

Proceedings of the 20th INSECT 2024

International Symposium on ElectroChemical Machining Technology 2024

Aachen, November 18-19, 2024

Thomas Bergs, Elio Tchoupe Sambou, Timm Petersen,
Tim Herrig, Andreas Klink (Eds.)

Manufacturing Technology Institute – MTI
RWTH Aachen University

Imprint

Proceedings of the 20th INSECT 2024

International Symposium on Electrochemical Machining Technology 2024

Aachen, November 18-19, 2024

Editors

Thomas Bergs

Elio Tchoupe Sambou

Timm Petersen

Tim Herrig

Andreas Klink

Manufacturing Technology Institute – MTI, RWTH Aachen University

Campus-Boulevard 30

52074 Aachen

Available via the institutional repository of RWTH Aachen University:

DOI: 10.18154/RWTH-2024-10228

Aachen 2024

This work is licensed under a

Creative Commons Attribution 4.0 International license.

Excluded from this license are photos in which persons are recognizably depicted and all logos shown.

Experimental analysis on local surface defects caused by short circuits in wire-ECM

F. Sous, M. Kemperle, T. Herrig, A. Klink, T. Bergs*

Manufacturing Technology Institute - MTI of RWTH Aachen University, Campus-Boulevard 30, Aachen 52074, Germany

**Corresponding author: f.sous@mti.rwth-aachen.de*

DOI: 10.18154/RWTH-2024-10231

Abstract

Wire-ECM is a potential material removal technology for high strength materials without affecting the workpiece mechanically or thermally. Possible applications can be found in the turbomachinery industry. However, when the working gap between wire tool and workpiece falls below a critical level, a short circuit can occur which results in a thermally damaged area. This paper introduces the latest results regarding improving machining stability with axial flushing and focusses on evaluating the local altered area in a short circuit event.

1 Introduction and state of the art

The advantages of Sinking-ECM like productivity and outstanding surface qualities regardless of the mechanical workpiece characteristics are always challenged by high costs for specific tools and complex electrolyte flow devices [1, 2]. Instead of using task specific tools, Wire-ECM uses a universal tool to perform 2.5 dimensional cuts [3]. By utilizing an axial electrolyte flow in combination with an additional wire rotation of structured tools like twisted wires, the flushing of the kerf was improved in previous studies, resulting in increasing cutting rates [4, 5]. However, especially at high feed rates the working gap between wire and workpiece is very small and runout errors lead to significant process instabilities, resulting in short circuit defects. Therefore, the achievable cutting rates are currently still too low for economic applications like the production of fir tree slots for jet engines. Simulations of the flow field have shown that

the electrolyte pressure has a huge impact on the electrolyte kerf flushing. By increasing the nozzle pressure from, for instance, p = 5 bar to p = 10 bar, the electrolyte velocity along the wire almost doubles [6]. In the following, the impact of the flushing pressure was investigated in experimental studies, where an increasing flushing pressure combined with a rigid static wire showed a significant increase in productivity. The results show a linear correlation between flushing pressure and cutting rate (Figure 1) [7]. Based on this, Wire-ECM was tested for machining a complex 2-dimensional fir tree sample, with the success shown in Figure 1 (right).

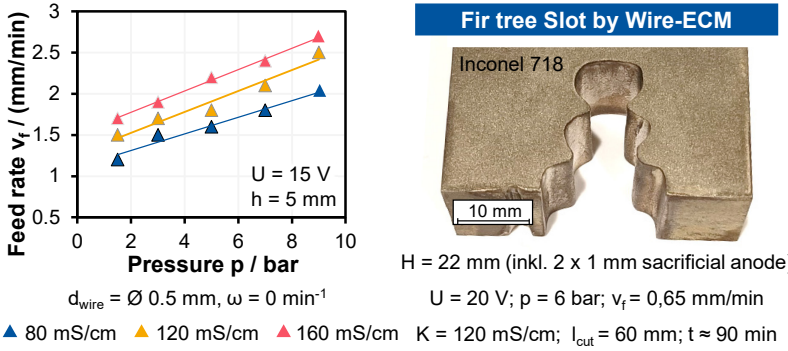

Figure 1: Linear correlation between flushing pressure and cutting rate, left. [7]; Fir tree slot in Inconel 718 DA, right.

