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Digital twin for the determination of process input variables for electrochemical precision machining according to DIN SPEC 91399

THIELECKE Alexander[1,a *], MEICHSNER Gunnar[1,b], and HACKERT-OSCHÄTZCHEN Matthias[1,c]

[1]Chair of Manufacturing Technology with Focus Machining, Institute of Manufacturing Technology and Quality Management (IFQ), Faculty of Mechanical Engineering, Otto von Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg

[a]alexander.thielecke@ovgu.de, [b]gunnar.meichsner@ovgu.de, [c]matthias.hackert-oschaetzchen@ovgu.de

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Abstract. The ablation results with electrochemical precision machining (PECM) are essentially influenced by the material to be processed and by the current density distribution in the working gap. Therefore, ablation experiments according to DIN SPEC 91399 are essential to determine the material-specific removal characteristics and to derive process input variables for the process design. A main limitation of these experiments is the lack of accessibility at crucial surfaces on the workpiece and on the device, which means that relevant information such as the local current density distribution or the local temperature field cannot be measured. To face the mentioned limitation, the aim of this work was to develop a digital twin for an experiment for PECM according to DIN SPEC 91399. The digital twin is based on a commercial multiphysics simulation software with the main property that the calculation time of the model is less than the real time for the experiment to allow a simultaneous processing of experiment and simulation. Via suitable interfaces, experiment and simulation can be interconnected in future. Based on this, the digital twin can be applied to evaluate parameters, monitor the process in real time and adapt it accordingly. The design and the properties of the digital twin will be shown exemplary for an experiment with the workpiece material steel 1.4301.

Introduction

Electrochemical Machining (ECM) is the generic term for a number of machining processes in which material removal is based on the principle of anodic metal dissolution. The workpiece is polarised as an anode and the tool electrode as cathode. An electrolyte, as a sufficiently electrically conductive medium, provides an electric charge transport between the electrodes. The ECM process is a non-contact machining process without heat input. Disadvantages of conventional cutting methods such as tool wear, negative influence on the component properties or burr formation can be avoided if ECM is applied.

A further development of the EC-countersinking process is electrochemical precision machining (PECM), in which the precision can be further increased by applying an oscillating cathode and a pulsed direct current. The PECM process is a separating manufacturing process and is classified according to DIN 8580 in the 3. main group Machining and further in the groups Ablation and Electrochemical Ablation [1]. Fig. 1 shows the principle of the PECM-process with oscillating cathode.

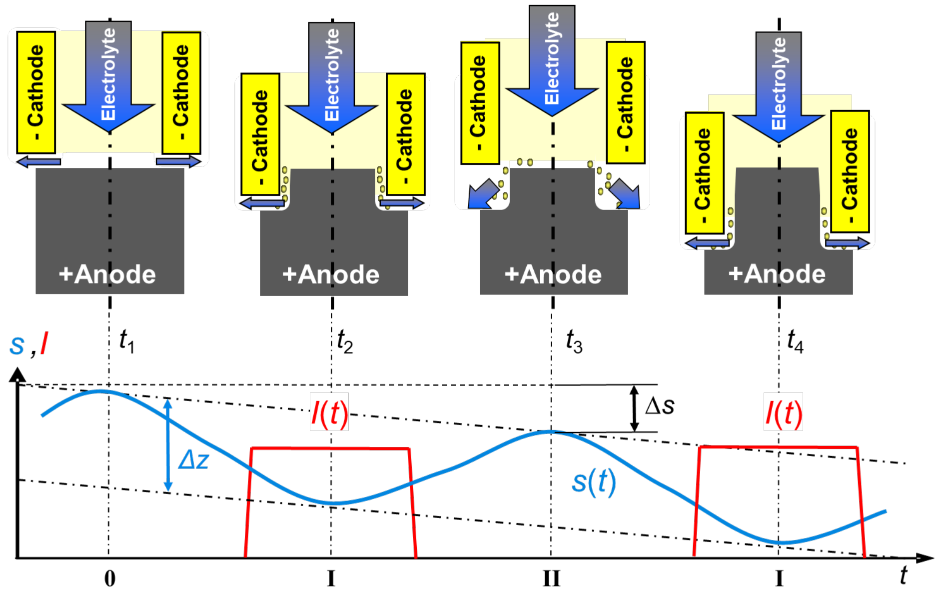

Fig. 1. Principle of a pulsed ECM-process with oscillating cathode according to [2].

