

# Experimental Investigation of the Effect of EDM Debris Particles Mixed into the Dielectric Fluid on Tool Feed Rate in Drilling-EDM

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**Abstract.** In this paper the potential of the recirculation of the EDM debris particles of the workpiece material into the dielectric fluid to increase the tool feed rate  $v_f$  in drilling Electrical Discharge Machining (drilling-EDM) is experimentally investigated. Two-Channel tool electrodes made of copper (Cu) and brass (CuZn) in the range from 1.0 mm to 2.5 mm were used. The effect of the EDM debris particles in the dielectric fluid was investigated at a discharge current  $i_e$  of 25 A, a discharge duration  $t_e$  of 50  $\mu$ s and a duty cycle of 80 % by comparing the EDM pulse characteristics and the feed rate  $v_f$  of the EDM process with and without debris particles added to the dielectric fluid (particle concentrations  $C_1 = 2.5$  g/l and  $C_0 = 0$  g/l, respectively). By the recirculation of EDM debris particles the feed rate could be increased up to 36 % depending on the machining conditions. Furthermore, it was observed that the increase in the feed rate is due to the increase of the percentage of discharge pulses and the decrease of short-circuit pulses as well as a more stable machining process.

## Introduction

Drilling Electrical Discharge Machining, also referred to as fast hole drilling, is a commonly used machining process in the die and mold making industry to produce start holes for the following wire-EDM process. In the case of start holes the main focus lies on a high machining speed and there are only minor requirements on the borehole quality. Nevertheless, for complex or multiple parts numerous start holes might be necessary and their production might become relatively time consuming. Therefore, new approaches to reduce the machining time are of interest to users of the drilling-EDM manufacturing method. Moreover, drilling-EDM is also used in other industries such as off-shore equipment, injection molding and automotive due to its capability to produce boreholes with high aspect ratio in hard-to-machine materials.

Powder Mixed Electrical Discharge Machining (PMEDM) is a widely studied approach to improve the EDM process [1, 2]. By adding electrically conductive particles such as Al, Cr, Ti or graphite to the dielectric fluid the dielectric strength is reduced leading to a greater distance between the workpiece and the tool electrode, also referred to as the frontal machining gap. Furthermore, a chain of particles is formed, temporarily bridging the gap between the electrodes, improving the discharge probability and the spark ignition at larger gaps [1, 2, 3]. Under appropriate machining settings a more stable machining process and higher material removal rates have been observed in various studies [4, 5, 6]. It is reported that by adding electrically conductive particles into the dielectric fluid the surface roughness and machining stability were improved during the finishing process [6, 5, 7, 8, 9, 10, 11]. However, the majority of these studies were done on sinking-EDM systems, in hydrocarbon-based dielectric fluids and with finishing regimes with rather low discharge energies. To date, most studies have been carried out with additional powder materials different from the workpiece material. In this paper, the potential of a cost-efficient way to increase the tool feed rate  $v_f$  in drilling-EDM by the recirculation of EDM debris particles of the workpiece material is explored.

## Experimental Setup and Procedure

All experiments were carried out on a drilling-EDM system of the German company “bes Funkenerosion GmbH” equipped with a static pulse generator. The EDM debris particles were

obtained through EDM drilling in the workpiece material X155CrMoV12-1 according to DIN EN 10027-1:2017-01 (AISI D2 according to ASTM A681-08).

When electric discharge machining in water based dielectric fluid the formation of smut was observed. In [12, 13] this phenomenon was explained to be the formation of a brittle oxide layer caused by electrolytic effects in water-based dielectric fluids due to its remaining electrical conductivity compared to hydrocarbon-based dielectric fluids. The observed smut might distort the measurement of the particle diameter distribution and the experiments. Therefore, the particles were collected and ultrasonically cleaned. Particle size analysis on a 'Cilas Particle Size Analyzer 920' showed a volume-related  $d_{90}$  quantile of about 20  $\mu\text{m}$  to 25  $\mu\text{m}$  (Fig. 1). It has to be mentioned that a higher pulse duration  $t_e$  leads to a greater value of the volume-related  $d_{90}$  quantile of the diameter distribution. The reason for that can be the increase in the diameter of the plasma-channel and the molten pool, leading to greater amounts of material removed per single discharge [14, 15, 16]. For the discharge current  $i_e$  no significant effect on the diameter distribution was observed.