Previous work has shown significant improvements in Wire-ECM. However, the kerf flushing remains the limiting factor for process stability and productivity. Recent studies address this issue by investigating higher flushing pressures and flushing the critical frontal gap through the wire with small nozzles [8]. Nevertheless, process instabilities continue to pose challenges. Critical instabilities can ultimately lead to short circuits (SC) between the wire tool and the workpiece. This is especially relevant for dynamically stressed components for example safety-critical parts in aviation, where the defects are of concern for the component functionality. The use of a thin, flexible wire and the relatively low electrical current in Wire-ECM create unique conditions compared to conventional ECM machining. The characteristics, such as the location, shape, and severity of short circuits in Wire-ECM, are currently unknown. However, they are of great interest when evaluating the technology, especially in cases of process interruptions during the machining of performance-critical components. Therefore, this study investigates short circuits in Wire-ECM machining for the first time.

2 Experimental Approach

In Wire-ECM, the wire is moved relative to the workpiece. The geometric conditions of the cutting path are shown in Figure 2 (left). The frontal gap (s_{90}) in feed direction is the smallest working gap and thus the most challenging to flush. Further, the widening of the lateral gap allows the electrolyte to escape from the frontal gap through the lateral gap, which negatively impacts the effectiveness of flushing the frontal gap area. Hence the risk of SC in the frontal gap is the highest. With unidirectional axial flushing, the electrolyte becomes increasingly contaminated, and the flushing effectiveness decreases along the vertical kerf, which raises the risk of SC as the removal height increases. As a result, SC are expected to predominantly occur in the lower regions of the kerf.

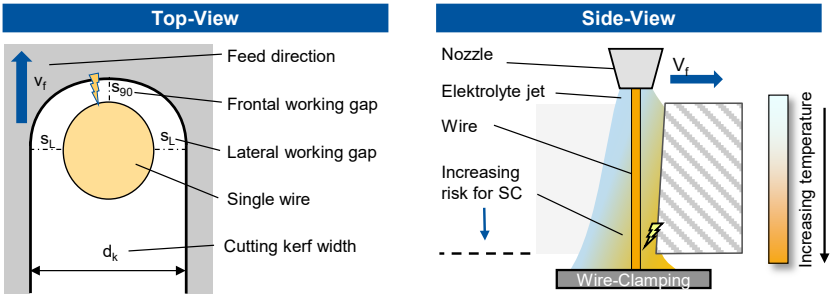

Figure 2: Geometric conditions of the cutting kerf.

For this study a new fixture concept was developed, enabling Wire-ECM machining to be realized on an industrial ECM sinking machine by the machine tool manufacturer EMAG ECM. This offers the use of state-of-the-art generator technology and industrial-standard rapid SC stops. To ensure a consistent electrolyte quality during machining, the EMAG electrolyte management system (EMS), with a capacity of approximately 1000 liters, is used. The fixture is based on an open, C-shaped, 3D-printed profile. 3D-printed polymers are non-conductive and non-corrosive, making them an excellent choice for construction in ECM. Additionally, because of the freedom of manufacturing, internal flow channels can be cost-effectively integrated. The wire tool is mounted horizontally in the fixture and pre-tensioned by a spring load. A sliding sleeve can adjust the free wire length to the workpiece height, maximizing the stiffness of the wire. The electrolyte is supplied from outside the wire axis and delivered through internal channels to the coaxial nozzle. The wire is clamped and connected from the non-spring-loaded side and is continuously flushed with cool electrolyte in the non-working areas inside the device to prevent overheating due to the high

current passing through. Figure 3 shows the fixture and the assembly with the workpiece in the working area. The workpiece is precisely feed down, toward the wire using a closed loop position controlled linear axis of the machine tool.

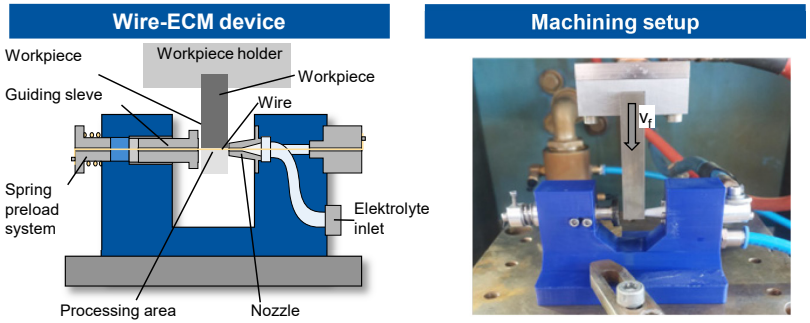

Figure 3: 3D-printed Wire-ECM device (left), Wire-ECM device mounted in the working area of an EMAG PT Smart 1500 (right).

