

## Special Features of the Non-Conventional Cutting (ECM, EDM) of Wool-Like Material Structures

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**Abstract.** The non-conventional cutting of electrically conductive materials using WEDM and WECM and their hybrid processes is already standard in manufacturing technology. This is essentially based on homogeneous or layered materials. In the future, cellular, wool-like, or similarly structured materials will play a greater role and will be more important; especially the cutting in conjunction with homogeneous materials. In the study, experiments were carried out with a standard WEDM system and a WECM test system. In preliminary tests, various EC machine structures with different flushing and cutting directions have been tested, and because of the static wire arrangement, adjustments to a maximum working current have been tried out. Various feed speeds have been implemented for the test series and the influence of the wool structure on the regulation of the short circuits in the working gap has been analyzed. A modified equivalent circuit diagram has been created from the special features of the processing. The process regulation must be adapted to the special conditions of the spontaneous working gap reduction and thus the higher number of soft short circuits. The study should primarily show where the deviations of the WEDM and WECM from wool structures are; which changes have to be made, especially for process regulation. Secondly, it was determined which cutting structures arise and whether the partial discharges have a marginal effect on the cutting result in both processes.

### Introduction

Resource efficiency and the mechanical properties [1] are first reasons for the use of metallic fiber networks. In general, cellular structures are also used to combining materials from any material group with one another using immersion alloys. The increased surface area due to the cellular structure is also of great importance. Therefore, cellular structures are the key technology for the manufacture and innovation of catalysts, heat exchangers and electrodes [2]. A challenge is the production and processing of such structures. That is why we are investigating the processing parameters cutting of inhomogeneous metallic structures at this point by Wire - ECM [3, 4] and Wire - EDM [5, 6]. In this study, is used steel wool with a fiber thickness of 35 µm. The samples has a cylindrical dimension of 95 mm length and a diameter of 35 mm (Figure 1) and a weight of 200 g. The material density is calculated to 2288 kg/m<sup>3</sup> in relation to 7874 kg/m<sup>3</sup> of Fe. We realize that just 29% of the probe volume is steal. According to Figure 1, this structure can be open or fitted into a metallic frame. The latter can reduce the inhomogeneity by compressing it, i.e. the air areas are extremely reduced. The open structures, on the other hand, have limited free mobility of the wool threads. This movement arises from the dissolution of internal tensions and leads to various types of short circuits, which will be analyzed later.

The aim of the study is to find out how the removal phases in WEDM and WECM change compared to the processing of homogeneous materials and how these changes must be taken into account in the process regulation.

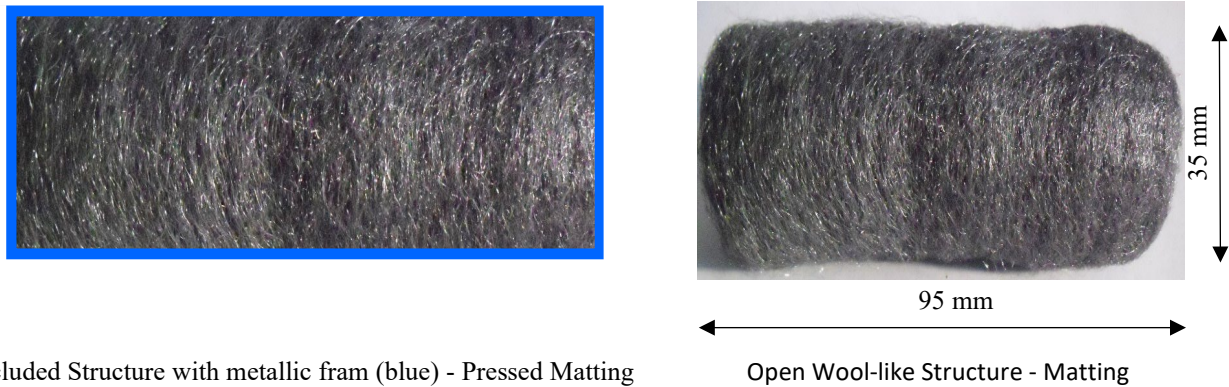


Figure 1 : Included and open wool-like structure

### Simple Models and Process Analysis

First, models have to be set up for various boundary conditions in order to analyze the changed influences; they then have to be converted into simple equivalent circuit diagrams. In the first analysis, the models should be considered based on the wool structure. A distinction can be made between three main cases. In case 1 (Fig. 2, left) the thread structure of the wool runs parallel to the cutting wire. In case 2 (Fig. 2, middle) the wool wire is perpendicular to the cut wire and does not represent a flat, homogeneous surface. In case 3 (Fig. 2, right) the wool- wire structure is a mix of the first two cases, pressed and the wires hooked together - matted.

