting rate $V_w = 39.4$ mm^2/min for one cut for a workpiece height of 40 mm, regardless the nonproductive time between different cuts. Using a double coated high-speed wire electrode the machining time of one slot can be reduced to 44.3 min which results in an average cutting rate of 71.3 mm^2/min . Due to the main working principle of wire ECM, the rim zone is not affected thermally or mechanically. Thus, wire ECM does not require trim cuts and the main cut has to be evaluated with the whole process time of wire EDM.

In the literature, the different promising electrolyte flushing strategies to increase the cutting rate were not combined. An axial electrolyte flushing in combination with a rotating structured wire was not implemented yet. Therefore, in this

paper experimental investigations of wire ECM with a combination of both promising flushing strategies are presented. The influence of typical machining parameters – voltage U , electrolyte pressure p , nozzle diameter d_{Nozzle} and the feed rate v_f – on the machining result – cutting kerf d_{kerf} , surface roughness R_a respectively R_z , a cross section analyzes and the reachable cutting rate V_w – are investigated.

2. Machining Setup

The basic research platform shown in Figure 1, left was used for the wire ECM investigations. The platform was constructed to investigate different electrolyte flushing principles for wire ECM. Workpieces can be machined in an electrolyte bath or with an axial flushing using a nozzle as well as a combination of both. Different nozzles can be mounted to the pressure chamber (Figure 1, left). A second pressure chamber can be installed under the workpiece for flushing from above and below. The test rig has two axes, an x-axis which is coupled with the workpiece clamping and a c-axis for the rotation of the wire electrode, cp. Fig. 1. Both axes are controlled by an SPS control unit. Electrode wires with different structures and diameters can be clamped in two rotation units and are tensioned by a spring in the upper unit. The rotation axis enables up to 5,000 rpm in both directions. Numerical investigations of the fluid flow showed that theoretically due to the small wire diameter the rotation has only a small influence on the fluid flow, whereas the geometrical design of the electrode affects the electrolyte flow clearly [7]. Figure 1, right illustrates the effect of electrode rotation and electrode design on the developing fluid flow. In the upper part of the electrolyte inlet the electrolyte jet is only little affected, in comparison at the end of the flow channel the electrolyte flow is suffered with a rotational component.

The rotation could also increase the efficiency of the wire ECM process regarding the removal of dissolved material and evolved gas. Furthermore, geometrical structure of the wire electrode is not formed at the cutting lines by the rotation of the electrode [8].

Workpieces with variable heights can be clamped and different distances between the nozzle and the workpiece can be set. For the following investigations, a distance of 0.3 mm between nozzle and workpiece was adjusted. The test rig has a separate electrolyte supply and the electrolyte pressure can be varied up to 10 bar.

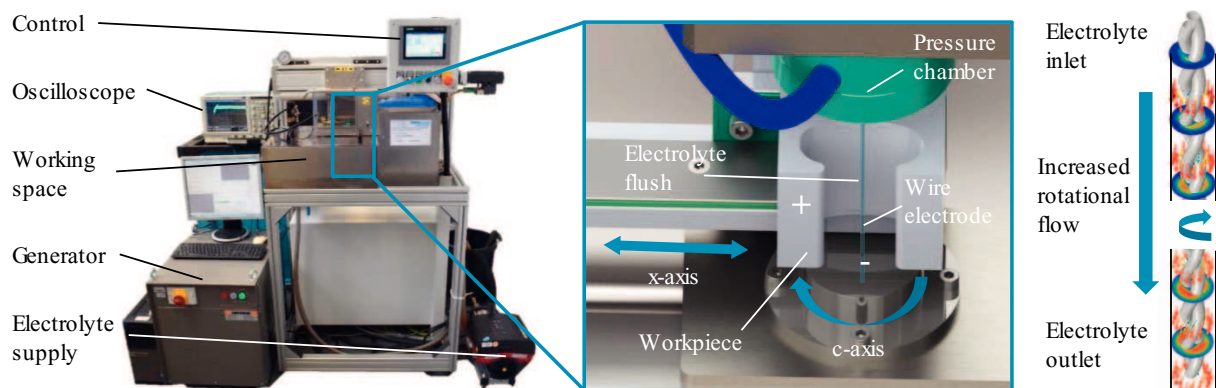


Fig. 1. Wire ECM basic research platform and Working space and kinematic (left), Simulated effect of rotation and wire structure on fluid flow (right).

