Materials Research Proceedings 28 (2023) 1781-1788 https://doi.org/10.21741/9781644902479-193

Influences in deep hole sinking (EDM, ECM) that make it difficult to analyze the process status

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Keywords: EDM, ECM, Hybrid Processes, Process Analysis

Abstract. A particular problem of deep hole sinking is the correct process analysis during the sinking process. It is important to know the primary technological objectives and to design the process regulation accordingly. Due to the objectives high removal rate, minimum roughness of the inner surface, high dimensional accuracy, etc., the analysis criteria are clearly changed and must be made available to process regulation. Another influencing parameter is the structure of the process energy source (PES).

Introduction

When sinking deep holes, it is of particular importance that the current process status of the machining process is precisely analyzed in order to give the process controller the correct signals to continue machining. In the following article, the two basic methods ECM and EDM will first be discussed, with the special features in the areas of the frontal, the lateral and the transition gap being considered. Differences in these areas occur particularly when the feed rate deviates greatly from the current removal rate. Another machining case is when the inner surface of the countersink is to be designed in a defined manner.

When using a hybrid processing method between EDM and ECM, the current and voltage curves analysis becomes even more complex because transient pulses also occur. It must also be noted that the ED parts of the machining take place in an electrolyte and are only local, while the EC removal always takes place over a large area. This raises the question of whether the pulse analysis can be used to regulate the feed rate or not. Finally, the topic of the applied process energy source (PES) is discussed.

Process Analysis ECM

In its process analysis, the ECM must distinguish whether it is used to sink a specified profile into an undefined surface, to rework a profile, or to sink deep holes, whereby aspects greater than 10 are assumed. EC milling is excluded from further considerations.

In the case of maximizing productivity and no special requirements for the inner surfaces of the holes, solutions are possible, as shown in Fig. 1 [1]. In the case of the insulation of the cathode surface, Fig. 1,II, it can be assumed that the current-voltage analyzes relate entirely to the front gap. As a result, this analysis can be used for feed regulation. The size of the lateral gap will depend on the insulation configuration at the edges of the lateral gap. It must be noted that if the lateral gap is too small, the flushing of the frontal gap will be negatively affected.

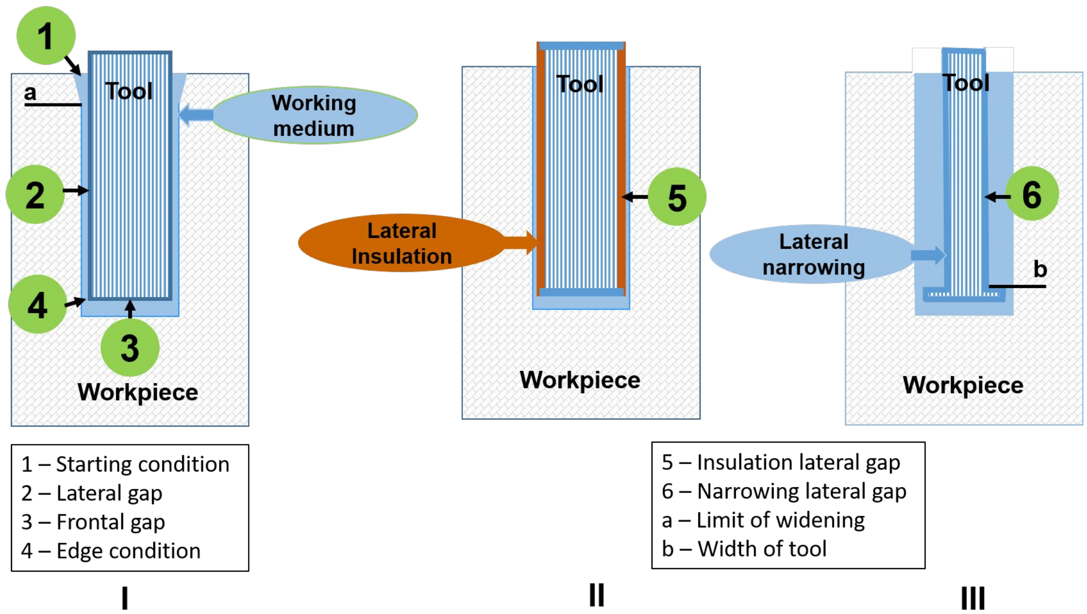

Fig. 1. Different conditions by ECM and EDM.