In the first case, the wool threads are removed evenly and quickly during WEC processing, and if the working gap is sufficiently large, there should be no major short circuit. When the cutting wire is fed-back, a wool thread is again parallel and, in addition, the thread ends of the wire that was previously removed. The latter are dissolved more quickly due to the higher current density or, in the worst case, a short partial discharge (PD) takes place. The PD can only become critical if more than the wool thread end evaporates, i.e. additional wool thread loops are separated. In the regulation of the process, these appear as electrical short circuits (soft short circuits) that do not have to be corrected. The current analysis categories are summarized in Table 1, and assigned to process regulation.

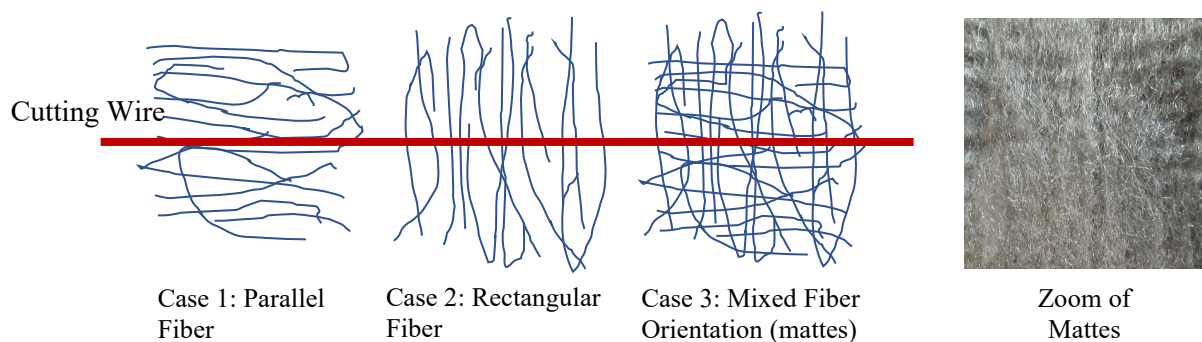


Figure 2: Left - parallel wool-thread; middle - rectangular wrapped wool-wire; right- matting-mix wool-thread

Table 1: EC processing categories

Categories	Description	Process control
A	ECM	Gap regulation
B	Short-term (soft) short circuits	no
C1	PD, short-term	no
C2	PD, long-term	Current off
D	Hard mechanical short circuit	Stop / reverse feed and power off
E	Arcs	Power off; Feed stop
F	Open circuit	Minimize via feed control

There is no homogeneous removal for the WED processing, i.e. the local removal of the wool threads can break the wool threads into smaller pieces of thread, which depending on the arrangement of the wool structure and cutting wire in the working gap, can form a hard short circuit or fall out of the working gap. The local discharges can also take place on other wool threads or the base points of the plasma channel can jump over to another wool thread. As a result, the first wires are not only ablated in the wool thread level, but also in the depths. The ignition voltage and the working current, more precisely the increase in current, primarily determine these case differences. The process analysis for the WEDM is compiled in Table 2.

Table 2: ED processing categories

Categories	Description	Process control
A	EDM	Gap regulation
B	Short-term (soft) short circuits – wool thread particles	no
C1	Possible EC ablation with contaminated deionized water	no
C2		
D	Hard mechanical short circuit	Stop / reverse feed and power off
E	Arcs	Power off; Feed stop
F	Open circuit	Minimize through feed control

For case 2 (Fig. 2), the initial phase of processing is primarily to be considered. In this arrangement, the cut wire is opposed to a wool structure that is initially uneven due to the wool thread diameter and the winding spacing. For the WECM application, there are different working gaps and different current densities, which try to level the wool structure at the beginning. In these leveling attempts, many woolen wire loops are cut and if there are no entanglements, it leads to many localized gap reductions or soft short circuits. The WEC- effective area is smaller than in case 1 and is further reduced by the loop breaks. Using a current source increases the depth of removal and the current efficiency factor.

