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Investigation of the transferability of pulsed electrochemical machining process parameters from simple substitute models to complex manufacturing applications

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Abstract

Pulsed electrochemical machining (PECM) is an innovative manufacturing technology that is used to produce high-precision components with finishing properties. Before starting to manufacture functional components, it is necessary to develop a tailored removal fixture. This consists of several components, whereby the fabrication of the cathode can be time-consuming and expensive. To prevent defects on the removal fixture during process launch or fine adjustment of the PECM process, typically operating at a front working gaps less than 0.030 mm, the use of a substitution model is advisable. By using a less complex removal fixture, as the one used in electrochemical material characterization DIN SPEC 91399, it is possible to quantify the material-specific dissolution behavior and determine initial process parameters for the desired application.
The investigations focus on the transferability of the PECM process from a simplified substitution model to the complex manufacturing fixture for producing an internal gear wheel. First, the two PECM removal fixtures are compared in terms of fixture design. Using the material characterization method DIN SPEC 91399 with the proposed substitution model, the removal of the difficult-to-machine martensitic stainless steel ASTM F899 is analyzed by varying the voltage, feed rate, and pulse length. By conducting experiments with both PECM fixtures using identical machine parameters, the change of the front working gap and the machine current is analyzed for lowering of the voltage potential.
Based on the comparison, the transferability of the proposed method for appropriately adjusted process parameter can be rated. By optimized machine input parameters for PECM applications, possible short-circuit errors can be prevented that could damage the customized removal fixture. Furthermore, this solution helps to predict the frontal end working gap during the fine adjustment of the dimensional accuracy of the components.

Keywords: Electrochemical machining (ECM), Fixture, Gear, Precision

1. Introduction

1.1. PECM process

Pulsed electrochemical machining (PECM) is a production technology that uses electrical pulses to process and shape electrically conductive materials. It is used in manufacturing and materials research founded on an advanced development of traditional electrochemical machining. The principle is based on the anodic material dissolution, in which a metallic workpiece is dissolved by electrochemical reactions into an electrolyte solution induced by a voltage potential between a tool (cathode) and the workpiece (anode). In PECM the material removal is superimposed with a pulsed direct current and narrow interelectrode gaps of less than 0.1 mm, creating the negative shape of the cathode direct onto the workpiece during a continuous motion of the tool. Besides typical process advantages like a cold, burr-free and contact-free material manufacturing without introducing process-induced residual stress into the workpiece, components manufactured by PECM show a high surface finish and tight tolerances [1].

1.2. Material processing in the interelectrode gap

Due to the contact-free machining, the machining area is basically emphasized as interelectrode gap, considering the area between the cathode and anode. It is commonly divided into a frontal gap and a lateral gap as shown in ***Figure 1***.

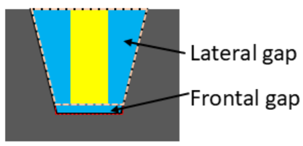

Figure 1. Basic scheme of the frontal gap s_f and a lateral gap s_l for ECM.

The distribution of the interelectrode gap is influenced by various factors. These include the working medium (electrolyte solution), the specific dissolution behavior of the workpiece material, the cathode geometry and the used electrolyte flow design. The applied electrical parameters, such as voltage potential, pulse length, and the pulse repetition frequency, causing a material processing through the electrical field distribution in the interelectrode gap. However, the multiphysical phenomena highlight challenges for achieving high process accuracy quickly. Nethertheless, an high precision PECM process requires knowledge of the exact size of the evolving interelectrode gap [2].

Previous investigations on the production of internal gears have shown that the design and fabrication of the shape cathodes can sometimes be time-consuming and expensive when using PECM as a finishing technology [3]. It was found that frontal working gap of less than 0.03 mm was necessary to achieve tight shape tolerances and at high surface qualities. The functionally necessary tight working gaps put high demands on the fine adjustment of the process parameter to prevent the tool from being damaged as a result of a undesired short circuit.