Fig. 1,I shows the areas of interest for analysis. In area 1, the starting conditions are at the surface. Due to larger stray fields, a larger area is removed than later in the hole area. The frontal erosion is reduced due to the areal removal with ECM. Area 1 can be minimized if the frontal area of the tool electrode is designed as a cone. In area 2, the side gap is widened by the fixed arrangement (a) until the current density no longer allows removal. Therefore, the side gap is usually slightly conical. In contrast to the arrangement in Fig. 1,II, where removal can no longer take place due to the lateral insulation (5), in Fig. 1,III, the active side gap is achieved by narrowing the tool electrode. This intensifies the rinsing effect (6), and which lateral gap is created depending on the front height of the tool electrode (b). The working gap on the front side depends on the ratio of the removal on the front side to the feed rate. It would be ideal if both were the same size, then, there would be a constant front gap. However, the current and voltage recordings only show us the overall picture of the individual ablation areas. It is sufficient for the critical process states such as soft short circuits or discharge since the machining process has to be interrupted or the rinsing has to be improved to achieve the desired surface quality.

Process Analysis EDM in the Electrolyte

If the EDM process is considered in the conventional sense, then we have a dielectric as the working medium and a cathodic polarity for the workpiece [2]. The discharge conditions are determined by the electrical field conditions and the degree of contamination in the working gap. In contrast to the ECM, a small area is removed locally but with a high frequency and constantly changing location. It can be assumed that the electrical discharge binds the entire energy through its plasma channel and that the removal ratios at the anode and cathode can be calculated from this.

Referring to Fig. 1, area 1 is mostly more frayed, while area 2 shows less taper. There is also a rounding in the corner area 4, but not as homogeneously as with the ECM. The primary removal area is the front gap, because there the gap is constantly regulated to a specified gap by the feed rate. Flushing in the side gap reduces the dielectric strength, so isolated discharges also occur there. These discharges determine the roughness of the hole wall. Even with the EDM, we cannot assign the current and voltage curves to the areas defined in Fig. 1, but only look at the effect afterward [3].

If hybrid-machining processes are to be analyzed, then some conditions from the conventional EDM conditions no longer apply [2,3,4].

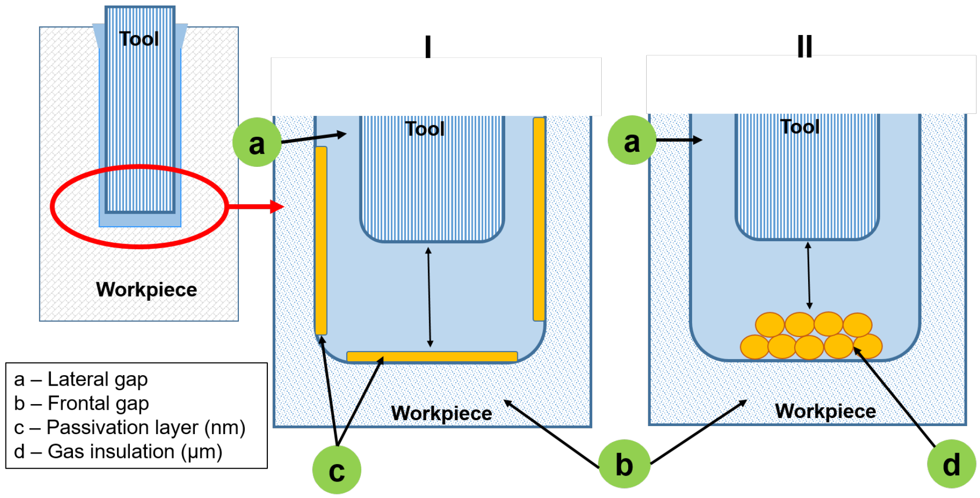

Fig. 2. Changed ED conditions in the hybrid ED-EC process.