In the initial state (0), the cathode is at top dead center, so that a maximum working distance is established between the anode and the cathode. Thus, the working distance is sufficiently supplied with electrolyte. State I describes the time of material removal. Here, the cathode geometry is transferred in the anode.

Shortly before the bottom dead center of the oscillation movement is reached, the machining voltage is switched on so that a current pulse with almost constant current is formed for a defined current pulse width. In the lower dead position of the oscillation movement, the working distance reaches the minimum. After exceeding the bottom dead center, the material is removed until the machining voltage is switched off.

The working distance is extended in state II until the top dead center is reached. This ensures that the working distance is sufficiently supplied with fresh electrolyte to remove reaction and removal products, which are created in state I.

The sequence of state I and state II is repeated until the target sink depth is reached. For this purpose, the oscillation of the cathode is superimposed with a feed movement. [3–5] Due to the reduced working distance in the PECM process, the production of complex shapes in the micrometer range is possible (structure size ≥ 5 µm). [6]

EC-removal is based on a complex mechanism. Material-specific removal parameters and the current density distribution in the working distance are essential process input variables, that cannot be derived with sufficient accuracy from literature values.

The DIN SPEC 91399 describes a method, which is based on determining the material-specific removal rate during PECM using an industrial machine tool. Applying a special removal device and complying with defined boundary conditions, the velocity of the relative movement between the cathode and anode can be evaluated as a comparison variable for determining the material-specific removal parameters.

With the help of systematic ablation experiments, the ablation functions of the material-specific ablation rate and the change of state in the working distance can be determined. From this, process input variables can be determined for the PECM process. [7]

Method

In addition to the time and cost issues, the challenge in PECM ablation experiments is the measurement of physical variables such as the distribution of the current density during the PECM process. A simulation model can serve as a digital twin, that provides missing measurement variables or make ablation experiments more efficient through preliminary investigations. With FEM-based simulation software, such as the commercial software COMSOL Multiphysics, it is possible to build a digital twin, obtain missing information from a PECM process and analyse it. A digital twin is the digital model of physical objects and has the task of generating a comprehensive exchange of information. The basis for this is, that the model not only includes anode, cathode and electrolyte region, but is designed in such a way, that the entire device unit is represented. The aim of the work is to build a simulation model, that confirms the results of a previous experiment with the workpiece material 1.4301. In order to monitor the process in future, it is also necessary for the digital twin to calculate the simulation results in a time which is lower than the machining time of the real process. This should enable real-time data exchange between the digital twin and the real process in future by help of the development of suitable interfaces.

Model Description

In order to create the digital twin, materials and PECM input parameters were taken from previous ablation experiments [8]. The design and the geometry dimensions of the simulation model are based on the recommendations of DIN SPEC 91399. Fig. 2 shows a cross-section of the PECM device and the derived geometry of the simulation model.

