2D Axisymmetric Simulation of the Electrochemical Finishing of Micro Bores by Inverse Jet Electrochemical Machining

Matthias Hackert-Oschätzchen[*,1], Michael Kowalick[1], Gunnar Meichsner[2], Andreas Schubert[1, 2], Bernd Hommel[3], Frank Jähn[3], Matthias Scharrnbeck[4], Rüdiger Garn[5], Andreas Lenk[5]

[1]Technische Universität Chemnitz, Professorship Micromanufacturing Technology, Chemnitz, Germany
[2]Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany
[3]SITEC Industrietechnologie GmbH, Chemnitz, Germany
[4]SITEC Automation GmbH, Chemnitz, Germany
[5]Continental Automotive GmbH, Limbach-Oberfrohna, Germany
[*]09107 Chemnitz, Germany, matthias.hackert@mb.tu-chemnitz.de

Abstract: Within this publication a wide scope of technology user, system developers and research institutes have worked together in a cooperation project funded by the European Union through the European Regional Development Fund (ERDF) and from state funds of the Free State of Saxony. Focus of the project was the creation of conditions for a quality-oriented mass production of micro bores with defined hydraulic flow. These micro bores are used for several high-precision applications, especially in hydraulic systems. In this case the shape of the micro hole, particularly the edge rounding, has a significant influence e. g. on atomization of fluids [1]. After wide-ranging experimental studies for the desired function, the application of shaped electrodes could be detected to be unsuitable and therefore an inversion of the Jet Electrochemical Machining process has been developed [2].
In this process the erosion area is localized by a continuous electrolytic free jet. Forming a free jet leads to a high localization of the current density resulting in a highly localized machining area [3].
In this study the inverse Jet-ECM process of micro bores is investigated by help of multiphysics simulations. Based on the micro bore of a commercial sample dispense tip a model geometry was derived. For simulating inverse Jet-ECM a transient and fully coupled model has been developed. Therefore the electric currents and the deformed geometry interface were used. As a result of the multiphysics simulations it could be demonstrated, that the maximal removal took place at the edge of the bore hole and only a slight removal at the internal bore wall. This reflects the high localization of the erosion area.
Based on this work an industrial setup was realized and the feasibility of targeted adjustment of the flow of micro bores by inverse Jet Electrochemical Machining could be proved.

Keywords: Electrochemical Machining, anodic dissolution, finishing of micro bores, fuel injection

1 Introduction

The function of hydraulic systems is often influenced by the geometry of micro bores, which are applied as throttles or dispense tips to control the dynamics of pressure and fluid flow. Such micro bores with a high structural accuracy, resistance to wear and also a high aspect ratio are required in automotive industry in the production of injection holes for direct injection fuel systems. In this case the shape, especially the edge shape of the injection hole, has a significant influence on the atomization of fuel and thus on the combustion process [4]. To adjust the edge rounding of the bore without influencing the roughness of the bore interior wall an inverse Jet Electrochemical Machining process has been developed in cooperation of Technische Universität Chemnitz, Fraunhofer Institute for Machine Tools and Forming Technology IWU, SITEC Industrial Technology GmbH, SITEC Automation GmbH and Continental Automotive GmbH. This process of inverse Jet-ECM was applied for a patent [5] and is based on a localized anodic dissolution of the work piece that is connected to a positive electric potential. A negative or zero potential is connected to the tool which is the cathode. The electrolyte jet determines the localization of the current density and therefore the shape of the edge rounding. The advantages of this process exist in the possible high localization of the erosion area, the high achievable surface quality and the possibility to work under high pressure conditions of the electrolyte.

The basic arrangement of this process is shown in figure 1. A micro bore is applied, which is imposed on the

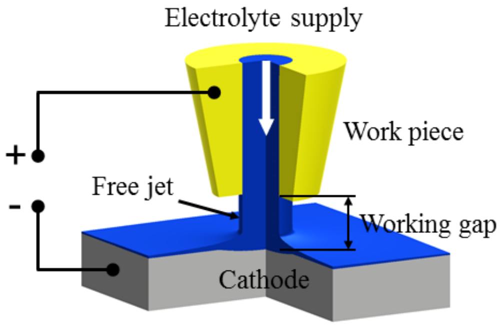

Figure 1. Principle of inverse Jet Electrochemical Machining [2]

anodic pole while a cathodic polarized metallic surface displays the antipole. The electrolytic liquid is pumped under high pressure through the bore hole and forms a free jet with a well-defined shape as shown in figure 1. Thus, the distribution of the current density is limited to a confined area at the front edge of the micro bore thereby limiting the removal geometry to this area. This guarantees the realization of an edge rounding without influencing the interior bore wall.

