Experimental Derivation of Process Input Parameters for Electrochemical Machining with Differentially Switched Currents

André Martin[a,], Tom Petzold[a], Matthias Hackert-Oschätzchen[a], Gunnar Meichsner[b], Andreas Schubert[a,b]*

[a]Professorship Micromanufacturing Technology, Faculty of Mechanical Engineering, Chemnitz University of Technology, 09107 Chemnitz, Germany

[b]Fraunhofer Institute for Machine Tools and Forming Technology, 09126 Chemnitz, Germany

*Corresponding author: andre.martin@mb.tu-chemnitz.de

Abstract

The manufacturing of components with complex internal features, e.g. for automobile industry, aeronautics or medical applications, is a significant challenge. Such components are often machined in temporarily and locally separated stages of production. Due to these separated stages, the form deviations and positioning errors increase, which leads to additional efforts for the quality assurance. The technology that shall be developed within the project SwitchECM is supposed to enable machining of components with differing complex features in one single production stage and shall simultaneously allow for high precision. For this purpose, a multi-cathode system will be developed, in which every single cathode can be switched with specific parameters. The specific switching parameters shall be adjusted according to the requirements of the pre-defined features.

For the manufacturing of different pre-defined features with one multi-cathode system the usage of pulsed direct current as well as continuous direct current shall be possible. Hence, removal experiments were carried out on 1.4301 stainless steel using a PEMCenter 8000 with varying feed rates and voltages at a pulsation frequency of 200 Hz. With this comparatively high frequency and a pulse duration of 4 ms pseudo direct current experiments are realized.

The results are compared to experiments with a more common pulse frequency of 50 Hz. The mass removal analyses show, in which degree the transferability of experimental results from pulsed current to pseudo direct current or rather direct current is feasible.

1 Introduction

Electrochemical machining (ECM) allows for machining of complicated geometries, e.g. injection nozzles with varying bore edges. Based on the anodic metal dissolution, materials can be machined regardless of their mechanical properties. The edge zone of workpiece is not affected by mechanical nor thermal influences [4, 5, 6]. It is also possible to handle difficult-to-cut and high-strength materials. However, the selection of adequate processing parameters is not trivial, if the removal mechanism of the specific material is not known. For this purpose, initial experiments on material-specific dissolution characteristics are carried out to define adequate processing parameters. In this study, the influence of an increased voltage pulsation frequency on the resulting removal characteristics of the workpiece material is analyzed according to [6]. The results are carried out at a pulsation frequency of 200 Hz in order to realize pseudo direct current (DC) characteristics and compared to experiments with the results of Pulsed Electrochemical Machining (PECM) at a more common voltage pulsation frequency of 50 Hz, in order to investigate the transferability of the results of common pulsed ECM to pseudo-DC ECM.

2 Experimental

The experiments were carried out on a PEMCenter 8000 according to [7]. The chemical composition of the workpiece material is charted in Table 1.

Table 1: *Alloying elements of stainless steel 1.4301*

Element:	*Fe*	*Cr*	*Ni*	*Mn*	*Si*	*N*	*C*	*P*	*S*
Percentage p [%]:	*69.76*	*18*	*9*	*2*	*1*	*0.11*	*0.07*	*0.045*	*0.015*
Valence z:	*3*	*6*	*2*	*2*	*4*	*3*	*4*	*3*	*2*
Molar mass M [g/mol]:	*55.85*	*52.0*	*58.7*	*54.94*	*28.09*	*14.01*	*12.01*	*30.97*	*32.06*

Austenitic stainless steel 1.4301 was chosen as workpiece material. The values charted in Table 1 were given by the data sheet [2, 3]. For the experimental analysis of the current efficiency, the specific removal mass m_{sp} and the specific removal volume V_{sp} were calculated according to

$$V_{\text{sp}} = \frac{1}{\rho} \cdot m_{\text{sp}} = \frac{1}{\rho} \cdot \sum_{i=1}^{n} \frac{p_i * M_i}{100 * z_i * \text{F}}. \tag{1}$$

The calculations with the values given in table 1 and under consideration of the Faraday-constant of F = 96485 C/mol and the material density of ρ_{Leg} = 7.56 g/cm³ result in a specific removal mass of m_{sp} = 1.847 · 10^{-4} g/C and specific removal volume V_{sp} = 2.443 · 10^{-5} cm³/C. The experiments were carried out with the processing parameters charted in Table 2.