For the contamination of the dielectric fluid a separate tank including a stirrer and a circular flow through a heat exchanger were set up for the dispersion of the EDM debris particle as well as the cooling of the dielectric fluid. Additionally, the supply line length from the high-pressure pump up to the infeed axis was shortened to a minimum. The bypass-valve for the recycling of the dielectric fluid was also moved to the infeed axis to ensure a maximum flow velocity in the supply line in order to reduce the danger of particle sedimentation. Preliminary tests were carried out to identify a sufficient particle concentration  $C_1$  of 2.5 g/L. Flushing tests showed that the maximum loss of the particle concentration was 20 %. With respect to the observations regarding a sufficient particle concentration the concentration loss was assumed to be negligible and the dispersion of the EDM debris particles to be sufficient.

To investigate the effect of the EDM debris particles on the drilling-EDM process, the EDM system's detected amounts of occurring short-circuit-pulses SCP, discharge-pulses DP and open-circuit-pulses OCP were recorded and stored. Using this data, appropriate machining settings for the feed gain setting SV were identified to avoid open-circuit-heavy machining conditions. A high percentage of open-circuit-pulses OCP with no short-circuit-pulses SCP might indicate an inefficient EDM process since the infeed axis movement "drags" behind the material removal process. By increasing the infeed axis' movement speed (increase in feed gain SV) the percentage of open-circuit-pulses OCP can be reduced to the benefit of a higher percentage of discharge-pulses DP and a higher feed rate  $v_f$  [17].

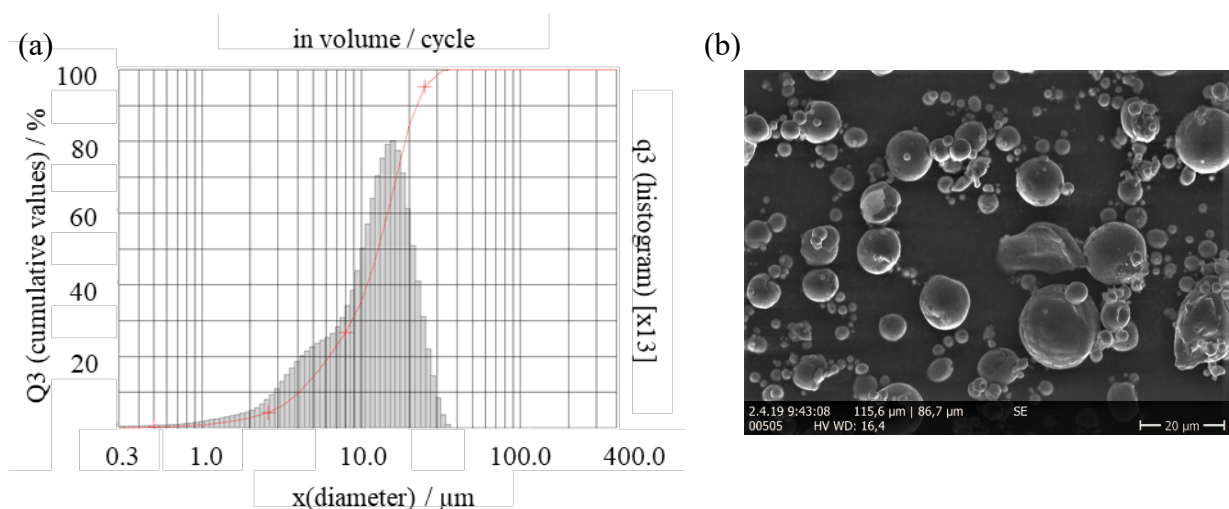


Fig. 1: (a) histogram of the particle size analysis obtained on the Cilas Particle Size Analyzer 920 and (b) secondary electron microscope image of the collected EDM debris particles.