2 Model Description

2.1 Geometry

A commercial dispense tip was applied as sample for the micro bore. The original shape of the outlet of the applied micro dispense tip is shown by the SEM image in figure 2.

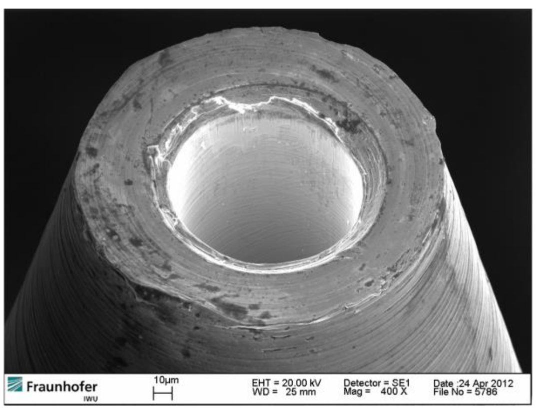

Figure 2. SEM image of an unmachined micro dispense tip [6]

The micro bore has a diameter of 100 µm and the outer diameter of the front surface is 200 µm. Between the front and the bore there is a chamfer, which is about 15 µm wide and 10 µm deep. The original dispense tip geometry was determined with a Keyence VK-9700 measuring microscope by detecting the cross-sectional profile as shown in figure 3.

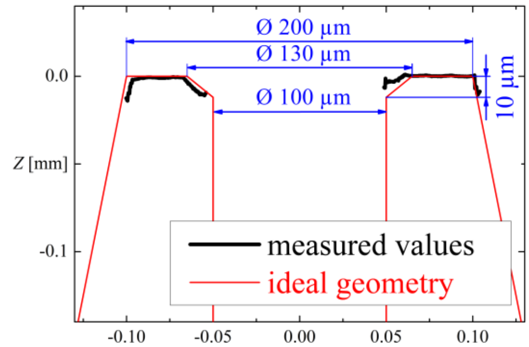

Figure 3. Cross-sectional profile of a micro bore before machining [6]

The ideal shape of an original dispense tip is highlighted by the red lines, as it was derived from the specifications given by the manufacturer. In the measurements, which are illustrated in black, certain deviations are visible, which result from the burrs shown on the SEM image. With the applied microscope a maximum inclination of 60° can be detected. Hence, the internal shape of the micro bore cannot be measured, because the angle is too steep as it is aligned vertically to the viewing direction.

To assist the process design of inverse Jet-ECM multiphysics simulations were performed with the help of COMSOL Multiphysics which was shown to be suitable to simulate ECM processes before [7].

Starting with the simulation an axisymmetric model geometry was created based on Yoneda's shape of electrolyte jet as shown in figure 4 [8, 9]. The simulation model consists of two areas. The first area represents the applied micro dispense tip and the second area the geometry of the ejected electrolyte. According to the planned experiments, the dispense tip is situated in a typical Jet-ECM distance of 100 µm perpendicular to the work piece surface. The electrolyte jet conforms to the dispense tip's bore diameter and the flow-off geometry conforms to the shape defined by Yoneda.

The lower edge displays the surface of the cathode. On the left side the axis of symmetry is defined parallel to the jet.

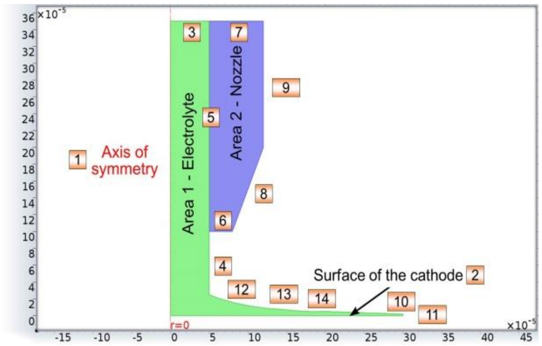

Figure 4. Simulation geometry based on the model of Yoneda [8]

2.2 Meshing

The FEM meshes that were used in the simulation for the calculation of the local current density and the material dissolution were created using the automatic mesh creator. The mesh for the static calculation of current density shows figure 5.