The test rig is equipped with a generator, which enables pulsed machining as well as direct current. Pulse on- and pulse off times are from 100 μ s upwards. Due to the non-productive time during pulsed machining, the electrolyte exchange in the working gap is increased. Thus, higher current densities can be realized and better geometry accuracies and surface roughness occur. Nevertheless, the feed rate has to be reduced, because of the non-productive time. Therefore, the experiments shown in this paper are performed with direct current in order to increase the cutting rate.

3. Experimental setup

The machined material was Inconel 718 direct-aged (DA) with a workpiece height of 5 mm. Inconel 718 is the most widely used nickel based alloy in turbomachinery construction. Discs of the rear high-pressure compressor and of the turbine are made of Inconel 718, which has an operating temperature between 650 and 700 °C. The tensile strength of Inconel 718 DA was increased by a further heat treatment compared to standard Inconel 718. The heat treatment results in a finer microstructure and the metastable γ'' -Phase is stabilized [9].

For the experiments, standard machining parameters were defined in preliminary investigations. These parameters can be seen in Table 1. Only one parameter was changed for the final experiments whereas the other machining settings were kept constant. All parameters were investigated, but not all had an influence on the machining result. The experiments were performed with a sodium nitrate based electrolyte with a constant electrolyte conductivity of 120 mS/cm at 20 °C.

Table 1. Standard machining parameters.

Machining parameter	Value
Feed rate v_f / [mm/min]	0.5
Voltage U / V	15
Electrolyte pressure p / bar	1.0
Electrode rotation ω / rpm	150
Nozzle diameter d_{nozzle} / mm	1.5
Wire diameter d_{wire} / mm	0.5 (two twisted wires 0.25 mm)
Wire windings for 200 mm length	12
Workpiece height h / mm	5

Two twisted wires were used as cathode electrode. The wires were standard EDM brass wires with a diameter of 0.25 mm. The wire was twisted 12 times on a length of 200 mm, which results in a double helix structure.

To ensure that the machining parameters enable stable process conditions, all experiments were performed until equilibrium conditions were established. A starting working gap of 0.4 mm between the cathode and the workpiece was set. Afterwards, a kerf of 15 mm length was machined. Depending on the feed rate, stationary conditions occur within the first 2 mm. The current was measured with an oscilloscope; under stationary conditions, the current is constant. However, the precise measurement of the real process current was hardly possible. Due to the free jet and the absence of a pressure device stray currents occur between the tool electrode and the workpiece clamping and were measured as well. After

machining, the workpieces were cleaned in an ultrasonic bath. The cutting kerf was measured at the three different positions on the top and at the bottom of the workpiece. Finally, one flank side was cut off to measure the surface roughness, which was measured three times distributed over the workpiece height on the cutting path.

4. Results and Discussions

Even if the effect of all in Table 1 presented machining parameters were investigated, only machining parameters with a significant influence on machining results or on the feed rate are presented within this paper. Varying the wire rotation speed did affect neither the cutting kerf nor the surface roughness. However, using the described wire electrode electrolyte is spread away from electrode without using an electrolyte bath at too high rotation speeds above 1,000 rpm. Short circuits occur and the process breaks down. Furthermore, number of windings of the wire electrode only has a small influence within the investigated range on cutting kerf and surface roughness.

However, the influence of the voltage has a significant influence on the cutting kerf, cp. Figure 2. The cutting kerf is getting wider with increasing voltage. A linear behavior is clearly visible. The cutting kerf is defined by the wire diameter and the lateral working gap on both sides:

$$d_{\text{kerf}} = d_{\text{wire}} + 2 \cdot s_L \quad (1)$$

However, this relationship is well known from the frontal working gap in classical sinking ECM and was predictable [10]. Nevertheless, a bigger working gap – both frontal and lateral – support the electrolyte flushing and thus can increase the feed rate, but also affects the minimal producible inner radii.