Therefore, open-circuit-heavy machining conditions need to be avoided, since the feed rate  $v_f$  might be limited by the feed gain setting SV and the detection of an effect of the EDM debris particles on the feed rate  $v_f$  might not be ensured.

All experiments were done in the tool steel material X155CrMoV12-1 (AISI D2). A cathodic tool electrode polarity and deionized water as base dielectric fluid were used for all experiments. The experiments were done with copper (Cu) and brass (CuZn) tool electrodes. Preliminary tests were carried out as through holes in a workpiece of 15.0 mm thickness. For the main experiments the feed gain SV was set according to the preliminary test results for the different tool electrode diameters and materials and kept constant for the experiments with and without EDM debris particle contamination (Table 1). At least five repetitions were done for each machining condition. The relevant target parameters feed rate  $v_f$  and tool wear ratio  $\vartheta$  were calculated according to equation Eq. 1 and Eq. 2 respectively.

$$v_f = \frac{\text{Machining Depth}}{\text{Machining Time}} \cdot \frac{\text{mm}}{\text{min}} \quad (1)$$

$$\vartheta = \frac{\text{Tool Electrode Wear}}{\text{Machining Depth}} \cdot \frac{\text{mm}}{\text{mm}} \cdot 100 \% \quad (2)$$

Table 1: Machining and experimental conditions for the main experiments.

D [mm]	Tool material	Feed gain SV [-]	Particle concentration C [g/L]	Open voltage $\hat{u}_i$ [V]	Discharge current $i_e$ [A]	Discharge duration $t_e$ [ $\mu$ s]	Duty cycle $\tau$ [%]	Referenc e voltage GAP [-]	Flushing pressure p [MPa]
1.0	Cu	15	C0 = 0.0 C1 = 2.5	70	25	50	80	20	4
	CuZn	30							
1.5	Cu	15							
	CuZn	25							
2.0	Cu	10							
	CuZn	15							
2.5	Cu	10							
	CuZn	10							

## Results and Discussion

Fig. 2 shows some results obtained by the preliminary tests. In plain deionized water with a CuZn tool electrode and tool electrode diameter of 2.0 mm about 500 short-circuits pulses SCP were recorded at the lowest feed gain setting  $SV = 5$  (Fig. 2a, CuZn, C0). With higher feed gain settings, the amount of recorded short-circuit pulses SCP increased linearly. At a feed gain setting of  $SV = 20$  the amount of short-circuit pulses SCP increased by a factor of four. At the same time an increase in feed rate  $v_f$  was observed with a maximum value of roughly 9.5 mm/min at a feed gain setting of  $SV = 15$  (Fig. 2b, CuZn, C0). With an even higher feed gain setting of more than  $SV = 15$  the feed rate decreased again to  $v_f = 8$  mm/min at a feed gain setting of  $SV = 20$ . With EDM debris particles added to the dielectric fluid at constant feed gain setting SV the amount of short-circuit pulses SCP was reduced significantly. The maximum feed rate  $v_f$  of roughly 12 mm/min was obtained at a feed gain setting of  $SV = 20$  (CuZn, C1, Fig. 2a and Fig. 2b respectively). A similar behavior was observed for Cu tool electrodes, whereas with CuZn tool electrodes a generally lower amount of short-circuit-pulses SCP and a higher feed rate  $v_f$  was obtained.

With higher settings for the feed gain SV the infeed speed of the infeed axis increases. Less short-circuit-pulses allow higher settings for the feed gain SV. Meaning a faster infeed of the infeed axis can be obtained without the occurrence of excessive retraction movements. Therefore, the maximum for the feed rate  $v_f$  shifts to a higher feed gain setting SV.

