Optimized Design of Electrochemical Machining Processes by CFD Simulation

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Content

- What is Electrochemical Machining?
- Overview on research project SIREKA
- CFD simulation of ECM
- Summary and outlook
What is Electrochemical Machining (ECM)?

Removal of metal by electrochemical process:
- Electric potential between work piece (anode) and cutting tool (cathode) with electrolyte between
- During metal removal, cutting tool is advanced into workpiece with small gap between (50 to 500 µm)
- "reverse electroplating"

Advantages:
- No direct contact, no stress, no tool wear
- Hard materials can be machined

Disadvantages:
- High energy consumption, slow process
- Only electrically conductive materials
What is Electrochemical Machining (ECM)?

- Complex physics
  - electric potential and electric current
  - metal dissolution and heat generation
  - material and heat transport due to electrolyte flow
  - geometry deformation
- Even more complex processes:
  - different processes for rough and fine machining
  - Pulsed Electrochemical Machining (PECM): pulsed current and/or oscillating working gap
- Main challenge:
  - How should the tool look like to get desired removal shape in the workpiece?
Research project SIREKA

Project partners

Associated partners:

- BOSCH Diesel Systems
- P&G Braun

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Research project SIREKA
Overview

- **Name:** SIREKA
  Simulationsunterstützte ressourceneffiziente Auslegung und Realisierung des Elektrochemischen Abtragens
- **Duration:**
  1.4.2015-31.3.2017
- **Research program:**
  KMU-innovativ
- **Executing organization:**
  Projektträger Karlsruhe Produktion und Fertigungstechnologien
- **Funded by:**
  German Federal Ministry of Education and Research

**Diagram:**
- Production order
  - Conception
    - EC-removal + machine
  - Construction
    - device + cathode
  - Manufacturing
    - device + cathode
  - Experimental
    - realization
  - Evaluation
  - Removal
    - geometry

**Approaches:**
- **Empirical approach**
  - Process adjustment
  - Removal characterization
  - Simulation
  - Rapid prototyping

**Numerical approach**
Research project SIREKA

Aims

- **Optimized design process for electrochemical machining (ECM):**
  - Empirical approach of construction, manufacturing, experiment and adjustment too inefficient
  - Improvement of design process through **3D simulations** of ECM
  - Simulations based on experimentally determined dissolving **material characteristics**
  - Optimization of process parameters and device shape
  - Speed-up of manufacturing through **rapid prototyping** of cathodes with Fused Deposition Modeling (FDM) or PolyJet technology, coated with metallic layer
Content

• What is Electrochemical Machining?

• Overview on research project SIREKA

• CFD simulation of ECM
  – Setup and boundary conditions
  – Verification cases
  – Validation cases

• Summary and outlook
Typical geometry for an ECM process:

- **workpiece**
  - of steel, often initially flat

- **flushing chamber**
  - for electrolyte

- **cathode**
  - of steel, copper, galvanized plastic with complex geometry
  - verification shapes on cylinder:
    - half sphere
    - cone
    - cuboid
    - part of retarder geometry
Boundary conditions for an ECM process:

- **Anode at voltage**
  - e.g. 7 V (already reduced by polarization voltage)
- **Cathode grounded**
  - 0 V
Boundary conditions for an ECM process:

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- Specified feed rate
  - e.g. 0.35 mm/min

- Process time or sinking depth
  - e.g. 10 min → 3.5 mm

\[ \text{0.35 mm/min} = 5.83 \, \text{µm/s} \]
Boundary conditions for an ECM process:

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- **Specified feed rate**
  - e.g. 0.35 mm/min
- **Process time or sinking depth**
  - e.g. 10 min ➔ 3.5 mm
- **Dissolution rate of metal at anode**
  - experimentally determined: local removal velocity $v_a$ as function of local current density $J$

<table>
<thead>
<tr>
<th>Bereich</th>
<th>$J$ in [A/cm²]</th>
<th>$\Delta v_a/\Delta J$ in [mm/min / A/cm²]</th>
<th>$v_0$ in [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>8 – 74</td>
<td>0,0106</td>
<td>-0,063</td>
</tr>
<tr>
<td>II</td>
<td>45 – 107</td>
<td>0,0116</td>
<td>-0,032</td>
</tr>
</tbody>
</table>
Setup for an ECM simulation:

- Simulation with ANSYS CFX
  - transient with time step size of e.g. 1 s
  - initialized with steady-state solution
  - duration of 10 min = 600 s
- Geometry deformation:
  - prescribed feed rate in fixed direction
  - metal dissolution $v_a(J)\Delta t$ in normal direction at anode-fluid interface
  - net motion via User Fortran at boundaries
- Equations solved for:
  - boundary scale / wall distance
  - mesh deformation (for inner vertices)
  - electric potential
  - NO fluid flow, NO turbulence, NO heat transfer
- Problem: Deformed mesh becomes invalid!
CFD simulation of ECM
Setup and boundary conditions