Table 2: *Processing parameters for pseudo direct current experiments*

Symbol	*Parameter*	*Value*
	Anode and cathode material	*1.4301*
d	*Anode and cathode diameter*	*Ø 12 mm*
h	*Anode height*	*40 mm*
	Electrolyte type	*Sodium nitrate ($NaNO_3$)*
σ	*Electrolyte conductivity*	*69 mS/cm ± 0.5 mS/cm*
p	*Electrolyte pressure*	*750 kPa*
f	*Voltage pulse frequency*	*200 Hz*
t_p	*Voltage pulse duration*	*4 ms*
	Cathode oscillation	*none*
U	*Voltage*	*5 V … 14.5 V*
v_f	*Feed rate*	*0.007 mm/min … 0.676 mm/min*
J	*Resulting current density*	*5 A/cm² … 100 A/cm²*
s_x	*Resulting frontal working distance*	*0.03 mm … 0.17 mm*

The diameter of the sample specimen and the opposed cathode of 12 mm results in a machining area of 113.09 mm², which was used for the calculation of the current density. The high voltage pulsation frequency of 200 Hz and the comparatively long voltage pulse duration of 4 ms result in a comparatively high duty cycle of 80 %. Thus, pseudo DC characteristics were realized.

3 Results of pseudo DC removal experiments

Figure 1 shows six exemplary surfaces as removal results of the spectrum of applied current densities. The surfaces were inspected qualitatively and displayed as function of the current density.

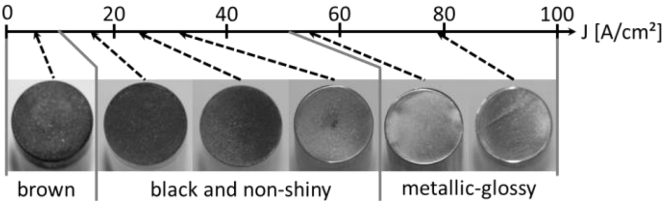

Figure 1: *Selected machined surfaces shown in correlation of current density J*

A classifications into three characteristic surfaces can be derived according to [6]. The sample surface machined at a current density of 5 A/cm² is characterized by a non-shiny, brown discoloration. In the range from more than 5 A/cm² until less than 50 A/cm² the surface colors appear black and non-shiny. At current densities higher than 50 A/cm² the surfaces appear metallic-glossy.

The machined surfaces were measured by confocal microscopy in three different sections distributed on the left, the right and in the center of the sample surfaces with a measurement area of 750 µm x 900 µm. The roughness values *Sa* and *Sz* of each section was analyzed and the average of the respective samples was calculated. The resulting roughness parameters of the six exemplary surfaces as function of the current density are shown in Figure 2.

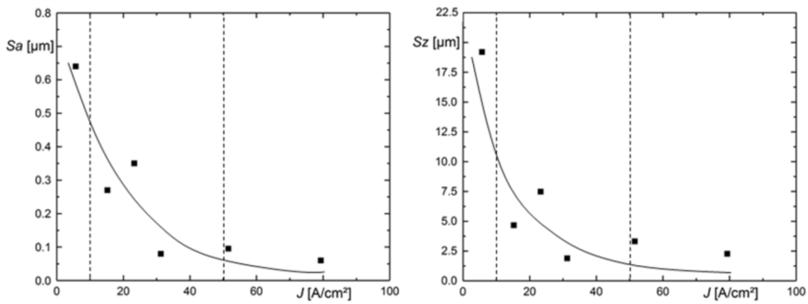

Figure 2: *Surface roughness Sa and Sz as function of the current density J*

Roughness values of *Sa* = (0.06 µm … 0.64) µm and *Sz* = (1.68 … 19.2) µm were detected. The values show a decreasing trend at increasing current density as highlighted by the bold line. The smoothest surface was achieved at a current density of 102 A/cm², where values of *Sa* = 0.06 µm and *Sz* = 2.27 µm were measured. The highest roughness was detected at a current density of 5.6 A/cm², where *Sa* = 0.64 µm and *Sz* = 19.2 µm were measured. The point diagram in figure 3 indicates the correlation between the feed rate v_f and the current density *J*.

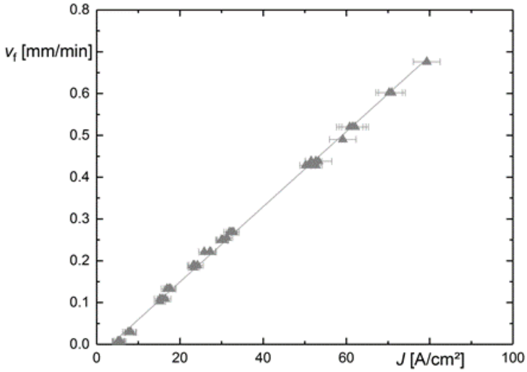

Figure 3: *Feed rate v_f as function of the current density J*

The feed rate rises linearly with a linear increase in current density after an offset of approximately 5 A/cm². The mathematical relation for the calculation of the feed rate given by equation (2) was derived from the experiments.

$$v_\mathrm{f} = 0.009\ \frac{\mathrm{mm{\cdot}cm^2}}{\mathrm{min\ {\cdot}A}} \cdot J - 0.0308\ \frac{\mathrm{mm}}{\mathrm{min}} \qquad (2)$$