With WEDM, the wool structure means that the discharges are localized largely at the beginning. Thanks to the very thin woolen threads (35  $\mu\text{m}$  in diameter), the discharge can also jump to deeper-lying woolen wires and thus cut several loops of woolen thread.

For case 3 (Fig. 2), the erosion states combine, but this is more favorable for regulating the process because the probability of hard short circuits, which can have a destructive effect, is very low.

### Equivalent Circuit Diagram

In the equivalent circuit diagram (Fig. 3), the resistance of the wool-like material structure, in which the resistance of the working fluid also has an effect, is of particular importance. The internal resistance of the PES and the  $R_{\text{line}}$  resistances are constant, while  $R_{\text{gap}}$  and  $R_{\text{wool}}$  change according to the EC or ED application. In the case of an ECM,  $R_{\text{gap}}$  assumes a few  $\text{m}\Omega$ , while with the EDM it

approaches a value of  $M\Omega$  and only assumes a value close to zero locally at the location of the discharge.

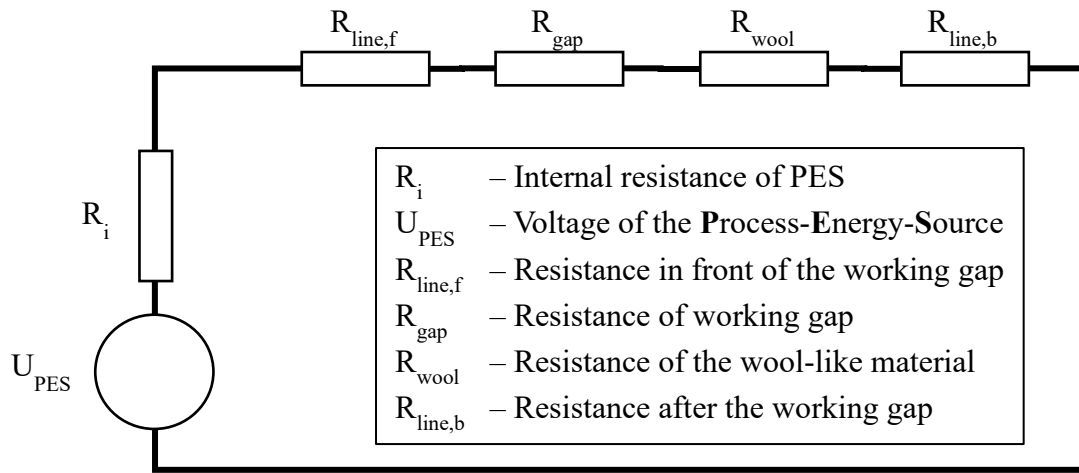


Figure 3: Equivalent circuit diagram

In simplified terms, the resistor  $R_{wool}$  is a parallel connection of very different elements. First, the parallel connection of the wool thread resistors can be considered. A second parallel resistance corresponds to the spaces between the wool threads. One can make at least three case distinctions. If the intermediate element is air, the resistance can be calculated towards infinity and this proportion can be neglected in the parallel connection. When the wool structure is immersed in the electrolyte, the resistance drops until the wool structure has soaked up with the electrolyte and assumes a final value.

In the case of the investigations, the measured value  $R_{wool,air}$  was about 800 to 900  $m\Omega$  a short time after immersion about “200  $m\Omega$  and after soaking 80  $m\Omega$ , which is of great importance because the  $R_{line}$  values are 15 to 25  $m\Omega$  and the  $R_{gap}$  value for smaller gap widths are of a similar order of magnitude. Assuming a constant working voltage  $U_{PES}$ , the current would drop extremely and cause no EC erosion.

### Experimental Setup

The wire cutting experiments were carried out on a Hitachi 6Q, while a wire cutting system according to Fig. 4 was set up for the EC experiments and a laboratory source developed in-house for DC / AC operation was used.