In Fig. 2, it can be seen that the electrical breakdowns are not determined by the working medium, but by passivated layers (Fig. 2,c) and/or gaseous deposits (Fig. 2,d). The breakdown takes place in these phases, while the formation of the discharge channel (plasma, gas volume) primarily takes place in the electrolyte. Since in hybrid applications, there is almost exclusively an anodic polarization of the workpiece, the sparks are removed over a larger area than with the original EDM. Passivation in the lateral gap prevents further erosion from a certain lateral gap width and is, therefore, decisive for the surface quality of the inner wall surfaces of the bore. For electrical breakdown, the condition I in Fig. 2, hence electrical breakdown in very thin solid layers, must be considered.

In the case of passivation layers in the nanometer range, a field breakdown occurs because even a small voltage drop across the passive layer leads to high electrical field strength. Assuming a layer thickness of 10 nm and a voltage drop of 1 V, the electric field strength would be 10^8 V/m. At these field strengths, altered effects of electrical conductivity (tunneling, hopping) take place in a dielectric solid. If the insulating effect is eliminated, a combined heat/field breakdown can occur via the remaining front gap. In the electrolyte, the discharge channel spreads out more, depending on the electrical conductivity of the electrolyte, than would be the case in a dielectric. As a result, energy is withdrawn from the discharge base, and the crater formations become smaller and larger.

Fig. 3 shows where one can speak of hybrid machining methods and which basic removal processes cause the main removal.

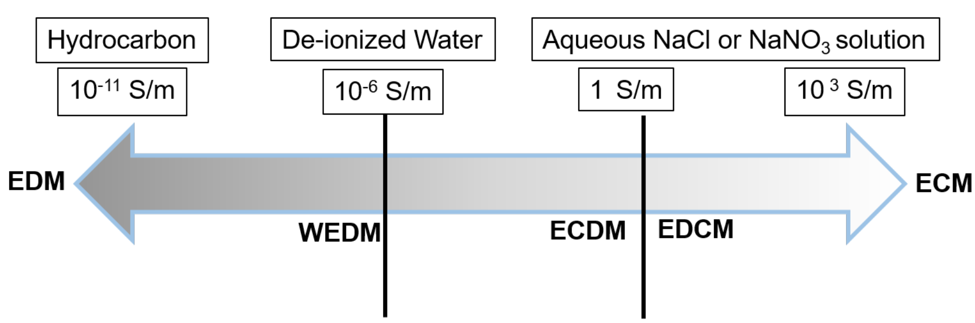

Fig. 3. Dependence of the hybrid ED-EC process on the electrical conductivity of the working medium [5].

A contrast to this is in Fig. 2II where the dielectric layer is a gas layer. The gas accumulations are usually thicker than the passive layers and more mobile in their formation, so the breakdown conditions can change quickly. The tool's rotation or the working gap's flushing can cause these changes, for example. Another special feature can be that the gas layer is accumulated as gas bubbles or as a homogeneous gas layer. In the latter case, the discharge can be described according to the EDM models based on gas discharges. With the accumulation of gas bubbles, a small EC removal can still have an effect, which leads to a heating breakdown due to the extremely reduced working surface with a very high current density.

Fig. 3 shows that the ECD erosion by the discharges is at electrical conductivities below 1 S/m, while the EC-dominant EDC erosion is at electrical conductivities above 1 S/m.

Process Analysis of the Hybrid EDM-ECM Process

For process analysis, two applications are available for comparison, which were intensively examined in two studies. In the first study, a wire EDM system [3] was analyzed in terms of its current and voltage curves, while in the second study, EDC sinking of smaller holes was considered. The primary objective was to assign the current-voltage pairs to a fundamental erosion or disturbance condition and internal surfaces with minimal roughness.

With sinking, the current and voltage curves shown in Fig.4 are typically related to the basic processes. The output data of the process energy source (PES) [6] are 30 A and 50 V, with a reduced EC current resulting from the impedance conditions (Eq. 1–4) of the test arrangement. By increasing the electrical conductivity of the working medium, the EC current could be increased accordingly.

In the case of the short circuit, the full PES current appeared and the voltage drops to almost zero volts. In the EC processing (Fig. 4), it was reduced to approx. 7 A here. The pulse in Fig. 4,B is an exception, which is determined by the characteristics of the PES. The number of partial overshoots (Fig. 4,C) increases with increasing immersion depth, which suggests very short partial discharges due to contamination of the working gap. An ED discharge (D) and an arc discharge (E) can then be seen in the right-hand diagram of Fig. 4. With a pulsing of 5 µs pulse-on and 5 µs pulse-off, these two discharges show a strong negative overshoot in the switch-off range, which can be attributed to the capacitive components (capacitor discharge) of the passive residual layer.