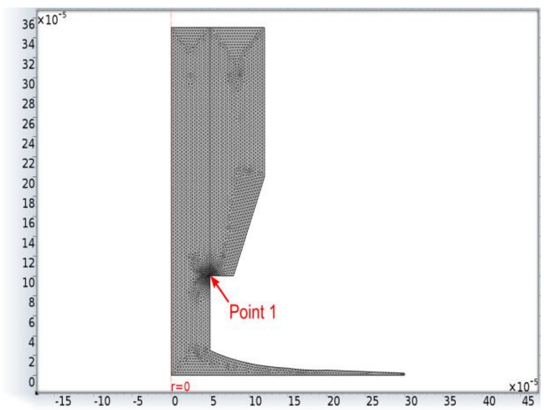

Figure 5. FEM mesh for the calculation of current density [6]

To generate this mesh a user-defined mesh with the setting extremely fine FEM mesh was chosen to be able to determine the local current density. This setting includes minimum element size of 0.007 µm and a maximum one of 3.5 µm. The region marked point 1 is meshed even finer as a concentration of the local current density in this edge can be assumed. Here the maximum element size was set to 1 µm. These settings resulted in a mesh with 7871 elements.

Figure 6 shows the FEM mesh for the simulation of material dissolution.

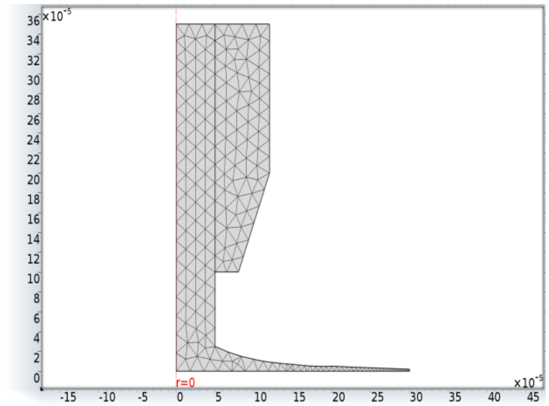

Figure 6. FEM mesh for the calculation of material removal [6]

In the matter of calculating the material removal a coarser meshing had to be applied, because the interaction between the simulations of the local current density resulting in a deformation of the FEM mesh is highly challenging. In this case the element size option fine was chosen, which includes a maximum element size of 18.6 µm and a minimum element size of 0.1 µm. This settings leads to 374 mesh elements.

2.3 Physics

The investigations of a defined edge rounding with an inverse Jet-ECM process were performed in a first step with the help of multiphysics simulations. Therefore a fully coupled model was developed. In this connection the electric currents and deformed geometry interface were used. Here, the material dissolution was investigated as a time-dependent study. Steel AISI 4340 (stainless steel 1.4541) was chosen from the materials library of COMSOL for the domain of the dispense tip. So this domain obtained an electrical conductivity of $4.032 \cdot 10^6$ S/m. The domain of the electrolyte was assigned to water from the material library and defined with a typical Jet-ECM conductivity for experiments, which is 13 S/m.

The boundary conditions of the electric current interface according to figure 4 are listed in table 1.

Table 1. Boundary conditions in the mode electric currents for the boundaries numbered in Figure 4.

Boundary	Definition
1	Axis of symmetry
2	
3	$\vec{n} \cdot \vec{J} = 0$
4	$\vec{n} \cdot \vec{J} = 0$
5	Continuity
6	$\vec{n} \cdot \vec{J} = 0$
7	$U = 34$ V
8-14	$\vec{n} \cdot \vec{J} = 0$

The boundary conditions used in this model are Axis of symmetry, continuity, ground, electric potential and electric insulation. The boundary conditions for ground and electric potential are reversed to a conventional Jet-ECM process. The cathode surface on boundary 2 is set to the electric ground, which means a voltage of 0 V and the dispense tip is imposed on the anodic potential of 34 V. The boundaries 3, 4, 6 and 8 to 14 have been assigned to the electrical insulation.