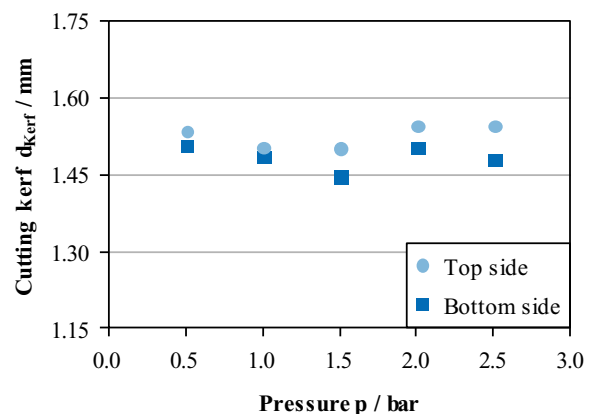


Fig. 2. Cutting kerf as function of the voltage.

Electrolyte is pumped into a pressure chamber of the test rig, cp. Fig. 1. A flushing nozzle is attached to pressure chamber and electrolyte is flushed axially along the wire electrode. The electrolyte pressure is adjusted to the pressure chamber.

The electrolyte pressure did not have a significant influence on the cutting kerf, Figure 3. A relationship between the flushing pressure and the width of the cutting kerf cannot be

identified. Differences between the individual examinations are only minor.

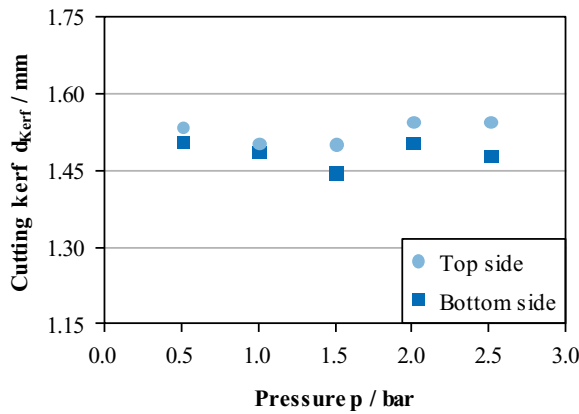


Fig. 3. Cutting kerf as function of the electrolyte pressure.

Fluid flow velocity of the electrolyte is determined by the electrolyte pressure and the nozzle diameter. For an effective flushing of the working gap, velocity of the fluid flow should be as high as possible considering arising of flow grooves.

Under the given conditions (Table 1), the programmed feed rate could be increased up to 0.7 mm/min without the occurrence of short circuits. Figure 4 shows that the feed rate – and thus the cutting rate using the same workpiece height – is a clear function of the cutting kerf width. The lateral working gap is decreasing with an increased feed rate. At a feed rate of 0.4 mm/min the average width of the cutting kerf is 1.7 mm, which results in a lateral working gap of 600 μm. In contrast, the lateral working gap at a feed rate of 0.7 mm/min is decreasing to 435 μm.

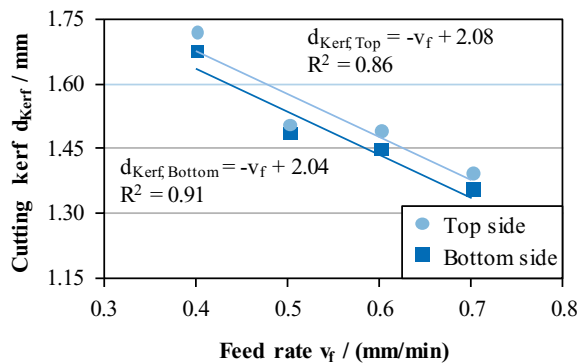


Fig. 4. Cutting kerf as function of the cutting rate.

As a function of the investigated parameter range, the cutting kerf behavior is linearly decreasing with the feed rate (Figure 4). The classic sinking ECM process is characterized by a decreasing hyperbolic course of the frontal working gap with increasing feed rate [10]. Future examinations with higher feed rates have to show, if the investigated range is just in the beginning of a hyperbolic curve or if the linear trend is maintained even at higher feed rates. The achievable tolerances in ECM are always within the width of the working gap. Therefore, the feed rate represents always a compromise

between flushing, manufacturing time and geometrical accuracies.