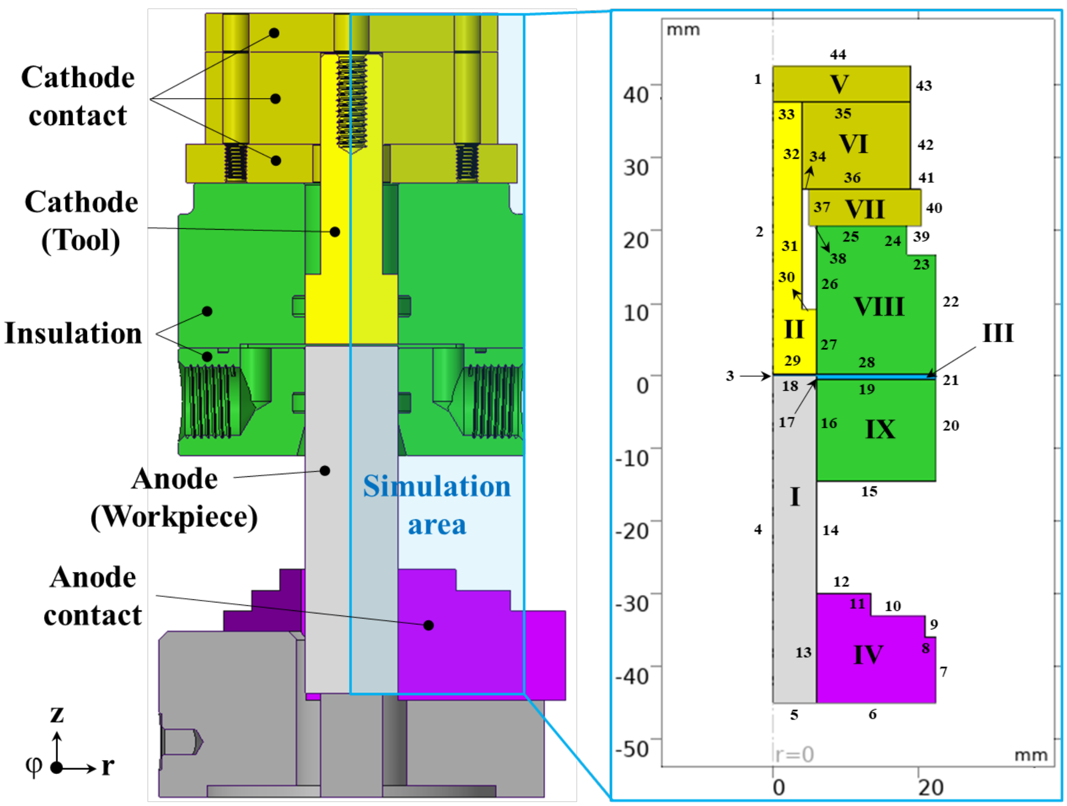

Fig. 2. Cross section of the PECM device and derived *2D axisymmetric model geometry with defined domains and boundaries.*

In the simulation model, the experimental end front working distance $s_{f\text{-}E}$ was set at the beginning of the simulation. The cathode unit was assigned a constant feed with superimposed oscillation movement for a period $T = 0.02$ s. Electric current flows through the application of a pulsed voltage with a pulse duration $t_p = 1$ ms at the dead center of the oscillating movement of the cathode. In order to keep the simulation time of the digital twin below the real process time, the oscillating movement and pulsed power supply were interrupted after the simulated period. The surface of the workpiece was then removed with calculated velocities for further 30 s. A process time of 30 s was selected in order to comply with DIN SPEC 91399, according to which the removal experiment run for further 30 s after the end front working distance $s_{f\text{-}E}$ has been established [7].

The model is evaluated according to simulation duration and working distance at the end of the 30 s simulated process time.

Due to the desired model solution time below 30 s and the almost rotationally symmetrical design of the device, the model was designed as an axisymmetric model with the coordinates r, φ and z, with the axis of symmetry at r = 0. The two electrodes, can be seen in gray (anode/workpiece) and yellow (cathode/tool). Both electrodes are cylindrical in shape. The workpiece has a diameter of 12 mm and a length of 45 mm. The cathode consists of a stepped shaft with diameters of 7.5 mm and 12 mm and a length of 37.5 mm. In the simulation the electric conduction processes in the cathode and in the workpiece as well as in the electrical contact geometries were considered, since otherwise some effects can be underestimated [9].

The oscillating movement of the tool unit occurs in z-direction. The allocation of the materials to the model domains and the material parameters used for the simulation are summarized in Table 1.