The time-dependent simulation of the material dissolution was carried out by coupling the mode electric currents with deformed geometry. The functional principle of ECM is the anodic dissolution of metals due to an electric charge transport *Q* following Faraday's law. The removed material volume *V* is calculated by [10]:

$$V = \eta \cdot \frac{M}{\rho \cdot z \cdot F} \cdot Q \tag{1}$$

M is the molar mass, ρ the density, *z* the electrochemical valence of the material, *F* the Faraday constant, and η is the current effciency. The velocity of material removal in normal direction $\vec{v}_n$ depends on the current density in normal direction $\vec{J}_n$ [7]:

$$\vec{v}_n = \frac{M}{\rho \cdot z_A \cdot F} \cdot \vec{J}_n \cdot \eta(J) \tag{2}$$

The boundaries 5 and 6, which should be machined, have been assigned to this condition. When applying ECM of ferrous workpieces using a solution of sodium nitrate as electrolyte, there is a passive region where no material will be resolved at low current densities [11]. This fact was additionally taken into account by implementing a conditional removal:

$$\eta(J) = \begin{cases} 1 \; for \; J > J_{min} \\ 0 \; for \; J \leq J_{min} \end{cases} \tag{3}$$

According to literature Jmin was set to 10 A/cm². Other required parameters for calculating the erosion according to equation 2 are listed in table 2.

Table 2. Variables in equation 2 and used values for the simulated and machined stainless steel 1.5920 [12]

Symbol	Name	Value
η	Current efficiency	100%
M	Molar mass	54.94 g/mol
z_A	Valency	2.4
ρ	Mass density	7.77 g/cm³
F	Faraday constant	$9.65 \cdot 10^4$ C/mol

3. Results of the Simulation

In figure 7 the result of a static calculation of the current density distribution is shown by means of a false colour rendering. From the simulation it can be derived, that the maximum of the local current density is reached at the edge of the bore, where values exceeding 1000 A/cm² were calculated. Accordingly, the electrochemical dissolution in this region will reach a maximum as well. Therefore a preferred rounding of the bore edge is expected. Furthermore a significant decrease in local current density can be seen along the inner bore wall at growing vertical distance from the cathode. Thus it can be assumed that the electrochemical dissolution will be concentrated to the front surface of the dispense tip.

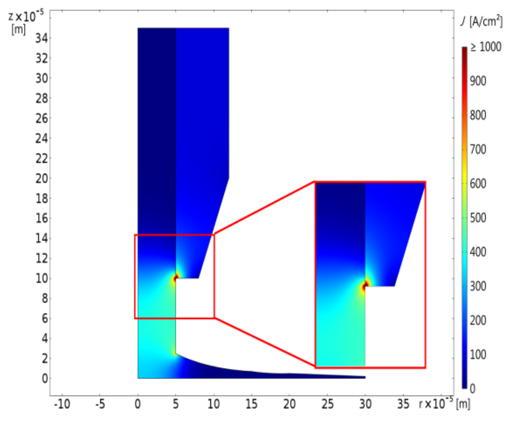

Figure 7. False color rendering of the distribution of the current density, overview and detailed view on the bore edge [6]

The calculation of total electric current was performed by integrating the local current densities along the surface of the cathode. Thereby a current of approximately 33 mA was calculated.

Figure 8 shows the simulation results of the local current density as a streamline illustration.

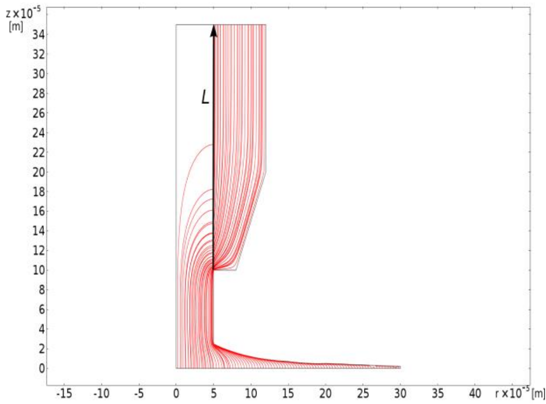

Figure 8. Streamline illustration of the current density distribution [6]

It can be seen, that the flow lines of the electric current density are concentrated to the edge of the bore on the dispense tip's front surface. This is additionally supported, when considering the electric current density along the bore interior wall. Figure 9 shows the electric current density as a function of the arc length L marked in figure 8.