As stated in the findings of other investigations with regards to the Powder-Mixed-EDM process, it is assumed that the EDM debris particles in the working gap lead to a lower dielectric strength causing discharges to occur at wider frontal gaps and avoiding short-circuits that cause retraction movements of the infeed axis.

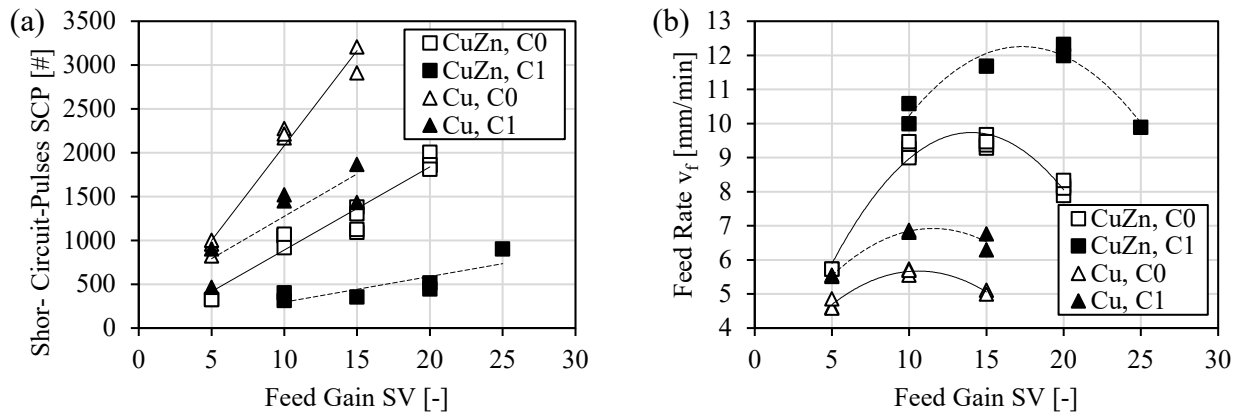


Fig. 2: (a) amount of short circuit pulses SCP and (b) feed rate  $v_f$  over feed gain SV without and with EDM debris particles added for CuZn and Cu tool electrode. Tool electrode diameter  $D = 2.0$  mm.  $C0 = 0.0$  g/L and  $C1 = 2.5$  g/L.

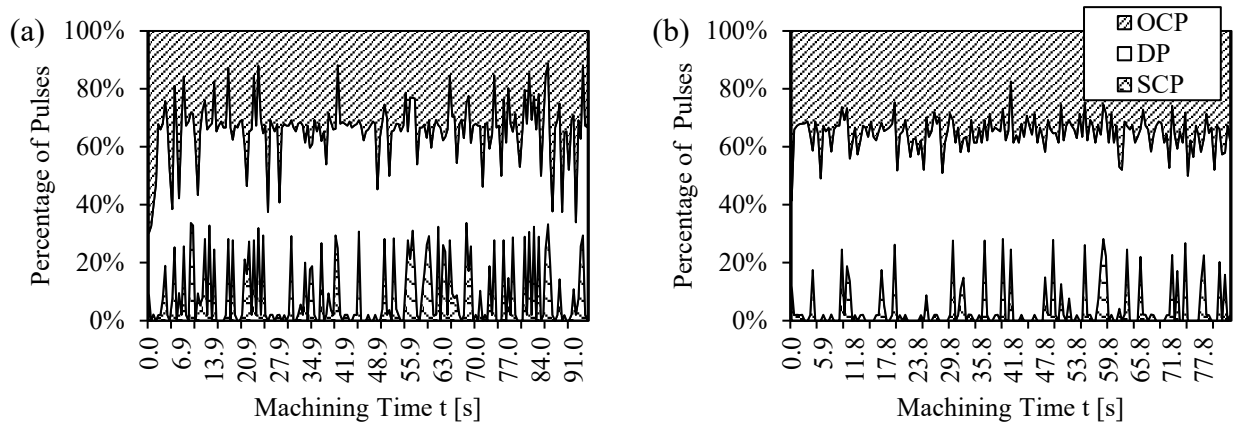


Fig. 3: Percentage of pulses over machining time  $t$  for (a) without (C0) and (b) with (C1) EDM debris particles added to the dielectric fluid.  $D = 2.0$  mm, CuZn tool electrode,  $SV = 15$ .