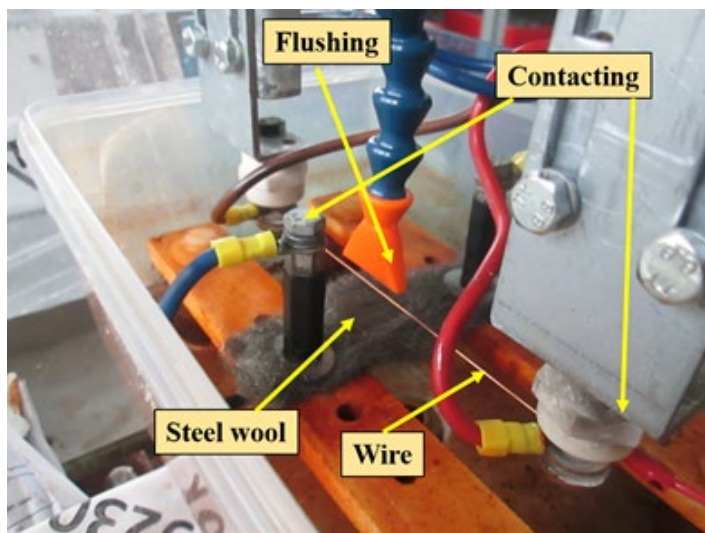


Figure 4: Experimental setup for WECM [7]



The cutting parameter for the WEDM is a feed rate of 25 mm/min. with three different processing stages. In the first cut, a post-cut configuration was used with a very low pulse energy and pulse duration of around 1  $\mu$ s. In two further cuts, main cutting parameters with low and high pulse energy were used. The process regulation was changed according to the technology requirements for Hitachi. In the case of the ECM, there was a rigid Cu wire 0.7 mm in diameter and a flat flushing nozzle over the cut area. The NaNO<sub>3</sub> or NaCl solutions used had an electrical conductivity of  $110 \pm 10$  mS/cm. Working currents of 20 A to 25 A were achieved at working voltages of 20 DCV to 24 DCV. The feed speeds varied from 1 mm/min. to 36 mm/min.

## Results of the Cutting Processes

### WEDM

The cutting results for the main and re-cuts are compiled in Fig. 5. The main cut and the re-cut show copper deposits, which may have been caused by the non-optimized cutting parameters.

The very straight cut surfaces have significantly less merging of the wool threads (fibers) in the main-cut-than in the re-cut-conditions. It can be assumed that the separated wool threads evaporate strongly, which also explains that the original wool structures are present in the re-cut parameter area.

The average processing time of 120 s can be optimized even further.