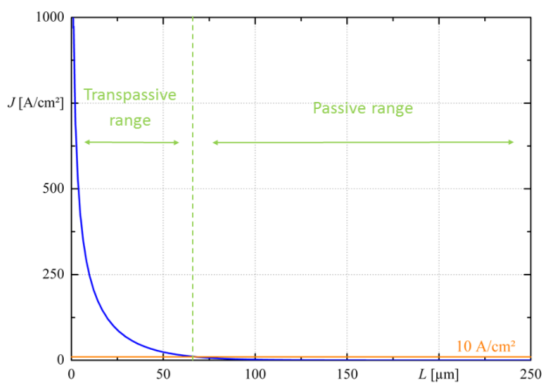

Figure 9. Function of the electric current density along the arc length of the bore interior wall [6]

It can be seen, that the maximal current density appears in the area of the bore edge at a value of more than 1000 A/cm². With increasing hole depth the electric current density decreases significantly. At a depth of about 70 microns the current density decreases in the passive range, which starts approximately below 10 A/cm² for machining steel with sodium nitrate ($NaNO_3$) [11]. Thus no material dissolution of the bore hole deeper than 70 µm has to be expected under the investigated process parameters.
Figure 10 shows the simulation result of the transient simulations at the 0.1 s time-step.

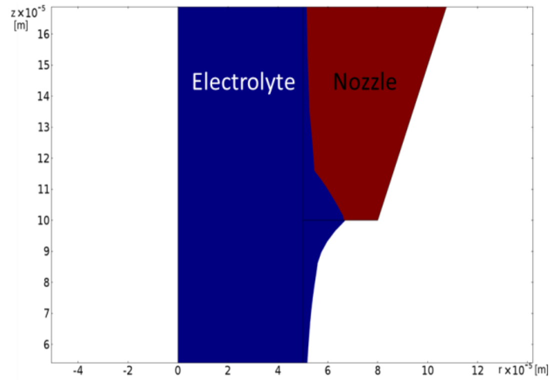

Figure 10. Simulation result of the transient electrochemical erosion at t = 0.1 s

According to the simulated current density distribution, the electrochemical erosion mainly appears at the edge of the bore, which indicates a preferred rounding of the edge. It is obvious that the mesh displacement decreases at increasing distance from the bore edge, which illustrates a decreasing electrochemical influence in the interior bore wall. Additionally, the outer front surface of the dispense tip is not influenced. However, the deformed shape of the jet is not consistent to its real geometry. At a certain rounding the separation of the jet from the bore edge has to be expected. The resulting enlarging of the bore diameter amounts 133 µm.

4. Validation of the Simulation Results

To validate the simulation results the commercial micro dispense tip was machined with inverse Jet-ECM. Figure 11 shows in a SEM image the machined dispense tip after a processing time of 0.1 s and figure 12 a cross-sectional profile determined with a Keyence VK-9700 measuring microscope.

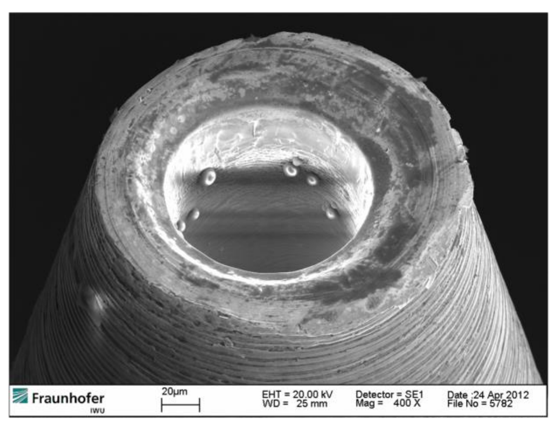

Figure 11. SEM image of a micro dispense tip after 0.1 s of inverse Jet Electrochemical Machining [6]

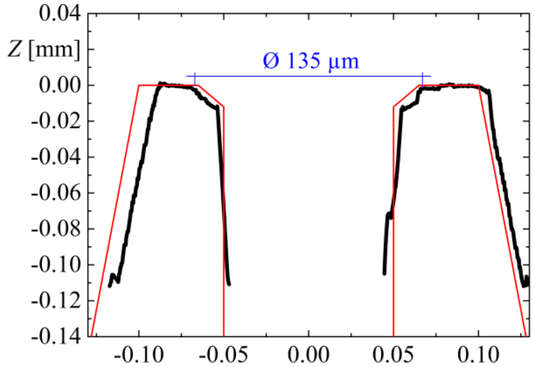

Figure 12. Cross-sectional profile of a micro dispense tip after 0.1 s of inverse Jet Electrochemical Machining [6]

After 0.1 s of processing time the edge on the front surface is widened around 5 µm compared to the original shape, while the depth of the chamfer is hardly influenced. It is obvious that the edge of the micro bore is rounded by the electrochemical machining process. The burrs on the front are completely removed, which results in higher surface finishes on the rounded edge. As can be derived from the SEM image, the interior bore wall is not influenced by Jet-ECM. From the measurements it can be derived that the electrochemical dissolution stops in a depth near to the simulated value of 70 µm.