Table 1. Material parameters of the simulation model derived from [8].

Domain	Material	σ [mS/cm]	ε_r
I, II, IV-VII	1.4301	$1.4 \cdot 10^{10}$	1
III	Electrolyte ($NaNO_3$)	67.4	65
VIII, IX	POM	10^{-10}	4

In order to analyse the ECM-specific parameters, the electrical conductivity σ and the relative permittivity ε_r were assigned to the domains. To represent the desired PECM process, 3 physics modes of COMSOL Multiphysics were applied. *Electric Current* mode was applied to supply the PECM process with external electric potential. The *Moving Mesh* was applied to simulate the oscillating motion of the cathode assembly and the flushing chambers as well as the removal of the surface of the workpiece. The *Events Interface* was applied to simulate the various PECM parameters in a precisely timed manner.

Eq. 1 describes the electrical potential $U_{\text{pulsed}}(t)$ which connects and disconnects the voltage according to the lower- and upper time limits. The electrical potential is determined by subtracting the process voltage U_{min} with the sum of overpotentials ΔU [4].

$$U_{pulsed}(t)\begin{cases} 0\,V, if\ t < t_{Low} \\ U_{min} - \Delta U, if\ t_{Low} \le t \le t_{Upp} \\ 0\,V,\ if\ t > t_{Upp} \end{cases} \tag{1}$$

with

$$t_{Low} = \frac{T}{4} - \frac{t_p}{2} \tag{2}$$

and

$$t_{Upp} = \frac{T}{4} + \frac{t_p}{2} \tag{3}$$

The pulsed current parameters used in the simulation model are summarised in the Table 2 below.

Table 2. Pulsed electric potential parameters derived from [3,8].

Definition	Symbol	Value	Unit
Process voltage	U_{min}	6.7	[V]
Sum of potentials	ΔU	4.6	[V]
Pulse width	t_p	0.001	[s]
Lower Limit	t_{Low}	0.0045	[s]
Upper Limit	t_{Upp}	0.0055	[s]

The electrical potential $\varphi_{el} = U_{pulsed}(t)$ was applied at boundary 6 and ground at boundary 44 and it was switched via the event interface. Boundary conditions of the electric current mode defined in the model are listed in the Table 3.

Table 3. Boundary conditions of electric current mode.

Condition	Boundary	Property
Axial Symmetry	1-4	-
Electric Insulation	5, 7-12, 14, 15, 20-24, 26, 30, 31, 34, 37-43	-
Ground	44	$\varphi_{el} = 0$ [V]
Electric Potential	6	$\varphi_{el} = U_{pulsed}(t) \cdot C_2$ [V]

The moving mesh mode was applied to simulate the movement of the cathode unit, including the flushing channel and flushing chambers. The oscillation of the cathode was defined as a harmonic oscillation superimposed with a constant movement in z-direction, which is explained in Eq. 4.

$$z(t) = \left(\hat{Z} \cdot \cos\left(2\pi \cdot f \cdot t + \frac{\pi}{2}\right)\right) \cdot C_1 - v_f \cdot t \tag{4}$$

$\hat{Z}$ is the range of the oscillation (amplitude), f is the frequency and v_f the lowering velocity. The discrete variable C_1 is a logical auxiliary variable to control which expression to use in an equation. C_1 is explained in more detail in the Events Interface section. When the oscillation has reached its lowest point in z-direction, $s_{f\text{-}E}$ is set. Table 4 allocates the motion parameters of the cathode.

Table 4. Motion parameters of the cathode derived from [8].

Definition	Symbol	Value	Unit
Period	T	0.02	[s]
Frequency	f	50	[Hz]
Amplitude	$\hat{Z}$	0.185	[mm]
Working distance	$s_{f\text{-}E}$	0.048	[mm]
Feed rate	v_f	0.01	[mm/min]

For numerical reasons, period *T* starts after 1 s simulation time. Figure 3 illustrates the cathode oscillation and the pulsed electrical potential in a period *T*, here the oscillation graph *z*(*t*) marked with blue line is plotted as in Eq. 4 and the pulsed voltage $U_{pulsed}(t)$ graph marked with red line is characterized as in Eq. 1.