The experiments were conducted without using an electrolyte bath. Therefore, the diameter of the nozzle has a great impact for the gap flushing. Contrary to the electrolyte pressure a larger nozzle diameter results in lower fluid flow velocities and thus dissolved products are removed slower. However, a larger area can be machined by the bigger electrolyte jet diameter and the working gap is increasing. Figure 5 shows the cutting kerf as a function of the nozzle diameter. The cutting kerf is widened linear with larger nozzle diameters. Using even bigger nozzle diameters, the trend will probably be asymptotically flattened and approximate machining in an electrolyte bath. Nevertheless, the reduced flow velocity will limit the reachable cutting speed.

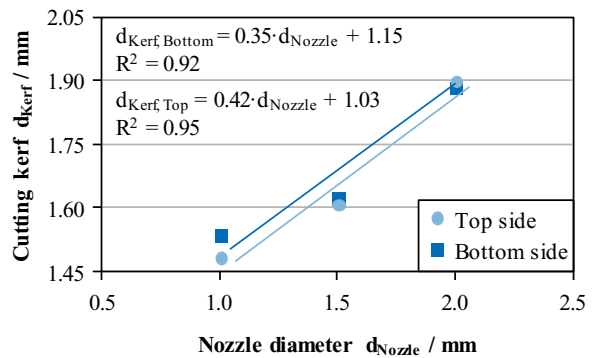


Fig. 5. Cutting kerf as function of the nozzle diameter.

Surface roughness in ECM is on the one hand highly dependent of microstructure of the processed material and on the other hand of the machining parameters. In classical sinking ECM the surface roughness is improved with higher current densities as long as no flow grooves occur. The effect of the parameters on the surface roughness is presented in Figure 6-8.

Figure 6 presents the developing surface roughness as a function of the applied voltage. The dissolution rate of the different material phases is depending on the current density and the voltage [10]. The best roughness values are attained at 17.5 V having surface values of Ra = 0.51 μm respectively Rz = 3.34 μm. Therefore, the voltage should be selected with regard to an optimization of the surface quality or the cutting kerf. Due to a more effective flushing of a larger cutting kerf,

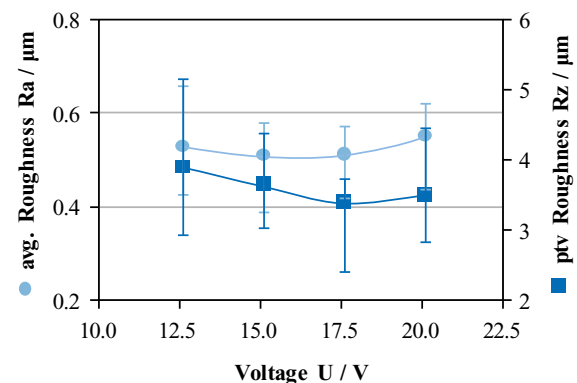


Fig. 6. Surface roughness as function of the voltage.

higher feed rates can be reached and thus higher current densities occur. Therefore, the relation between voltage and feed rate should be further investigated.

The relation of the surface roughness and the electrolyte pressure is shown in Figure 7. While the surface roughness – using an electrolyte pressure of 0.5 bar – is relatively bad, the best roughness values are achieved using 1 bar. An Ra value of 0.51 μm respectively Rz = 3.61 μm occur. The roughness values are getting worse with further increase of the pressure. Flow grooves on the flank of the cut arise and influence the roughness values.

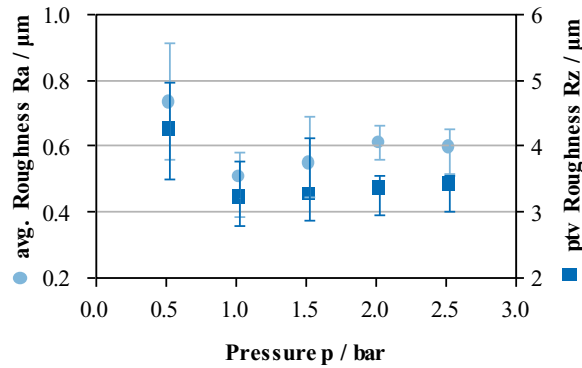


Fig. 7. Surface roughness as function of the electrolyte pressure.