This study addresses the question of the potential for utilizing a simplified substitution model to determine the PECM process input variables in advance and, in a second step, apply those for the development of a dedicated gear application process. The transferability is examined based on comparisons of the frontal end working gaps.

2. Material, experimental setup and methods

2.1. Material

In the experiments the stainless steel X30CrMoN15-1/ ASTM F899/ DIN 1.4108 was used. The martensitic phase allows a widely usablility for medical equipment, wear-resistant and corrosion-sensitive drivetrain or maritime applications, to highlight a few. Through the hardened condition of the samples between 40 to 44 HRC, this steel can be classified as difficult-to-cut material. The primary alloying elements of the chemical composition are listed in ***Table 1*** [4].

Table 1. Primary alloying elements of the stainless steel ASTM F899.

	Cr	Mo	N	C	Si	Fe
Min	14.5	0.30	0.35	0.28	0.30	Balance
Max	16.0	0.60	0.44	0.34	0.80	

2.2. PECM machine

The experiments were conducted on an industrial PECM machine, model PEM Center 8000 from PEMTec SNC. The electrical power has a maximum voltage of 20 V at a machine current up to 8000 A. An integrated electrolyte purification with regulation of temperature, electrical conductivity, and pH-value guarantees a reproducible PECM processing. During the experiments, the parameters listed in **Table 2** were constant.

Table 2. Constant parameters during the PECM experiments.

Constant Parameter	Value
Electrolyte solution	Sodium nitrate $NaNO_3$
pH value	7.0
Temperature	20.5°C ± 1.0°C
Electrical conductivity	72.0 mS/cm ± 1 mS/cm
Tool oscillation (Amplitude)	On (0.350 mm)
Pulse frequency	50 Hz
Frontal start working gap	0.050 mm ± 0.005 mm

2.3. Design of PECM removal fixtures

All electrochemical machining tasks can essentially be broken down into the basic elements of an electrolytic cell. These consist of a tool (cathode), the workpiece (anode), the electrolyte solution, and an electrolyte flow system which delivers the fresh working medium to the processing area (inflow) and removes the reaction products from the processing point (outflow). A stable mounting in the machining room is achieved using clamping elements. Figure 2 shows a conceptual design of these fixture components for removal fixture 1 (proposed substitution model) and removal fixture 2 (gear manufacturing). Further core aspects of the removal fixture design are summarized in **Table 3**.

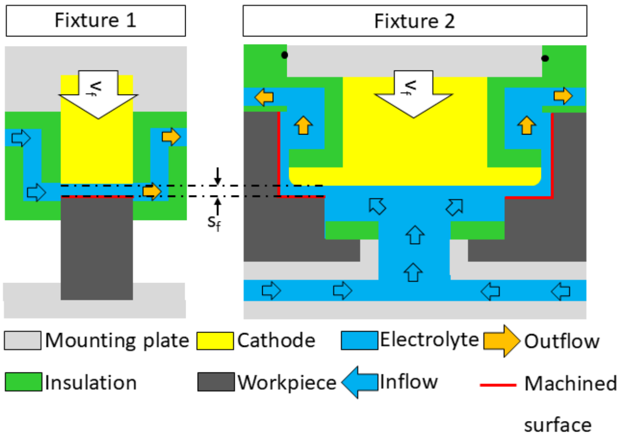

Figure 2. Conception of PECM removal fixtures.

Table 3. Core aspects of the removal fixture design.

	Fixture 1 Substitute model	**Fixture 2** Gear application
Machining orientation	Frontal gap only	Frontal and lateral gap
Cathode shape (projection area)	Circular area	Inverse gear profile
Cathode area	113 mm²	618 mm²
Sample dimension (projection area)	Rod, d = 12 mm	Circular ring with Internal diameter of d_i = 75.75 mm
Flushing direction	Side	Side
Sinking depth	Max. 60 mm	Max. 29 mm