All experiments are carried out using a Ø 0.5 mm hardened stainless steel wire, a Ø 1,5 mm nozzle and a high spring preload of approximately 50 N, which is in the upper elastic range of the material. On the workpiece side, Inconel 718 DA, a high-strength nickel-based alloy commonly used in turbomachinery, is used [9]. All experiments are performed on 20 mm high samples. Sufficient flushing of the process area on sharp edges like at the beginning of the cut is one of the biggest challenges. Therefore, each experiment starts with a reduced feed rate (0.4 mm/min) until the wire has cut approximately 4 mm into the material. Then, the machining process is gradually pushed to the stability limit by increasing the feed rate in small steps. Each step is maintained for 4 minutes and increased by 0.1 mm/min until the process becomes instable and the machine stops due to the short circuit detection is triggered. The parameters used are listed in Table 1.

Table 1: Parameters of the experimental investigation

Parameter	Value
Material	Inconel 718 DA, h = 20 mm
Electrolyte	K = 120 mS/cm, t = 20 °C, p = 5 bar
Voltage	U_{ECM} = 20 V, 30 V, 40 V, pulsed, t_{on} / t_{off} = (5/5) ms
SC-Current	I_{max} = 60 A, 100 A, 140 A
Wire	Ø 0.5 mm, stainless steel

The rapid stop in a SC event is based on a static current limit. This approach is used to analyze the full behavior of short circuits and to investigate the worst-case scenario for a Wire-ECM short circuit. Relevant process parameters, such as voltage and current, are recorded using an external data acquisition setup based on a high-frequency oscilloscope with a sampling rate of 5 MHz. The resulting damage zone will be examined by microscopic analysis of the external crater shape as well as metallographic cross-section analysis. Finally, the work-piece damage will be evaluated in relation to the cutting kerf width.

3 Results

Figure 4 provides an overview of typical Wire-ECM cutting paths in the "as-cut" condition, without additional post-processing such as intense cleaning. The top side is more affected by deflected electrolyte, and the cutting kerf shows increased rounding. The bottom side is less rounded and has a smaller area attacked by the electrolyte. Overall, the machining process runs stable due to the improved setup, until the feed rate becomes too high, and a short circuit occurs. However, as described earlier, the initial phase of the process has a higher risk of short circuits due to the challenging flushing conditions. This can be seen in test no. 16, where a short circuit occurred right at the start of machining, even though the feed rate was reduced. Due to the increase in feed rate, the kerf continuously becomes smaller, as can be clearly seen at the bottom side in test no. 10, or no. 12, for instance. The correlation between feed rate and kerf width is well investigated and has been documented in numerous publications [3,5,10].

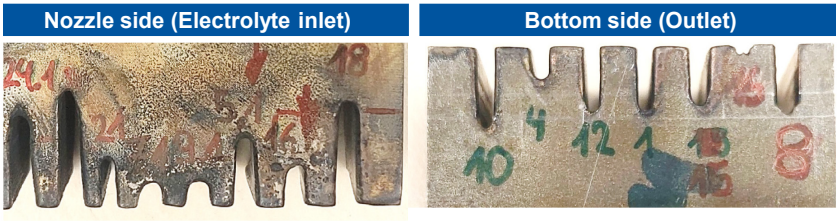

Figure 4: Overview on typical Wire-ECM cutting paths

Figure 5 shows characteristic behaviors of the current and voltage in different states of the machining. The regular pulse is characterized by a typically constant current and voltage profile.

With increasing feed rate, a current peak develops at the beginning of the pulse. This current peak is not interpreted as a short circuit, as the voltage behaves normally, and no short-circuit damage was visually identified when the machining was stopped. It is assumed that the gap regenerates during the pulse pause with fresh, uncontaminated electrolyte, allowing the first part of the pulse to result in a high current flow until the gap is saturated with gas and particles, causing the conductivity to decrease. To avoid false shutdowns with a cut-off static threshold, the current peak at the beginning must be considered, and the minimum usable static threshold must be set accordingly higher.