The percentage of open-circuit-pulses OCP, discharge-pulses DP and short-circuit-pulses SCP over the machining time  $t$  for a single borehole without (C0) and with (C1) EDM debris particles added to the dielectric fluid are shown in Fig. 3a and Fig. 3b respectively. It can be seen that the percentage of short-circuit-pulses SCP were slightly lower and occurred less frequently compared to the drilling process without EDM debris particles added. Furthermore, the deviation of the percentage of detected discharge-pulses DP was reduced indicating a more stable EDM process.

For all main experiments the percentage of short-circuits-pulses SCP was lower and the tool feed rate  $v_f$  higher when EDM debris particles were added to dielectric fluid (Fig. 4 a and b). With a CuZn tool electrode of  $D = 1.0$  mm a feed rate  $v_f$  of 35.5 mm/min was obtained which was the highest feed rate of all experiments. The reference feed rate with no added particles (C0) was about 27.1 mm/min. With a Cu tool electrode of 1.0 mm a feed rate of 15.8 mm/min was obtained. The reference feed rate with no added particles (C0) for this tool electrode was about 12.0 mm/min. The observed feed rate  $v_f$  declined with larger tool electrode diameter  $D$ . The reason for a generally declining feed rate is the greater machining surface in feed direction and larger material volume that has to be removed.

With increasing tool electrode diameter and therefore, increasing machining surface more discharge-pulses are necessary at constant discharge current  $i_e$  and discharge duration  $t_e$  for a certain increment of infeed resulting in a generally longer machining process and lower feed rate  $v_f$ .

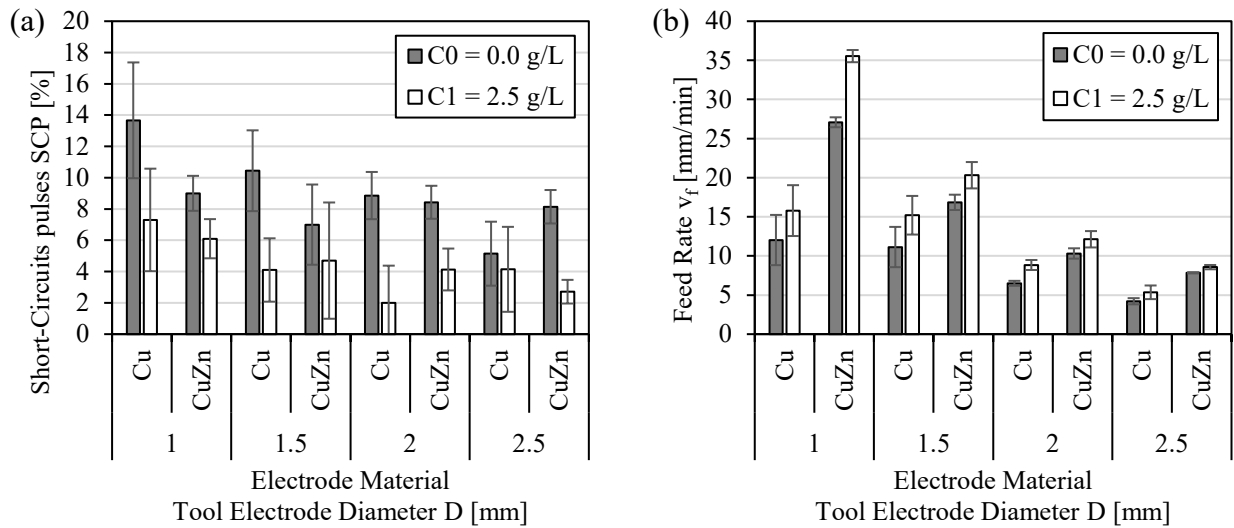


Fig. 4: (a) percentage of short-circuit pulses SCP and (b) feed rate  $v_f$  for different tool electrode diameter, material and EDM debris particle concentrations  $C$ .