2.4 Analytical aspects towards the adjustement of the interelectrode gap

Pulsed electrochemical machining enables high dimensional accuracy and surface quality using small interelectrode gaps of less than 0.1 mm. To adjust the dimensions of applications, often the variation of the voltage potential is selected [5]. As a result of the voltage potential reduction, the electrical resistance of the electrolyte solution decreases, allowing a stable reduction of the interelectrode gap width s, which can be determined using analytical methods as follows [1]:

$$s = \frac{(U - \Delta U) \cdot V_{sp} \cdot k}{v_f}$$

The value U is voltage potential in V, ΔU the polarization voltage, V_{sp} the specific material removal, k the electrical conductivity of the electrolyte and v_f the applied feed rate. The process input parameter are determined using the method DIN SPEC 91399. The results provide information about the specific material removal depending on the applied machine input parameters [6]. For the determination of the frontal interelectrode gap width, the machine's internal short-circuit detection system was used. The gap width value was accepted, after a constant material removal and machine current of at least 30 seconds had been realized.

3. Experimental validation of the PECM process

3.1 Repeatibilty measurement of the sinking axis

First, the repeatability of the sinking axis was measured using removal fixture 1. Ten contact runs were performed along the sinking path to determine the position of the component surface at the frontal gap, while the resulting axis coordinate being recorded for each experiment. The following **Figure 3** shows the deviation of the sinking axis repeatability, normalized to the first measurement R1.

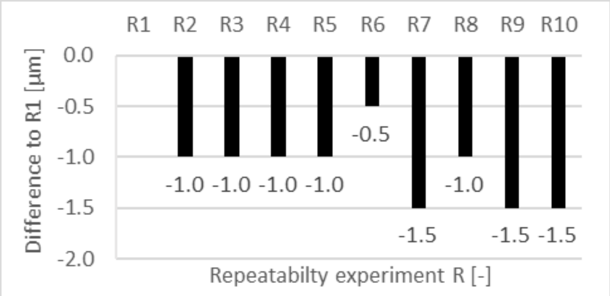

Figure 3. Summary of the 10 experiments for checking the repeatabilty of the PECM sinking axis.

After 10 experiments, the average deviation was within 1 µm. Regardless of the surface roughness of the samples before processing, the initialization shows that the PECM machine has a very high position accuracy of the sinking axis.

3.2 Process input parameter derivation for the material 1.4108

The electrochemical material characterization was conducted using the DIN SPEC 91399 method to derive the process input parameter for the material ASTM F899. During the experiments the machine input parameter voltage, pulse length and feed rate were varied from large to small. The interelectrode gap remained in the range of 0.05 mm ± 0.005 mm during the experiments using fixture 1. **Figure 4** shows the feed rate v_f as function of the current density J.

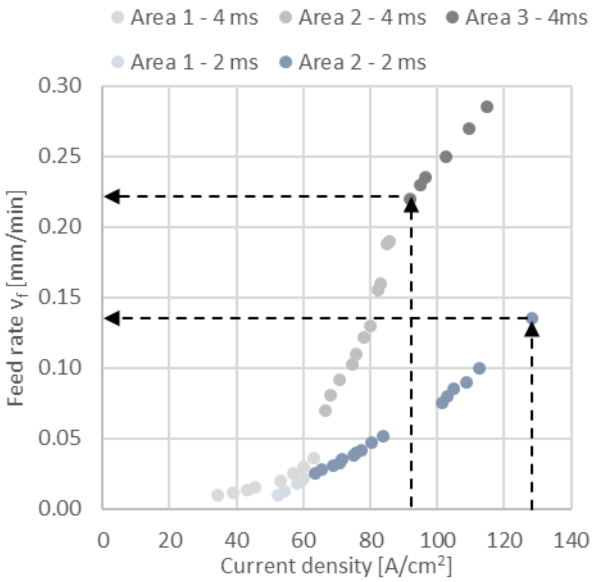

Figure 4. Feed rate v_f as function of the current density J at a frequency f of 50 Hz and two pulse lengths t_p 2 ms vs. 4 ms for ASTM F899.