However, in order to increase the feed rate the electrolyte pressure should be as high as possible. The onset of flow grooves is dependent on the electrolyte flow velocity [11]. The combination of high electrolyte pressures with larger working gaps could prevent flow grooves. Therefore, higher electrical voltage in combination with higher electrolyte pressure and feed rate could reduce the surface roughness values again.

The best surface roughness is obtained using a feed rate of $v_f = 0.5$ mm/min, cp. Figure 8. In contrast to the classic theoretical behavior of sinking ECM the surface roughness is not getting better with increasing feed rate.

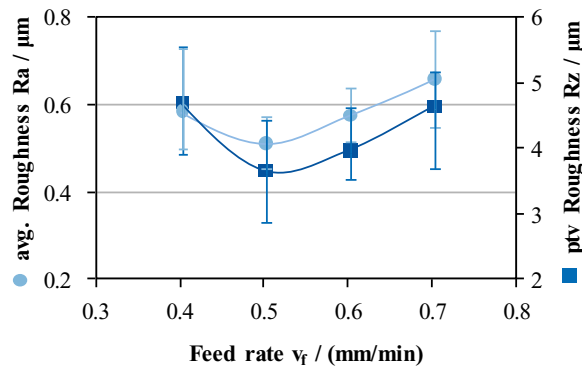


Fig. 8. Surface roughness as function of the cutting rate.

A possible reason for the deterioration could be occurrence of flow grooves. Due to the smaller working gap, cp. Figure 4, flow velocity is increasing, grooves occur [11] and machining gap is not flushed sufficiently. Surface roughness is not affected by a variation of the nozzle diameter. Therefore, using higher voltages and larger nozzle diameters are possibilities to enlarge working gap and thus to avoid flow grooves.

In total, mostly machining parameters affect both the cutting kerf as well as the surface roughness. In order to increase the feed rate and the cutting rate, the flushing should be optimized, regardless of the occurring surface roughness.

In a first step, the effects of a wide cutting kerf and the electrolyte flow velocity on reachable cutting rates V_w were investigated, not considering the surface roughness. Figure 9 shows the maximum reachable cutting rate under the given boundary conditions. A workpiece with a height of 5 mm was used. Except voltage and electrolyte pressure standard parameters shown in Table 1 were used. For each voltage and electrolyte pressure combination, the feed rate was increased until stationary processing was no longer possible and short circuits occurred.

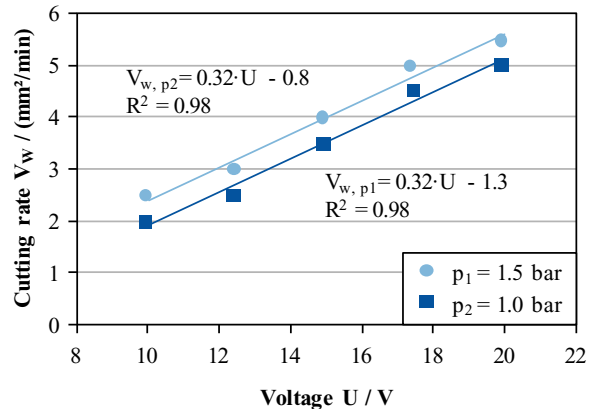


Fig. 9. Achievable cutting rate as function of the voltage using different electrolyte pressures.

In Figure 9 it is clearly visible, that the cutting rate can be linearly enhanced with an increasing voltage. Comparing the cutting rate of 10 volt and 20 volt the cutting rate could be increased by 150 %. Furthermore, the cutting rate can also be increased by an increased electrolyte pressure for each voltage. Using an electrolyte pressure of 1.5 bar and 20 volt a cutting rate of $V_w = 5.5$ mm²/min respectively a feed rate of $v_f = 1.1$ mm/min was realized. For a further increase of the cutting rate, higher electrolyte pressure and voltage could be used. Future investigations should also consider the effects of the wire geometry and the workpiece heights on the achievable feed rates. Furthermore, a higher electrolyte conductivity should also be investigated to form larger working gaps. ECM is well known for its advantage of machining without influencing the materials processed rim zone thermally or mechanically. Figure 10 a) shows a cross section of a wire ECM machined kerf. Figure 10 b) and c) show details of the rim zone. As expected no process influence on the rim zone can be seen. However, the entrance edges of the cutting kerf are rounded, the left edge is more rounded than the right edge (cp. Figure 10 a). Furthermore, the leading edge of the kerf is not equally rounded. The left part of the leading edge of the semicircle has a radius of 1.49 mm whereas the radius of the right edge is only 0.64 mm (Figure 10 a). The electrode rotation could be an explanation for this non-symmetrical development of the cutting kerf. The electrolyte is influenced differently by the right rotation and the local dissolution rate changes. Future