The highest increase in feed rate  $v_f$  of 36.5 % was obtained with a Cu tool electrode of  $D = 1.5$  mm (Fig. 5a). With a CuZn tool electrode the increase in feed rate  $v_f$  was generally lower compared to Cu tool electrodes. Here, the highest increase in feed rate  $v_f$  was about 31.2 %. The effect of increased feed rate  $v_f$  also showed a declining trend with larger tool electrode diameters. A clear dependency of the effect on the tool electrode diameter and material cannot be given since the machining parameters that define the discharge energy were kept constant. Other machining parameters such as the reference gap voltage GAP, the feed gain setting SV and the dielectric flow rate, which also have a significant effect on the machining performance as reported in [12, 17, 18], were not optimized for the different tool electrode diameters.

On the other hand, EDM debris particles in the dielectric fluid mainly led to a higher tool wear ratio  $\vartheta$  (Fig. 5-b). Only for the tool electrode diameter of  $D = 1.0$  mm a lower tool wear ratio  $\vartheta$  was observed compared to plain deionized water. With a 2.5 mm Cu tool electrode the highest increase in tool wear ratio of 39.4 % was observed. With a 1.0 mm tool electrode the tool wear ratio was lower compared to machining with plain deionized water for both tool electrode materials. The CuZn tool electrodes showed a generally lower change in the tool wear ratio  $\vartheta$  compared to Cu tool electrodes.

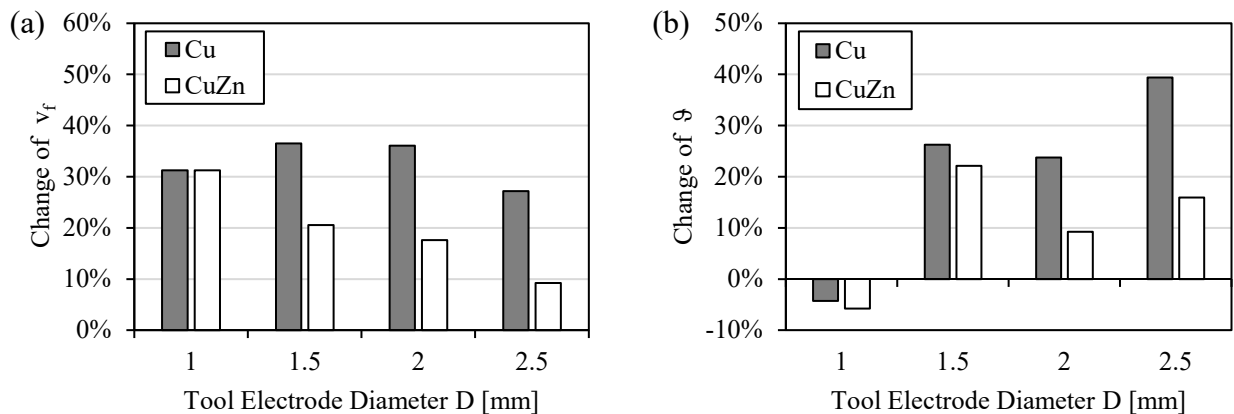


Fig. 5: Average change in (a) feed rate  $v_f$  and (b) tool wear ratio  $\vartheta$  for different tool electrode diameter  $D$  and material due to 2.5 g/L EDM debris particles added to the dielectric fluid.

Photographs of the borehole entry are shown for the tool electrode diameter of 1.0 mm (Fig. 6a and b) and 2.5 mm (Fig. 6c and d). Fig. 6e shows the normalized borehole diameter and the standard deviation (error bars) of the borehole diameter for all main-experiments done. The normalization was done for visualization purposes. For the normalization the borehole diameter obtained with plain

deionized water for each tool electrode diameter and material was used as reference value ( $C_0 = 0.0$  g/L). Regarding the borehole roundness, diameter and standard deviation no significant influence of debris particles added to the dielectric fluid was observed (Fig. 6).