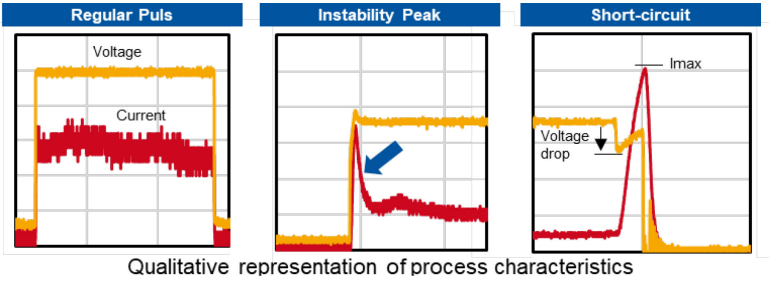

Figure 5: Different stability stages of Wire-ECM

As the feed rate continues to increase, the machining process becomes increasingly unstable until a short circuit suddenly occurs. The short circuit is clearly identified by a drop in working voltage and a rapid rise in working current.

Figure 6 provides an overview of short circuit marks on the wire tool at different machining parameters. The short circuit marks appear as circular to elliptical melted areas, typically forming a single, continuous short-circuit zone, without multiple individually distributed spots on the wire.

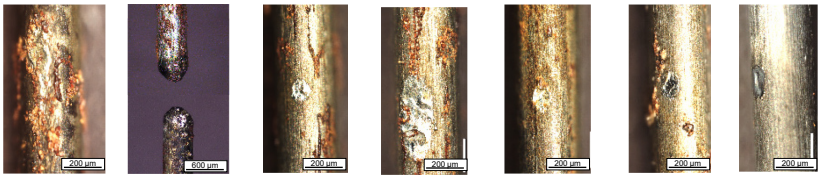

Figure 6: Overview on short circuit marks on the wire

As expected, the damaged area increases with rising current limits, since the short-circuit energy increases accordingly. However, it can also be observed that the working voltage influences the size of the short circuit. For instance, at

a lower voltage of 20 V, there is a tendency for large-scale melting. This can lead to a complete wire breakage, as shown in figure 6 (20 V; 140 A). In contrast, at 40 V, the short-circuit area is significantly smaller, with only small, point-like defect spots visible.

To evaluate the SC-defects on the workpiece, the cutting paths were shortened using Wire-EDM, allowing microscopic inspection of the craters. Figure 7 provides an overview of the positions of the short circuit areas and a detailed view of the short circuits themselves.

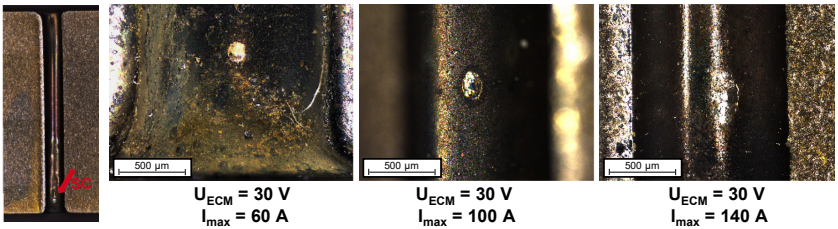

Figure 7: Cutting kerf with short circuit marks

As can be observed, the short circuit spots are in the frontal area, where the working gap is smallest. Additionally, they appear in the lower third of the cutting path due to the increasing contamination of the electrolyte along the wire path. No defects were detected in the kerf side. The short circuit defects range in size from approximately min. 50 µm to max. 450 µm in diameter on the workpiece. To precisely characterize the defects, metallographic cuts were carried out (Figure 8). Due to the small size of the defects, these areas must be precisely manually cut, ground and polished by experienced metallographers.

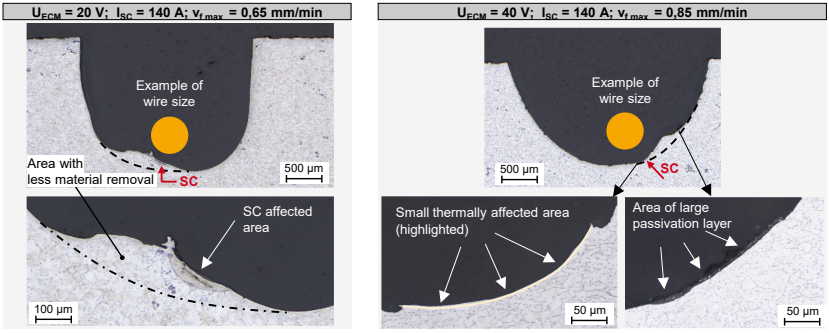

Figure 8: Cross section analysis of wire ECM short circuit areas

It can be observed that in the frontal area, material is not properly removed and remains, which is where the short circuit occurred. Adjacent to this region, a