The graph shows that increasing the current density results in higher feed rates. The curve is not linear due to metal oxidation during processing in sodium nitrate. For 50 Hz pulse frequency and a pulse length of 2 ms (duty cycle 10 %) and 4 ms (duty cycle 20 %) individual dissolution zones were found and classified using the removal efficiency analyses [7]. A metal oxidation occurring at lower current densities is caused by a change of the valence reaction capability, representing a functional electrical resistance. This leads to a more intense gradient of the current density occurring between dissolution zone 2 and zone 3 for 4 ms pulse length [8]. Using linear regression models, for each dissolution zone the removal functions are derived and summarized in **Table 4** [6].

Table 4. Derived material-specific removal functions depending on the current density.

Dissolution area	Current density range	Anlytical function
Area 1 – 4 ms	35 – 63 A/cm²	$v_f = 0.0009 \cdot J - 0.022$
Area 2 – 4 ms	64 – 90 A/cm²	$v_f = 0.0060 \cdot J – 0.336$
Area 3 – 4 ms	91 – 115 A/cm²	$v_f = 0.0028 \cdot J – 0.034$
Area 1 – 2 ms	52 – 63 A/cm²	$v_f = 0.0015 \cdot J – 0.068$
Area 2 – 2 ms	63 – 145 A/cm²	$v_f = 0.0016 \cdot J – 0.080$

For 4 ms pulse length a process start was chosen at 92 A/cm² and 0.220 mm/min representing the edge between dissolution zone 2 and 3. At 2 ms pulse, the 50 % shorter removal time leads to a lower sinking speed at equal current density [1]. Thus, a sinking speed of 0.135 mm/min was selected at a current density of 128 A/cm².

3.3 Comparison of the frontal end working gaps

Experiments were conducted using the material-specific process input parameter derived in advance. After PECM processing, the stability of the frontal end working gap s_f was tested for both removal fixtures for the reduction of the voltage potential. **Table 5** summarizes the varied parameters, the resulting frontal end working gaps s_f and their deviation Δs_f of both fixtures.

Table 5. Comparison of the frontal end working gap for fixture 1 and 2 using similar machine input parameter.

#	Pulse length [ms]	Voltage potential [V]	Fixture 1 s_{f1} [µm]	Fixture 2 s_{f2} [µm]	Δs_f [µm]
1	4	13.8	53	64	11
2		11.8	39	49	10
3		9.8	27	34	7
4		8.8	26	28	3
5	2	15.0	47	50	3
6		13.0	34	39	4
7		11.0	29	33	4
8		10.0	23	23	0

Basically, a reduction in voltage potential by 5 V resulted in a decrease of the frontal working gap by almost 50 % after PECM processing. Nethertheless, both fixtures show different frontal end working gaps and a strong dependence on the set voltage potential as well as pulse duration. It is noticable that for the same applied voltage potential removal fixture 2 had higher gap widths compared to removal fixture 1. However, the deviation of the frontal end working gaps decrease with lowering the machine voltage. For a pulse length of 4 ms, the deviation was reduced from 11 µm at 13.8 V to 3 µm at 8.8 V. For a pulse length of 2 ms it becomes clear, that the deviation Δs_f is smaller across the tested voltage range. The frontal end working gap decreases from 3 µm at 15.0 V to 0 µm at 10.0 V, representing an ideal transferability. It is assumed that the larger processing area and machining orientation of fixture 2 produces overall a higher material removal volume at high voltage potentials and 4 ms pulse durations, resulting in larger final working distances. The shorter the current pulse such as for 2 ms pulse length, the smaller is the resulting removal volume and the process precision increase by the smaller interelectrode gap. Thus, for a pulse duration of 2 ms and the lowest set voltage potential of 10.0 V, an identical value was achieved for both removal fixtures at 23 µm frontal end working gap.

3.4 Comparison of the machining current for both fixtures

As shown in Table 3, the removal fixtures differed in terms of machining direction and current-transmitted area. Fixture 1 is designed for complete front gap machining, while the more complex removal fixture 2 produces the desired geometry in the lateral working gap. The different machining direction is also visiable in the machine current that was recorded in the machine log. The machine current values show the last 30 seconds of the removal process. For 4 ms pulse length, the machining current for both fixtures are compared **Figure 5**.