Program
- Perl-Script
  - ANSYS CFX-Solver*
  - ANSYS CFD-Post
  - ANSYS ICEM CFD
  - ANSYS CFX-Pre
  - ANSYS CFX-Solver*

Data transfer
- Result file
  - STL file
  - Mesh file
  - Definition file

User files
- Definition file
  - Session file
  - Geometry file
    - Replay script
  - CFX file
    - Session file

Iterations until full run-time duration is reached

* Stop if mesh quality is bad

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CFD simulation of ECM
Verification case: Half sphere
CFD simulation of ECM
Verification case: Half sphere

Stromdichte in A/cm²

Time = 0 [s]

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CFD simulation of ECM
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CFD simulation of ECM
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Stromdichte in A / cm²

Time = 300 [ s ]

Stromdichte in A / cm²

Time = 600 [ s ]

cia. 118 µm distance

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CFD simulation of ECM
Verification case: Truncated cone
CFD simulation of ECM
Verification case: Cuboid
CFD simulation of ECM
Verification case: Part of Retarder geometry
CFD simulation of ECM
Verification case: Final shapes

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Micro-Calotte validation case:

- Cathode with 97 identical cavities
- 6 different process parameter sets
  - voltage and feed rate values
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- Cathode with 97 identical cavities
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  - voltage and feed rate values
- Simulation of one cavity:
  - cylindrical part of anode, electrolyte and cathode with 1 mm diameter
  - initial distance of electrodes: 50 µm
  - cavity depth: 94 µm
CFD simulation of ECM
Validation case: Micro-Calotte

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- Simulation of one cavity:
  - cylindrical part of anode, electrolyte and cathode with 1 mm diameter
  - initial distance of electrodes: 50 µm
  - cavity depth: 94 µm
  - meshed with tetras/prisms
  - good resolution of 50 µm gap
CFD simulation of ECM
Validation case: Micro-Calotte

30 A/cm², 0,048 mm/min

t = 314 s

delta Z in µm
53.63
47.05
40.48
33.91
27.33
CFD simulation of ECM
Validation case: Micro-Calotte

Initial position

Final bump position

Cathode shape

VV1: 100 A/cm², 0.222 mm/min
VV2: 90 A/cm², 0.199 mm/min
VV3: 70 A/cm², 0.153 mm/min
VV4: 50 A/cm², 0.107 mm/min
VV5: 30 A/cm², 0.048 mm/min
VV6: 10 A/cm², 0.008 mm/min

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Final bump shape in simulation compared to experiment:

- good quantitative agreement
- trend not captured correctly
- asymmetry in experiment due to fluid flow
Macro-sphere validation case:

- **Cathode as half-sphere**
  - with radius 20 mm
  - and boring of radius 3 mm

- **Anode:**
  - initially flat with boring of radius 5 mm

- **ECM process:**
  - approx. 300 µm gap size
  - 6 mm sinking depth
  - two steps for rough and fine machining
Macro-sphere validation case:

- Cathode as half-sphere
  - with radius 20 mm
  - and boring of radius 3 mm
- Anode:
  - initially flat with boring of radius 5 mm
- ECM process:
  - approx. 300 µm gap size
  - 6 mm sinking depth
  - two steps for rough and fine machining
- ECM simulation:
  - Simplified cathode shape
Geometry for an ECM process:

- workpiece
  - of steel
- flushing chamber
  - for electrolyte with through-flushing and outlets at sides
- cathode
  - complex geometry with sharp edges and copper coating
Geometry for an ECM process:

- **workpiece**
  - of steel

- **flushing chamber**
  - for electrolyte with through-flushing and outlets at sides

- **cathode**
  - complex geometry with sharp edges and copper coating
  - consists of three parts:
    - adapter plate (stainless steel)
    - base body from Fused Deposition Modeling (plastic) with copper coating
    - insulation body from FDM (plastic)
• Research project SIREKA to optimise the ECM design process:
  – Experimentally determined dissolving material characteristics
  – Numerical 3D simulation of ECM process with validation cases
  – Rapid prototyping with Fused Deposition Modeling and selective copper coating

• Simulations of ECM process with ANSYS CFX:
  – Solution for electric potential and mesh deformation only
  – Script-based solution workflow with remeshing
  – Applied on verification and validation cases

• Next steps:
  – Validation on micro and macro geometry and retarder
  – Optimisation of process parameters and/or cathode shapes
  – Export of optimised cathode shape towards rapid prototyping → validation

➢ Extension to fully coupled system for ECM processes including electrolyte flow and material and heat transport