strongly passivated area is visible. This suggests that the flushing was insufficient, leading to inadequate material removal, which resulted in the short circuit. As seen at the wire tools before, the damage is significantly greater at 20 V compared to a short circuit at 40 V. At 20 V, a clear melting zone is visible, whereas at 40 V, the damage is limited to just a few micrometers on the surface. The parameter set using 20 V resulted in a feed rate of 0.65 mm/min before a short circuit occurred, while the 40 V test achieved 0.85 mm/min. The varying feed rates also influenced the widening of the lateral gap. The kerf widens further at 0.65 mm/min because the wire moves more slowly, allowing additional time to machine the sides. In contrast, the wire travels faster at 0.85 mm/min, and the lateral gap remains narrower overall. For comparison, the wire tool was placed in the cutting path, showing the proportions between wire and kerf width. Given these geometric conditions and considering that the SC occurs in the frontal gap of the wire tool, it is unlikely that the SC will extend into the sidewall area. However, for components with thinner dimensions, the achievable feed rate increases, reducing the lateral gap widening and potentially increasing the likelihood of short circuits in the sidewalls. This risk is further heightened if the wire breaks and moves around, or if the shutdown is too slow. Overall, it can be concluded that, due to the size ratio between the lateral gap and the wire tool, it is unlikely that short circuits will remain in the sidewalls.

4 Summary

This paper presents the first analysis of the effects of short circuit defects on the workpiece damage in Wire-ECM machining. The machining process was intentionally destabilized until a short circuit occurred, enabling the assessment of its impact on the surface. It was observed that short circuits are individual spots, primarily in the frontal gap zone, without affecting the kerf side due to the large lateral gap. If machining continues, the damaged frontal area will be removed, leaving no damage on the cut sidewalls. In the next step, a correlation analysis between electrical parameters and rim zone effects can be considered.

Acknowledgements

The authors would like to acknowledge the German Research Foundation (DFG) for funding project 423318338: “Electrochemical wire cutting with axial high-pressure flushing and internally flushed tube tools” and project 532772852: “Characterization of component damage due to short circuits during electrochemical machining”.

References

[1] Bergs T. Harst S. Development of a process signature for ECM, CIRP Annals, Vol. 69 No.1, 2020, pp. 153 – 156,

[2] McGeough, J.A., Principles of ECM. Chapman and Hall; Halsted Press Division, Wiley, London, New York, 1974, ISBN: 978-0470584132

[3] Sous, F.; Heidemanns L.; Herrig, T.; Klink, A.; Bergs, T.: Experimental analysis on the accuracy of two-dimensional curved cuts in wire ECM, Proc. CIRP, Vol. 113, 2022, pp.398-403

[4] Klocke, F. Herrig, T., Klink, A. Evaluation of wire electrochemical machining with rotating electrode for the manufacture of fir tree slots. Proc. of the ASME Turbo Expo, GT2018-76910, V006T24A024

[5] Fang, Xiaolong; Han, Zhao; Chen, Mi; Zhu, Di; Pulse-current wire ECM with axial electrolyte flushing along a rotating helical wire tool; Journal of the electrochemical Society, vol. 167; 2020

[6] Klocke, F.; Herrig, T.; Zeis, M.; Klink, A.: Modeling and simulation of the fluid flow in wire ECM with rotating tool (wire ECM) AIP Conference Proceedings, Dublin, Ireland, 2017

[7] Sous, F.; Klink, A.; Herrig, T.; Bergs, T.: Experimental analysis on process performance as function of electrolyte properties and usage of sacrificial anodes in wire ECM, INSECT 2022, Tokyo

[8] Elektrochemisches (Draht-)Schneiden mit axialer Hochdruckspülung und innengespülten dünnwandigen Rohrwerkzeugen, DFG-Projekt Nr. 423318338, https://gepris.dfg.de/gepris/projekt/423318338

[9] Donachie, M.; Donachie, S.: Superalloys, A technical Guide, second edition, ASM international, 2002

[10] Herrig, T. Dissertation: Elektrochemisches Schneiden mit rotierender Drahtelektrode, RWTH Aachen University, 2020