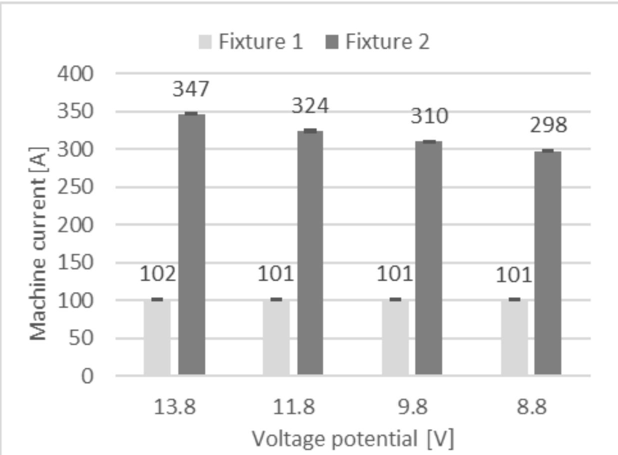

Figure 5. Comparison of the machining current of both removal fixtures for 4 ms pulse length, showing the last 30 seconds of the machining.

The comparison of the machine currents show very different behavior for a reduction voltage potential of 5 V using both removal fixtures. Removal fixture 1 has a negligible reduction of machine current by 1 A. This change of around 1 % is considered to be approximately constant. Removal fixture 2 shows for the same reduction a decrease in machine current of 49 A, representing a machine current drop of approximately 14 %.

It is expected that the constant current-transmitting surface area during only frontal gap machining of fixture 1 results in an almost constant machine current for lowering the machine voltage. The significant decrease of machine current for removal fixture 2 is explained by the fact that the current-transmitting surface area in the lateral gap is reduced by the change of the electrical field distribution [5].

4. Summary and outlook

Electrochemical precision machining offers great potential to produce various shapes in components in favored high-strength or difficult-to-cut materials. In this paper, a comparison of the PECM process using two different removal fixtures was researched for the machining of the martensitic stainless steel ASTM F899. The two fixtures, an simple substitution model for only frontal machining, and an complex fixture for internal spur gear manufacturing using lateral gap machining, were compared regarding their design and their core features. Experiments were conducted, considering the material-specific dissolution zones determined with the electrochemical material characterization in advance. Based on the evaluation of the experiments, the transferability of the frontal end working gap for various machine settings was shown. The main findings are:

1. A very high positioning accuracy of 1 µm was found for the sinking axis of the PECM system
2. Initial machine input parameter were derived for the studied material using DIN SPEC 91399. For the tested current density range, an nonlinear removal behaviour was found for both pulse lengths. This is typical for machining in sodium nitrate, due to the changes of the reaction manner of the valence electrons.
3. It was approved that a reduction of the voltage potential leads the smaller frontal end working gaps.
4. Compared to removal proposed fixture 1, fixture 2 tends to a higher material removal at larger frontal end working gaps. Netherthless, at 4 ms pulse length a minimum deviation of 3 µm at 8.8 V and for 2 ms at 10.0 V even no deviation was achieved.
5. Hightlighting the change of the machine current for 4 ms pulse length, lowering the voltage showed an almost constant machine current for only frontal gap machining using fixture 1, meanwhile for fixture 2 showed an reduction of the machine current by 14 %. It is expected that during lateral gap machining a reduced current-transmitting surface area is the root cause for the machine current decrease.

Summarizing the approach to use a simplified substation fixture for the PECM process initialization, the comparison of the process with a complex gear manufacturing fixture evidenced an sufficient transferability of the frontal end working gap adjustment. Thus the basic process input parameters can be determined using the simplified substitution model. However, a final parameter optimisation is necessary for complex manufacturing tasks to guarantee the dimensional accuracy for the evolving interelectrode gap.

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