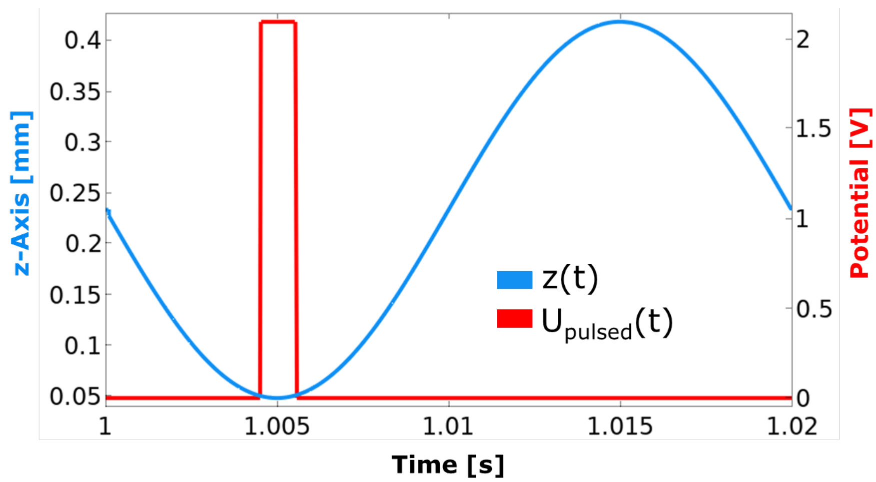

Fig. 3. Cathode oscillation and pulsed potential in one period.

The surface of the workpiece is removed with 2 different removal rates. According to [3,4], the removal rate is recorded as follows during the pulse on time t_p.

$$v_a(J) = ((V_m \cdot J + v_0) \cdot c) \cdot C_2 \tag{5}$$

with

$$c = f \cdot t_p \tag{6}$$

The removal rate is therefore strongly dependent on the current density distribution *J* [A/cm²] on the workpiece surface. The pulsed current flow is characterized by the duty cycle *c*, which is composed of the multiplication of the frequency *f* and the pulse on time t_p. V_m ($0.0106\,\frac{mm/min}{A/cm^2}$) and v_o ($-0.063\,\frac{mm}{min}$) result from the removal experiment and are described in more detail in [8]. V_m, v_0 and *c* are thus constant values, while *J* is calculated during the pulse on time. In order to save computing time of the model, an average removal rate $\hat{v}_a$ is calculated after the time period *T*, with which the workpiece surface is removed for another 30 s.

$$\hat{v}_a = \frac{1}{T} \cdot \int_{1.0045\,s}^{1.0055\,s} v_a(J)dt \cdot C_3 \tag{7}$$

Boundary conditions of moving mesh mode defined in the PECM simulation model are listed in the Table 5.

Table 5. Boundary conditions of moving mesh mode.

Condition	Boundary	Property
Fixed Boundary	5	-
Prescribed Mesh Displacement in Normal Direction	3, 4, 13, 14, 17, 21	$d_n = 0$ [mm]
Prescribed Mesh Displacement	1, 2, 15, 16, 19, 20, 22-44	$d_r = 0$ [mm] $d_z = z(t)$ [mm]
Prescribed Normal Mesh Velocity	18	$v_n = -v_a(J) - \hat{v}_a$ [mm/min]

The event interface is used to trigger events. When an event occurs, the solver stops and provides a possibility to reinitialize the values of variables. The events are controlled with the state variables C_1, C_2 and C_3, which can assume the values 0 and 1. The course of the variables can be seen in Fig. 4.