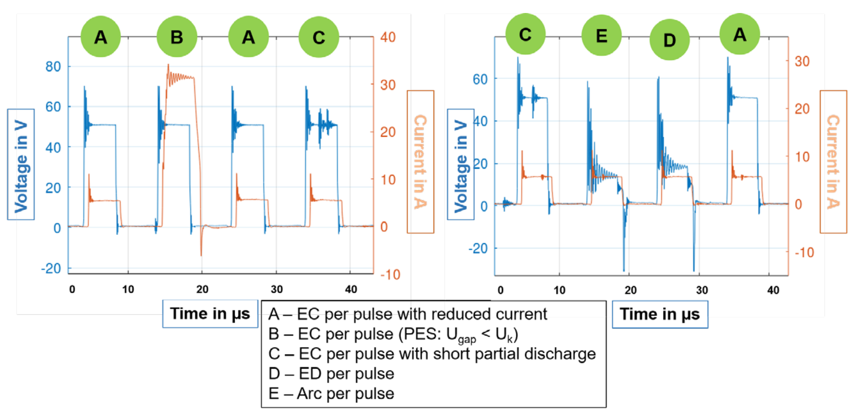

Fig. 4. Basic processes in hybrid hole sinking EDCM [7].

In Table 1, the pulses that occur after the current and voltage curves are selected must be differentiated according to the basic pulses, the pulses with transitions between basic erosion and the pulses that are specifically given by the characteristics of the PES. From the percentage number of pulse types per time unit, it can be concluded whether the lowering process is ideal or needs to be corrected by the process regulation.

Table 1. Categorization of the pulses according to base, transition, and PES-dependent pulses.

Index	Conditions	Comments	Typ
a	$U_{max} = U_{PES}$ and $I_{gap} = I_{EC}$	EC-Pulse	Basic
b	$U = U_{spark}$ and $I_{gap} = I_{ED}$	ED-Pulse	Basic
c	$U < U_{spark}$ and $I_{gap} = I_{arc}$	Arc-Pulse	Basic
d	U = 0V (very close) and $I = I_{PES}$	Short circuit	Basic
e	U falls below the spark burning voltage	ED-Pulse → Arc-Pulse	Transition
f	U increases to U_{max}	ED-Pulse → EC-Pulse	Transition
g	U_{max} falls to U_{spark}	EC-Pulse → ED-Pulse	Transition
h	U_{max} falls to U_{arc}	EC-Pulse → Arc-Pulse	Transition
i	Solution of the Passivation via ECM		PES
k	Dynamics of the gas layer loosens the insulation		Flushing
l	Collapsing voltage U_k of the PES gives security of processing		PES

In Fig. 5, the pulse transitions are visible, which are defined in Table 1 under the indices e to h. The position in Fig. 5,A corresponds to the transition from the EC phase with an intermediate plateau to the ED phase. The intermediate plateau may be because the final ED erosion arose from thermal breakdown. In Fig. 5,B,C EC ablations can be seen, which are determined by the characteristics of the PES used, which is explained in more detail in the next section. Finally, Fig.5,D shows the transition from the ED phase to the EC phase.
These findings were also found largely in the WEDM investigation [3], which was used to work with a static PES.