For the characterization of the realized removals the current efficiency was calculated according to

$$\eta = \frac{v_\mathrm{f}}{V_\mathrm{sp} \cdot J \cdot c} \qquad (3)$$

as the quotient of the feed rate v_f and the product of the specific removal volume V_{sp}, the current density *J* and the duty cycle *c*. The calculated current efficiencies as function of the applied current densities are shown in Figure 4. The resulting development corresponds to typical developments of passivating electrolytes [4]. Hence, no removal is realized due to passivation effects at current densities below 5 A/cm². Electrochemical removals in transpassive state are realized at current densities between 5 A/cm² and 20 A / cm², where a rapid increase in current efficiency with increasing current density was derived. At a further increase in current density an almost constant current efficiency of approximately 80% is achieved.

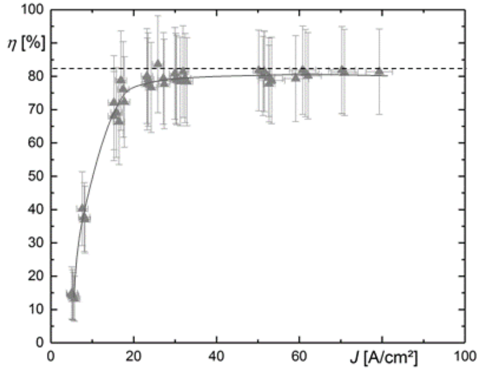

Figure 4: *Calculated current efficiency η as function of the current density J*

4 Comparison of the material removal rate of pseudo DC and pulsed DC electrochemical machining

In order to compare the removal rate of different voltage pulsation frequencies, the material removal speed v_a was calculated according to

$$v_\mathrm{a} = v_\mathrm{f} \cdot c \quad (4)$$

as the product of the feed rate v_f and the applied duty cycle c. The duty cycle c represents the product of the voltage pulsation frequency f and the pulse width t_p according to equation (5).

$$c = f \cdot t_\mathrm{p} \quad (5)$$

The resulting material removal speed as function of the current density for pulsed DC ECM with a voltage pulsation frequency of 50 Hz and pseudo DC ECM with a voltage pulsation frequency of 200 Hz are shown in Figure 5. While at current densities higher than 55 A/cm² almost the same material removal speed was calculated for both pseudo-DC ECM and pulsed DC ECM, there is a significant difference at lower current densities. The relative deviation between pseudo-DC ECM and pulsed DC ECM exhibits 0 % at 0 A/cm² and increases up to 14.3 % at 51 A/cm².

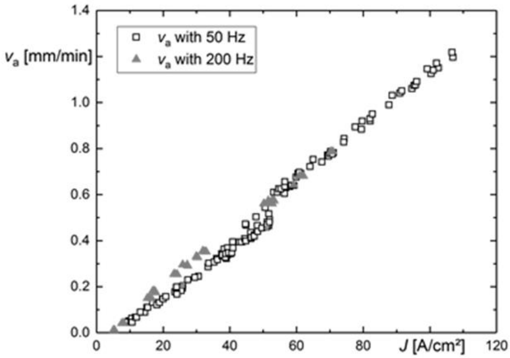

Figure 5: *Material removal speed as function of the current density for pseudo-DC ECM at voltage pulsation frequency 50 Hz and pulsed DC ECM at voltage pulsation frequency 200 Hz*

According to [1] a possible cause could be the complete removal of the polishing film in pulsed DC ECM, when the pause time between the voltage pulses exceeds 10 ms. In this case the polishing film is flushed away due to electrolyte flushing and is rebuilt in the following voltage pulse, which results in a decrease in removal rate due to consumption of electric energy. For the present parameters of pulsed DC ECM with 50 Hz and 4 ms of pulse duration the pause time between the voltage pulses exhibits 16 ms.

5 Summary

In this paper, the dissolution characteristic of stainless steel 1.4301 at pseudo-DC ECM conditions with a voltage pulsation frequency of 200 Hz were investigated and compared to existing experiments in pulsed DC ECM at a voltage pulsation frequency of 50 Hz. High surface qualities with roughness values down to *Sa* = 0.06 µm were achieved at current densities between 30 A/cm² and 80 A/cm². The resulting surface qualities of pseudo-DC ECM and pulsed DC ECM are almost comparable.

Considering the current efficiency, the typical characteristics of the applied passivating electrolyte was determined in the pseudo-DC ECM process. But investigations into the material removal speed revealed that there is a difference at current densities below 55 A/cm², where a significantly higher material removal speed was asserted in pseudo-DC ECM. Hence, the general transferability of the characteristics of pulsed DC ECM to pseudo-DC ECM is not feasible. Specific analyses according to [7] will be required to analyze the removal characteristics in pseudo-DC ECM even if the characteristics of pulsed DC ECM are known for the applied material.

Acknowledgements

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