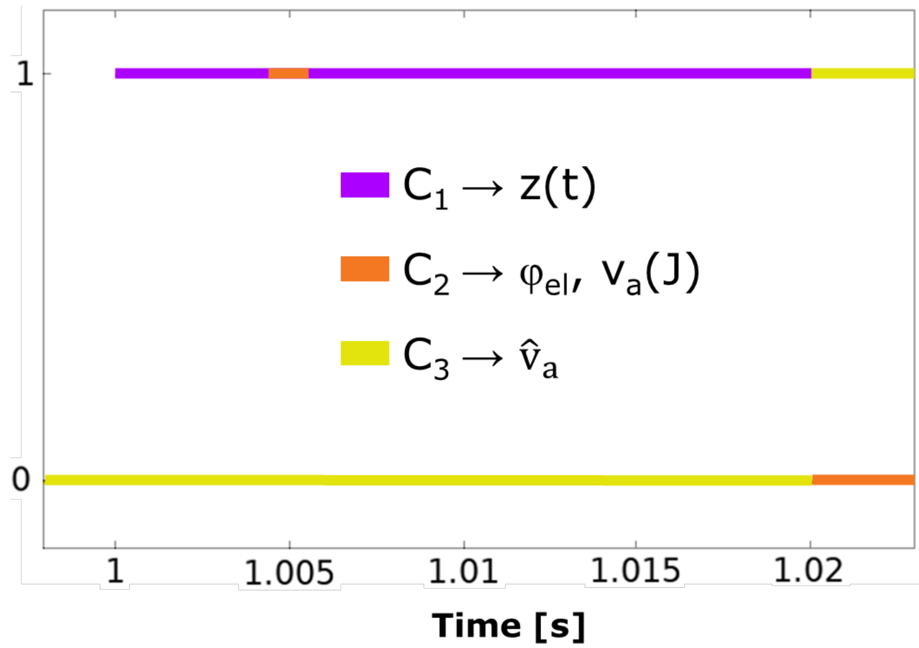

Fig. 4. Discrete auxiliary variables as function of the time.

The variables are linked to the equations and boundary conditions. C_1 triggers the oscillation from $t = 1$ s to $t = 1.02$ s, after that the first term of Eq. 4 becomes zero and the cathode moves on without oscillation with the constant feed motion v_f. C_2 switches from 0 to 1 at $t = 1.0045$ s and back to 0 at $t = 1.0055$ s ($t_p = 0.001$ s). The electrical potential φ_{el} (see Table 3) and the removal rate $v_a(J)$ (Equation 5) are linked to the state variable C_2. Variable C_3 is coupled to $\hat{v}_a$ (Equation 7). The average removal rate is calculated during the pulse, then the workpiece surface is removed with the calculated velocity $\hat{v}_a$ for 30 s.

The mesh for the model was generated using a physics-driven mesh as the sequence type. The physics-controlled mesh is the default mesh setting in COMSOL Multiphysics, which in turn distinguishes different element sizes from very fine to very coarse. The mesh encloses an area of

1356 mm² with 1155 triangular elements. The maximum and minimum element sizes are 5.8 mm and 0.026 mm.

Results

Fig. 5 shows the current density distribution in the entire model at the bottom dead center of the oscillation.