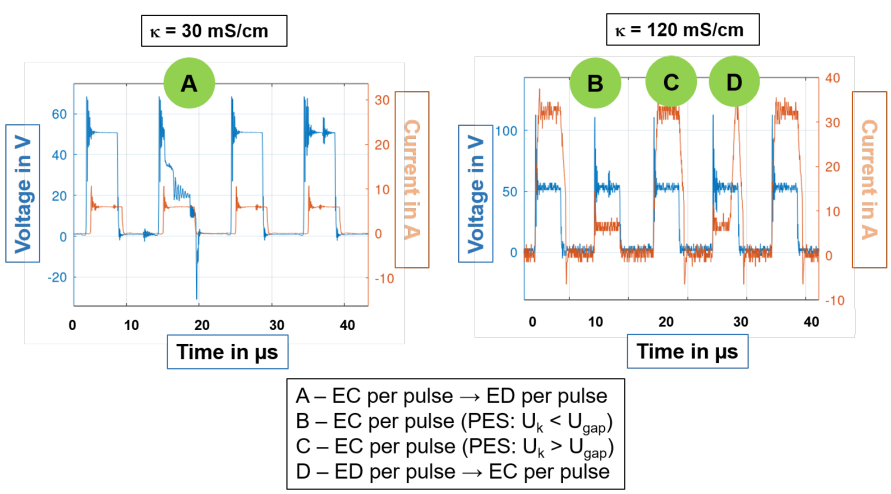

Fig. 5. Pulses with process transitions in ED hole sinking [7].

Influences of PES
A special process energy source (PES) was used for the hole sinking, the characteristics of which are shown in Fig. 6. Up to the break voltage U_k, it acts as a current source. It determines the pulse energy of the ED discharge and the arc discharge with its set current IPES. The operating point of the ECM is then determined by the load characteristic of the working gap. The working point ECM 2 is present when the working voltage is close to the maximum voltage U_{max}. As the electrical

conductivity of the working-gap resistance increases, the voltage drop across the gap decreases compared to the total impedance of the PES load, i.e. smaller currents automatically appear in the working gap.

The total impedance of the PES load is Z_{PES} Eq. 1 and is made up of the components of the contact Z_{ko}, the leads Z_{Li} and the working gap Z_{el}. If the electrolyte has high electrical conductivity, the remaining impedance components must also be small so that the PES voltage drops completely across the working gap. In the case of a current source, however, the same current would always be impressed, which would be important for the ECM. With a voltage source, a desired current can be achieved by changing the voltage, leading to ED discharges in the side gap for a long time. The voltage difference ΔU in Fig. 6 determines how quickly the current falls after exceeding U_k and depends on the structure of the PES.

According to Eq. 2, only the impedance of the working medium Z_{wm} is decisive for EC machining, which depends on the working gap a_x, the machining area A_x and the electrical conductivity κ of the working medium. Due to the passivation (Eq. 3, Z_{pass}) or the formation of gas bubble layers (Eq. 4, Z_{bub}), the impedance changes in that these layers have their impedance, with the capacitive components also playing a role. Furthermore, the impedance of the remaining working gap fluid remains (Eq. 3, Z_{fl1} and Eq. 4, Z_{fl2}). Only the layer impedances are then of interest for the breakdown conditions.

The advantage of the PES used is that it has a self-regulating effect, which means that process regulation can be significantly reduced.

$$\underline{Z}_{PES} = \underline{Z}_{ko} + \underline{Z}_{Li} + \underline{Z}_{el} \tag{1}$$

$$\underline{Z}_{el} = \underline{Z}_{wm} \qquad \text{for ECM} \tag{2}$$

$$\underline{Z}_{el} = \underline{Z}_{pass} + \underline{Z}_{fl1} \qquad \text{before EDM} \tag{3}$$

$$\underline{Z}_{el} = \underline{Z}_{bub} + \underline{Z}_{fl2} \qquad \text{before EDM} \tag{4}$$

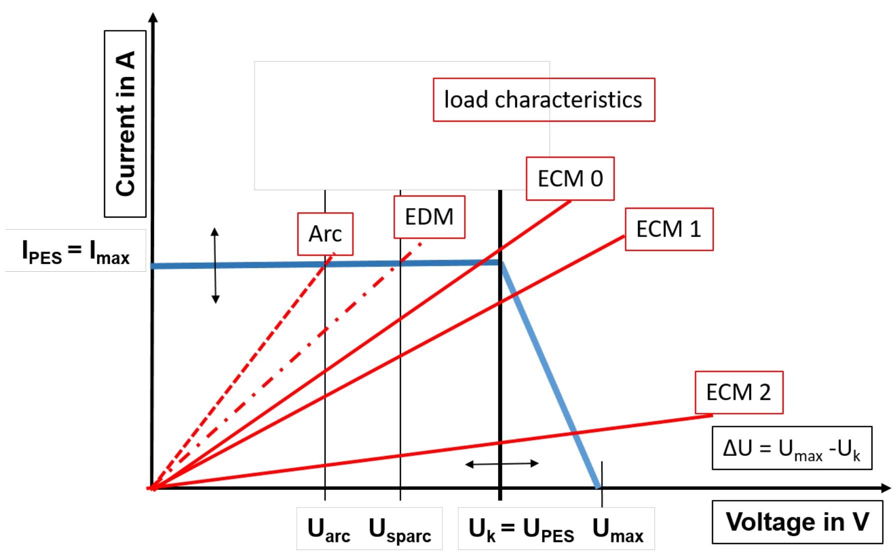

Fig. 6. Characteristic of the PES with different load curves.