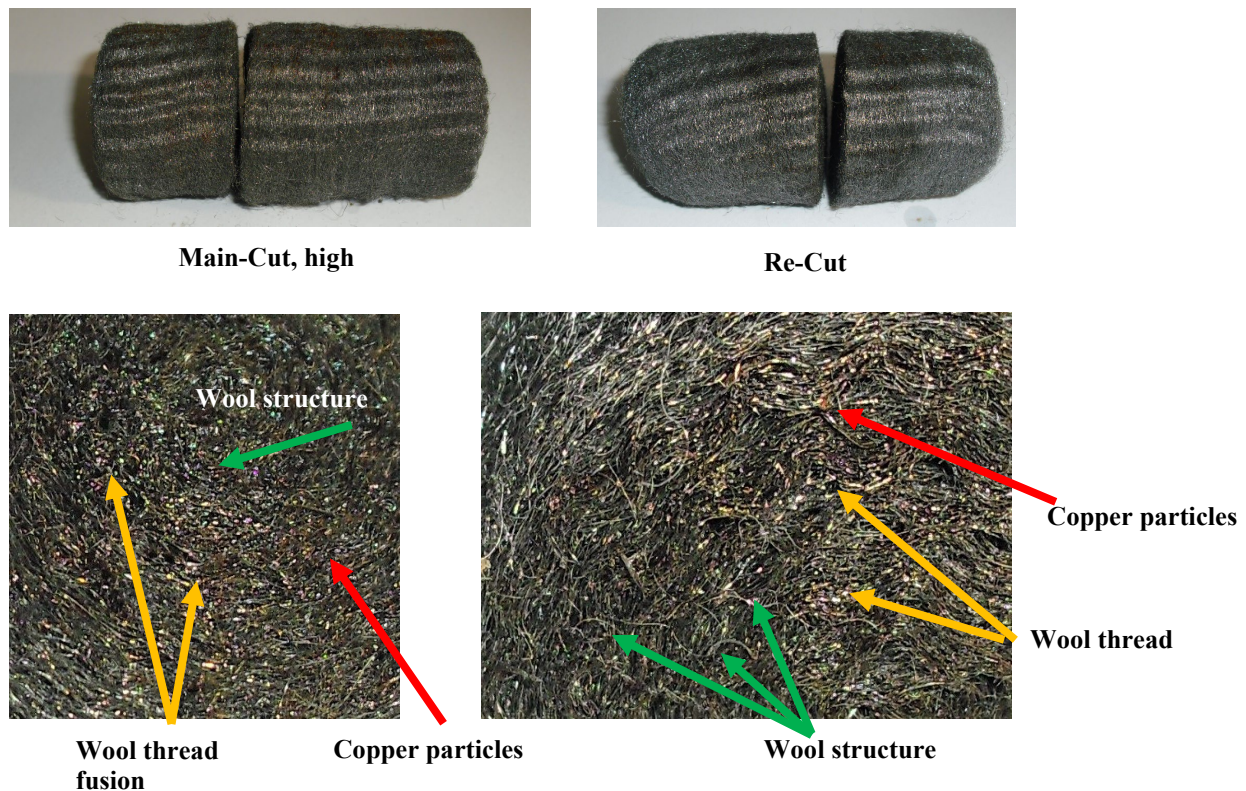


Figure 5: Cut-Working gap and Cut-Surface for different pulse energy

### WECM

In Fig. 6 the results of a series of tests are shown, which arise in the WECM in an electrolyte bath or in a broad jet flushing.

It can be seen that the cut gaps are very different; while the bath flushing (Fig. 6,D) has a smaller but very irregular cut, the jet flushing (Fig.6,C) shows a wider working gap in a more homogeneous form. In both cases, in contrast to WEDM processing, there is also a strong removal effect in the side-areas (Fig. 6,A, B).