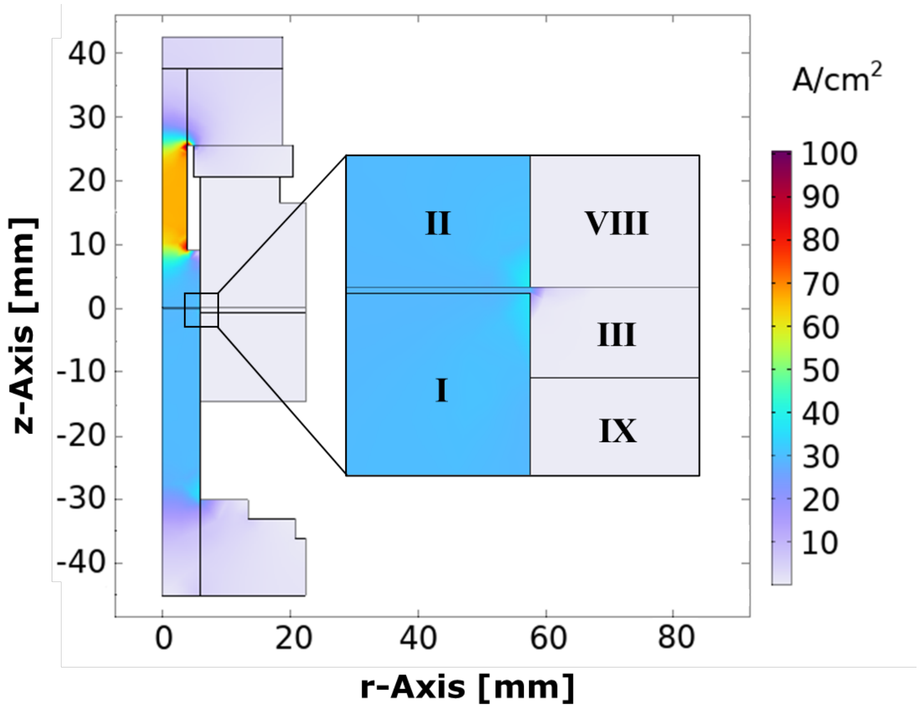

Fig. 5. Current density distribution at time t = 1.005 s.

In the model, a maximum current density J of 101 A/cm² occurs during the pulse on time, which can be attributed to peak effects at points on the cathode. A current density J of 29 A/cm² is established in the working gap between the cathode and the workpiece surface during $t = 1.005$ s. The removal rate v_a depends on the current density distribution on the workpiece surface (boundary 8). Figure 6 shows the 3 applied velocities, of which v_f represents the constant feed of the cathode while v_a (J) and $\hat{v}_a$ are calculated during the simulation.

Since $v_a(J)$ depends on the current density acting in the pulse, the curve is not linear but increases as the cathode approaches the workpiece surface due to the oscillating movement. The maximum removal rate is reached at the bottom dead center of the oscillation.

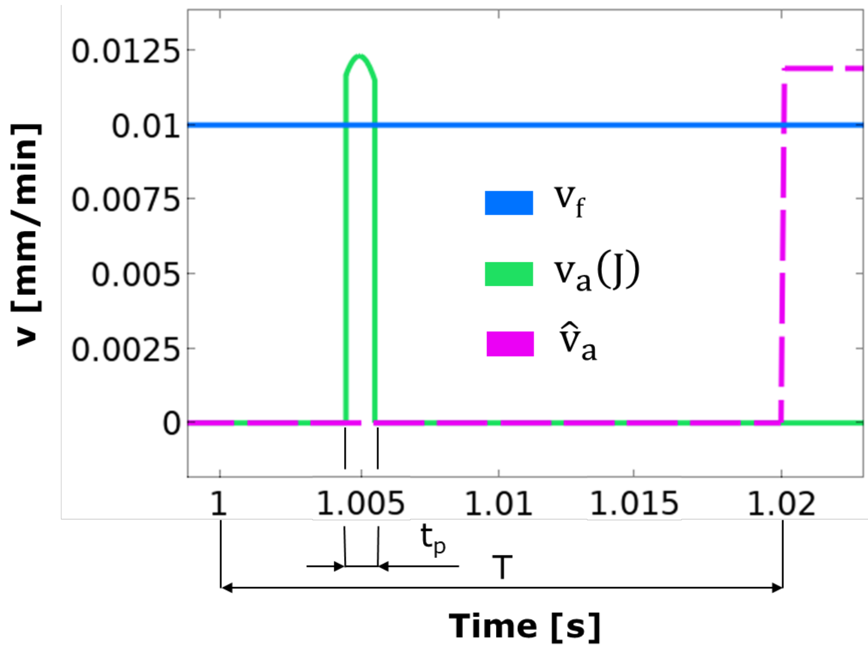

Fig. 6. Course of the velocities vf = 0.01 mm/min, va(J) = 0.0115…0.0123 mm/min and $\hat{v}_a$ *= 0.0119 mm/min.*