investigations with reverse electrode rotation have to show the dependency of the edge rounding.

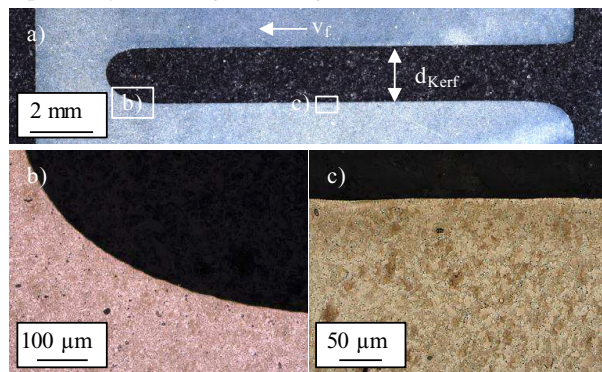


Fig. 10. Cross section of wire ECM machined Inconel 718 DA.

First fundamental relations in wire ECM were shown. A cutting rate of $V_w = 5.5 \text{ mm}^2/\text{min}$ is still not in the technological range of wire EDM. However, in particular, the fact that there is no tool wear and the excellent surface integrity associated with potentially low machine tool costs (due to the low machine complexity) shows the high potential of this manufacturing process. Furthermore, youngest investigations yield a cutting rate of $20 \text{ mm}^2/\text{min}$ machining a workpiece height of 40 mm using optimized parameters, which will be presented in a future paper.

5. Summary and outlook

Summarizing the investigations regarding the cutting kerf and the surface roughness it can be noted, that the electrolyte pressure does not affect the cutting kerf but the achievable surface roughness. An increasing feed rate reduces the cutting kerf width, but also negatively affects the surface roughness at high values. The nozzle diameter is directly related to the cutting kerf width while the surface roughness is not affected by the nozzle diameter. The voltage is also directly linear connected to cutting kerf width. Occurring surface roughness is determined by the local dissolution of the microstructure. On the one hand, the voltage influences the dissolution of the different phases on the other hand the surface roughness is affected by occurring flow grooves due to high electrolyte flow velocities. Therefore, the working gap, both lateral and frontal, are highly correlated to the occurring surface quality.

Furthermore, the cutting rate of wire ECM can be improved by an enlarged working gap and an increased electrolyte pressure. Future investigations regarding the electrode geometry, workpiece height, additional bottom flushing or combined with an electrolyte bath and electrolyte conductivity have to show further potentials to improve the cutting rate.

Possible material influences by wire ECM machining were investigated by rim zone analyses. No influence of the process or the electrolyte could be recognized. However, the electrode rotation cause a non-symmetrical dissolution of the leading edge and the entrance edges.

In this paper cutting rates of $5.5 \text{ mm}^2/\text{min}$ were reached. However, in wire EDM cutting rates up to $72 \text{ mm}^2/\text{min}$ in consideration of the trim cuts with a double coated high-speed

wire electrode are reached for the production of fir tree slots. Surface roughness of wire EDM was $R_a = 0.7 \text{ μm}$ using two trim cuts compared to $R_a = 0.5 \text{ μm}$ in wire ECM. A potential of a further increase of the cutting rate is given using other wire geometries and adjusted machining parameters. Latest investigations achieved a cutting rate of $20 \text{ mm}^2/\text{min}$. These results will be presented in future. A cutting rate within this range in combination with a low machine hour rate, wire ECM in future could be an attractive alternative for the manufacture of fir tree slots as well as other cutting applications.

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