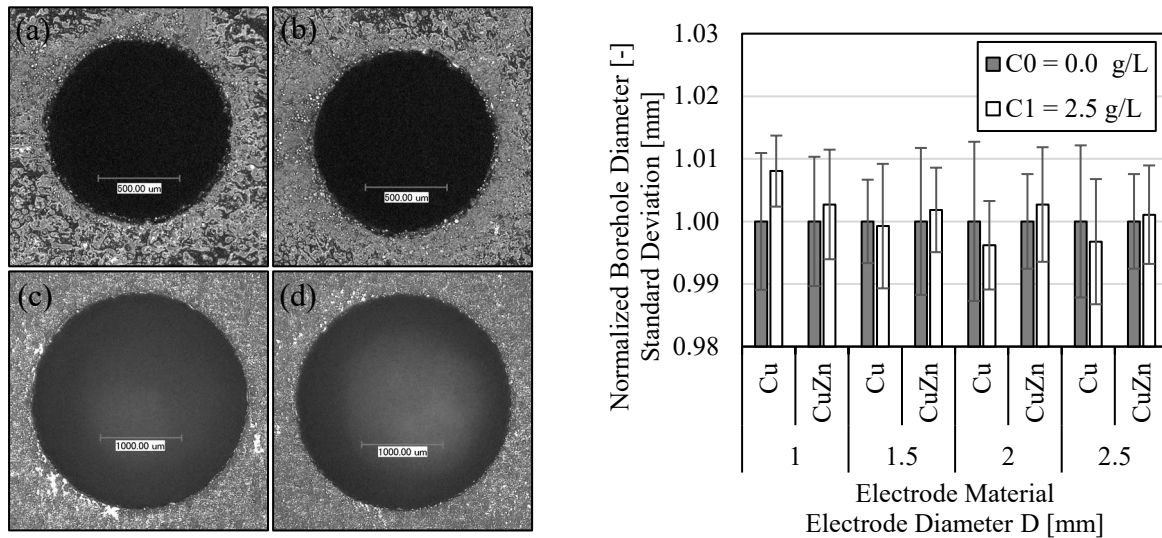


Fig. 6: Photograph of borehole entry produced with tool electrode diameter of 1.0 mm (a) without and (b) with respectively an electrode diameter of 2.5 mm (c) without and (d) with debris particles added to the dielectric fluid. (e) normalized borehole diameters and standard deviation for all main experiments done.

## Conclusion

In the investigations carried out it was observed that the recirculation of 2.5 g/L of EDM debris particles of the workpiece material to the dielectric fluid led to a lower percentage of short-circuit-pulses and a higher percentage of discharge-pulses detected by the drilling-EDM system. The lower percentage of short-circuit-pulses led a more stable infeed of the infeed axis and stabilizing the drilling-EDM process which could be shown by a lower standard deviation of the detected pulses over the course of a single drilling procedure. Furthermore, a slight increase in the percentage of discharge-pulses was observed and the feed rate  $v_f$  was increased compared to the reference experiments done in deionized water with no added EDM debris particles. The effect was observed for four different tool electrode diameters ranging from 1.0 mm to 2.5 mm and for the tool electrode material copper (Cu) and brass (CuZn). The experiments have shown that EDM debris particles added to deionized water can be a measure to increase the feed rate  $v_f$  and improve the productivity of the drilling-EDM process.

However, in the experimental results shown here the effect was declining with increasing tool electrode diameter and a mainly higher tool wear ratio was observed when EDM debris particles were added to the dielectric fluid. It has to be mentioned that the results presented in this paper are of experimental nature and cannot be directly transferred to other EDM systems or machining conditions. Further experiments have to be carried out to investigate the full potential as well as the practicality of the recirculation of EDM debris particles to increase the drilling-EDM productivity.

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