If the cathode moves away from the workpiece surface, the removal rate drops until the pulse ends and no more removal takes place. The effect of the course of $v_a(J)$ is thus an effect of the combination of feed and oscillation of the cathode. After t = 1.02 s, the cathode moves at a constant speed v_f in the z-direction and the workpiece is removed at the average velocity calculated from $v_a(J)$. In Figure 7, the evaluation is based on the final working distance after t = 31.005 s.

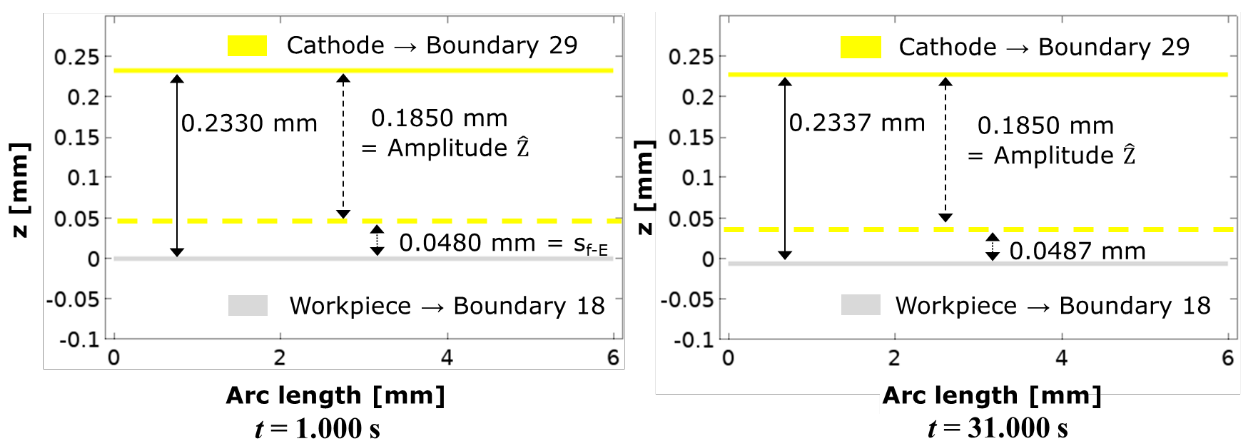

Fig. 7. Comparison of the end front working distance at the initial state and after the process time.

The end front working distance is set at the bottom dead center of the oscillation. After the process time of 30 s, the working distance between the surface of the cathode and the surface of the workpiece is 0.0487 mm. The difference between the defined end front working distance and the calculated working distance after a process time of 30 s is therefore 0.7 µm. The computing time of the simulation model for a real removal time of 30 s was 25 s.

Summary

In this study, a digital twin for the determination of process input variables for electrochemical precision machining according to DIN SPEC 91399 was developed. For this, a simulation model for a PECM process according to DIN SPEC 91399 was build up in COMSOL Multiphysics based on the geometry of an entire device unit. To design the PECM process, the oscillation of the cathode and the current pulse conditions were integrated in the model. The input parameters were set according to previous ablation experiments. A validation was carried out by maintaining the working gap after the process time of 30 s. It was shown, that the simulation time of the developed model is less than the real time of the machining process. The model can be expanded in further work. For example, the effective electrical conductivity of the electrolyte, which is influenced by the generation of heat and the formation of gas bubbles, is also decisive for the removal process in the PECM process. Approaches would be the coupling of further physical interactions like thermodynamics and fluid dynamics, multiscale approaches and the implementation of current control characteristics. In order to carry out parameter studies with this model, it is essential to integrate further ablation periods into the calculation. This will allow the removal rate to be updated as the process progresses, to match the feed of the tool electrode and the removal rate on the workpiece.

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