Simplifications of the Process Analysis in the Hybrid Process Under Defined Technological Target Parameters

The machining process can be evaluated using pulse analysis for its process regulation but also for the technological objective. The technological objectives can be minimizing the machining time, the quality of the inner surface of the hole or the accuracy of the countersunk hole. In Fig. 7, a processing example is used to show how specific process states and a sequence of process states appear in the voltage-current characteristic [8, 9]. What is not apparent are the transition pulses. In the example, the frequency of the basic processes can be seen, with ED and EC pulses taking place in roughly the same number, while soft short circuits represent around 10% of the processing cases.

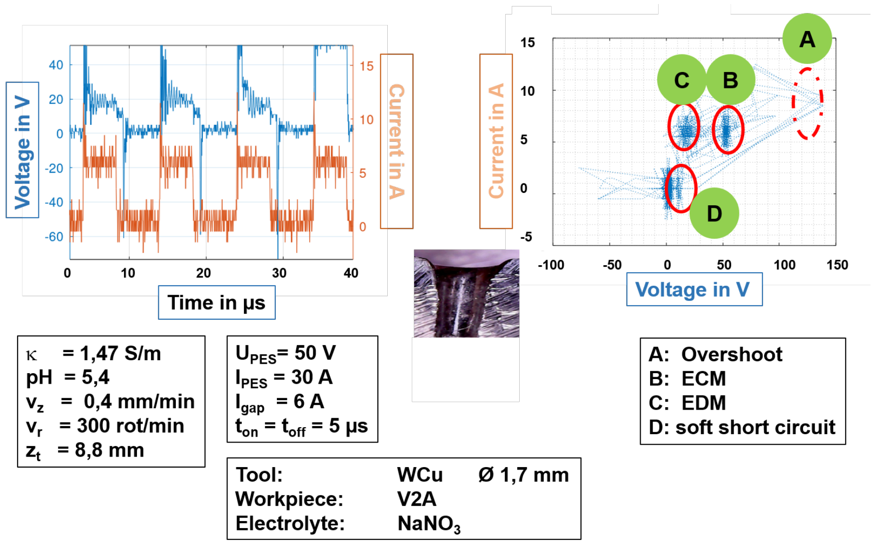

Fig. 7. Voltage – Current curve for 100 pulses in sinking deep of 8.8 mm [7].

If a more precise statement is to be made about the process states for regulation, then the sequence of pulses defined in Tabelle 1 must be made. The current and voltage limit values required for this are known from the literature or can be determined from a test run. With a smooth, shiny inner surface of the holes, the proportion of ED discharges in the side gap should be minimal. From the sequence of the pulse phases, there is a higher probability of isolated ED phases occurring in the side gap, since ED phases in the frontal gap only expose small areas for ECM.

Summary

To predict the processing result with pulsed hybrid EDM-ECM methods, assigning the individual pulses to a specific basic processing or a transitional behavior is necessary. It is difficult to find out where the effects of the removal take place. They are primarily to be found in the front gap because here, the size of the working gap is continuously tracked by the feed rate. In the lateral gap, on the other hand, static behavior can be assumed, which means that no further removal or application mechanisms are effective after the lateral gap has reached a certain size.

In the hole sinking study, a special process energy source was used, which acts as a current source up to a voltage U_k, after which it acts as a voltage source. The advantage of this PES is that it protects itself against working currents that are too high and causes a kind of self-regulation for the critical processing pulses.

The process regulation via the feed regulation can take place through targeted analysis of the pulse processes in terms of their phases and sequence. This makes it possible to achieve smooth, shiny surfaces even for deeper countersinks.

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