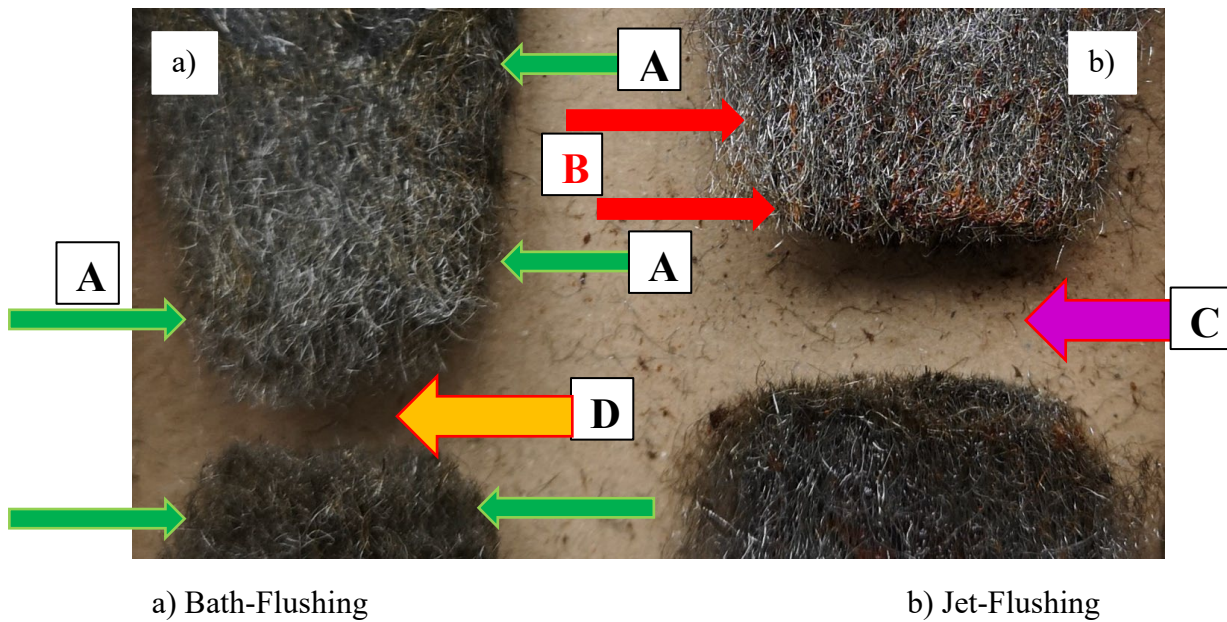


Figure 6: Comparison on Bath-WECM and Jet-WECM

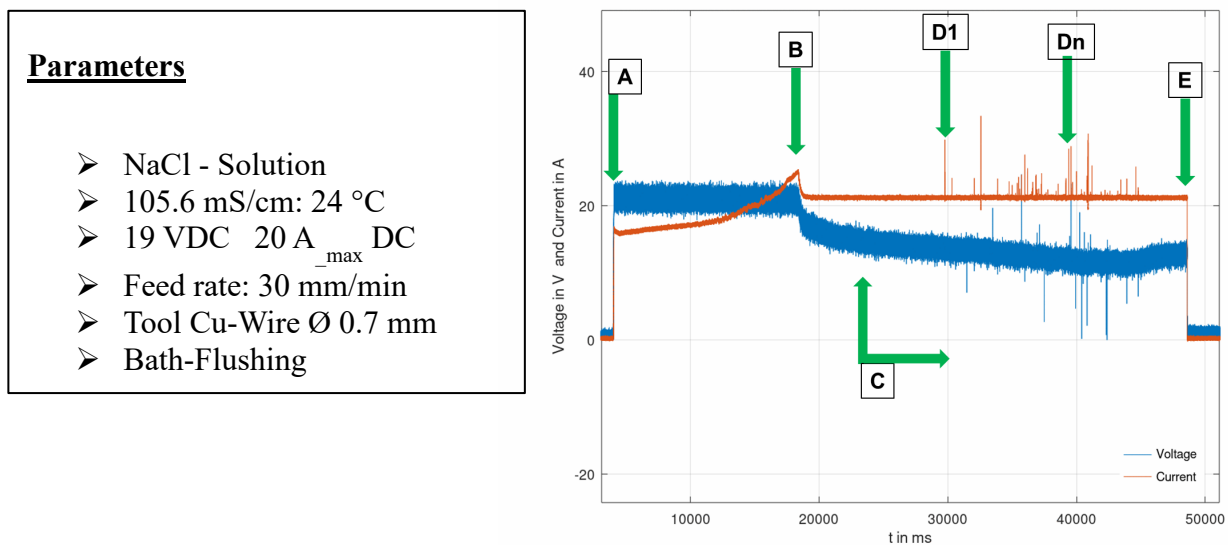


Figure 7: WECM on wool-like structure with bath flushing

It can be seen that the cut gaps are very different; while the bath flushing (Fig. 6,D) has a smaller gap. An almost optimal section under bath conditions can be seen in Fig. 6. The maximum feed rate is 30 mm/min, slightly higher than with the WEDM, but the lateral removal (Fig. 6,D,C) is significantly higher; therefore, the WEDM cut must be classified as better.

In the diagram of Fig. 7A-B, it is to be seen that the current increases at constant voltage until the current limit is reached. Since the process energy source (PES) is a current source, the voltage then collapses somewhat and the current remains constant (Fig. 7C). The subsequent partial, soft short circuits (Fig. 7,D1 ... Dn) no longer disrupt the cutting process.

An uninterrupted cut is shown in Fig. 8, the cutting process beginning at point B and ending at point F in the diagram. With a constant working voltage, the current increases continuously, which is explained by the fact that the contact surface changes with the relatively large copper wire. A current dip occurs at point Re, which occurs because the wool-like structure is wrapped around the tool wire and short circuits occur both in the forward feed and when the feed is stopped. The maximum feed

rate of 15 mm / min. Is therefore not achieved in all sections of the cutting course. At the end of the cut, soft short circuits occur more frequently after point D1.