5. Adjustment of the Flow Rate of Micro Bores

The results from the performed simulations and preliminary experiments were incorporated into the development of a tool system. With this tool system it is possible to round micro bores, so that a defined flow rate can be adjusted. SITEC Industrietechnologie GmbH and SITEC Automation GmbH developed such a device and machine system. Figure 13 shows in schematic illustrations the design of the tool system.

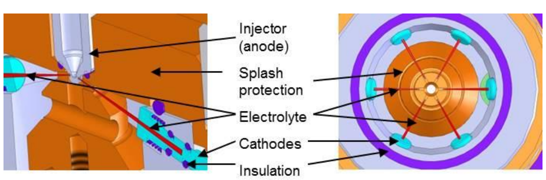

Figure 13. Scheme of the tool system for inverse Jet-ECM [2]

The micro bores, in the particular case the injector, is connected to a positive electrical potential. The electrolyte, which is marked red, passes through the bores and incident on an opposing and insulated electrode. An integrated splash protection between the two electrodes prevents a machining of the tool system. So only the micro bores of the injector are integrated into the EC process. During the machining process the electrolyte pressure, electrolyte flow rate and flow velocity are measured.

A first aim of the investigations with this tool system was to transfer the flow behavior of the electrolyte on the behavior of fuel. For this purpose comparison studies were performed by Continental Automotive GmbH and SITEC. In a first step the flow difference of diesel and aqueous electrolyte through the micro bores before machining were determined. Then the micro bores were machined with inverse Jet-ECM. After that process the flow difference of the two liquids were determined again. The investigations have shown a good agreement of the correlations between the diesel and electrolyte. In a first approximation can be assumed that there exists a direct relationship between diesel and electrolyte.

Considering this, it is possible to machine the micro bores of the injector and perform a flow measurement at the same time to predict the behavior of fuel in the engine. To achieve this, the flow rate is determined at a working pressure of 100 bar. Figure 14 shows in a diagram the flow rate within one processing cycle.

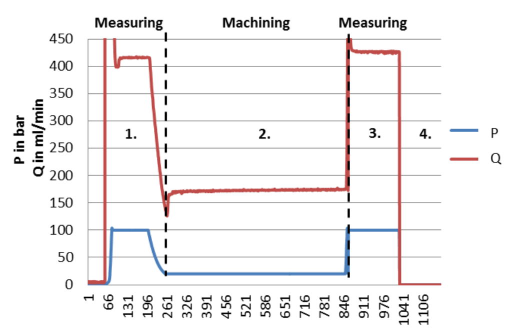

Figure 14: Diagram of flow rate and working pressure within one processing cycle [2]

As it can be seen, typical flow rates of approximately 400 ml/min are reached. This volume the apparatus has to absorb or drain in a statistically determined processing time of 1 min. In the performed series of experiments it was detected that this is not possible at a pressure of 100 bar, because the system runs full of electrolyte. As a result the machining proceeds in a bath of electrolyte. For this reason, the following procedure for the determination of the flow rate was used. These points are marked in figure 14.

1. Determine the initial flow rate at 100 bar
2. Machining at 20 bar
3. Measuring at 100 bar

4. If the target flow rate was reached, machining is completed, otherwise the cycle begins with step 2.

It can be seen that while the machining at 20 bar, the flow rate increases. In addition, the increased flow rate in range 3 compared to the initial flow rate can be observed.

6. Summary

In this study multiphysics simulations of the electrochemical finishing of micro bores by inverse jet electrochemical machining were performed. Therefore a coupled model, using the electric currents and deformed geometry interface, has been developed. As results of the simulation the current density distribution and therewith the transient erosion of the bore edge could be demonstrated. Here, the principle and the localization of the dissolution could be shown.

With the knowledge of the simulations experiments on a commercial micro dispense tip as sample for the micro bore were carried out. Here, a good agreement between simulation and experiments was observed.

Based on these preliminary tests a tool system was developed. With the help of this tool system a direct relationship between fuel and aqueous electrolyte could be detected. In further investigations a defined adjustment of the flow rate of micro bores by inverse jet electrochemical machining was carried out. Furthermore, it could be proven by help of simulation and experiment that the bore internal wall is not influenced by the electrochemical machining process due to passivation effect at a depth of approximately 70 µm under the investigated process parameters.

Acknowledgements

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