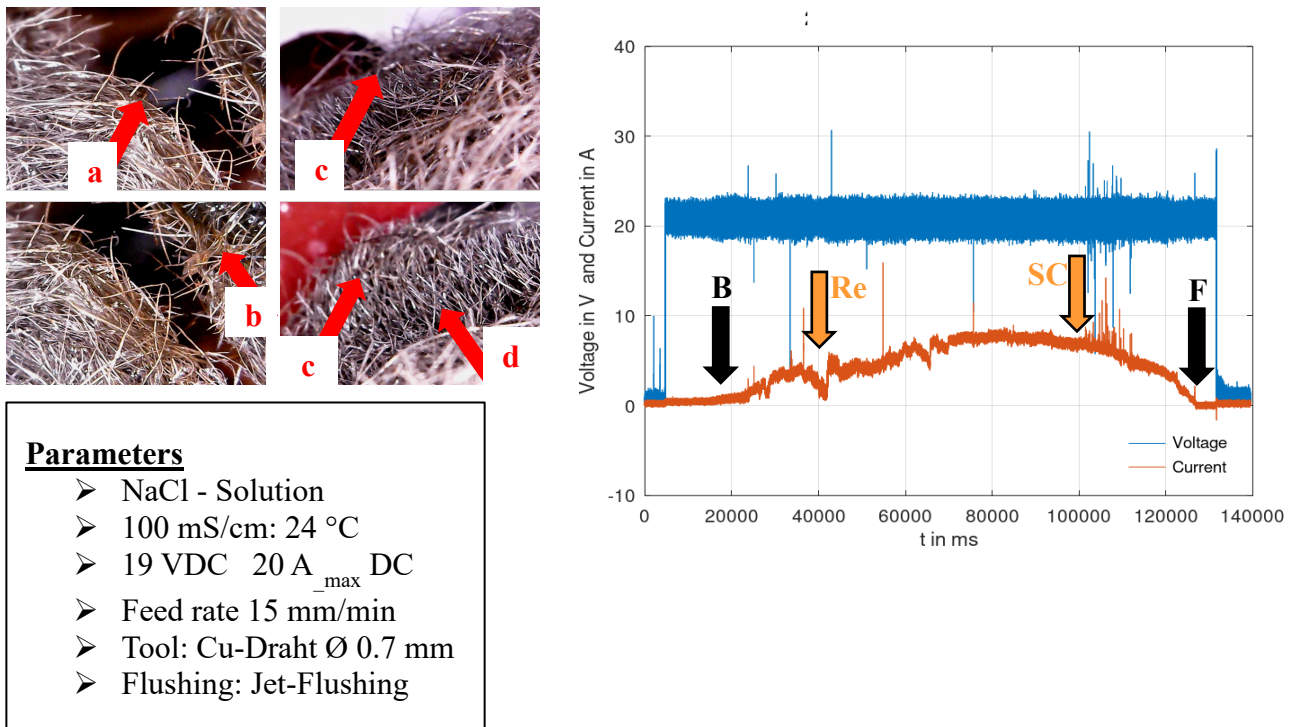


Figure 8: WECM of wool-like material and Diagrams of voltage and current

In contrast to WEDM processing, significantly fewer melting pearls (Fig. 8,c) can be seen with the WECM. This effect can occur because soft short circuits usually lead to the evaporation of longer wool threads and the subsequently dominant EC ablation removes the melt beads. With WEDM, the wool structure is removed locally and the subsequent pulse takes place on a very distant surface area. With WECM, too, material (Fig. 8,b) of the Cu workpiece is transferred, which can also be due to the fact that no process optimization took place and thus the deposition processes are still occurring more frequently. That the depth effect of the EC removal process is very great can be seen in Fig. 8,d. Position a shows that the wool threads are removed after the model presentation in Fig. 2.

## Conclusion

The processing of wool-like structures shows that both WEDM and WECM have additional effects that must be taken into account when regulating the process. A main effect is that the wool structure can wrap itself around the copper wire tool and thus more and more soft short circuits. However, these short circuits cannot be localized, so that retraction of the feed will not necessarily be a solution. The soft short circuits must therefore be accepted and assessed according to their effective time. The aim here is to select a larger front gap for machining and to aim for a high feed rate. The pulsing brings clear advantages and more control options in both cut variants.

In the case of wool-like structures, the quality of the cut can no longer be determined by the roughness or a gloss effect. New criteria will be the penetration depth of the cut effect, the number of melting pearls in the area of influence, the transfer of the tool material into the wool structure and the retention of the properties of the wool structure.

## Conflict of Interest Statement

The authors certify that they have NO affiliations with or involvement in any organization or entity with any.

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