Characterisation of the Influence of Material Hardness in Precise Electrochemical Machining of Steel

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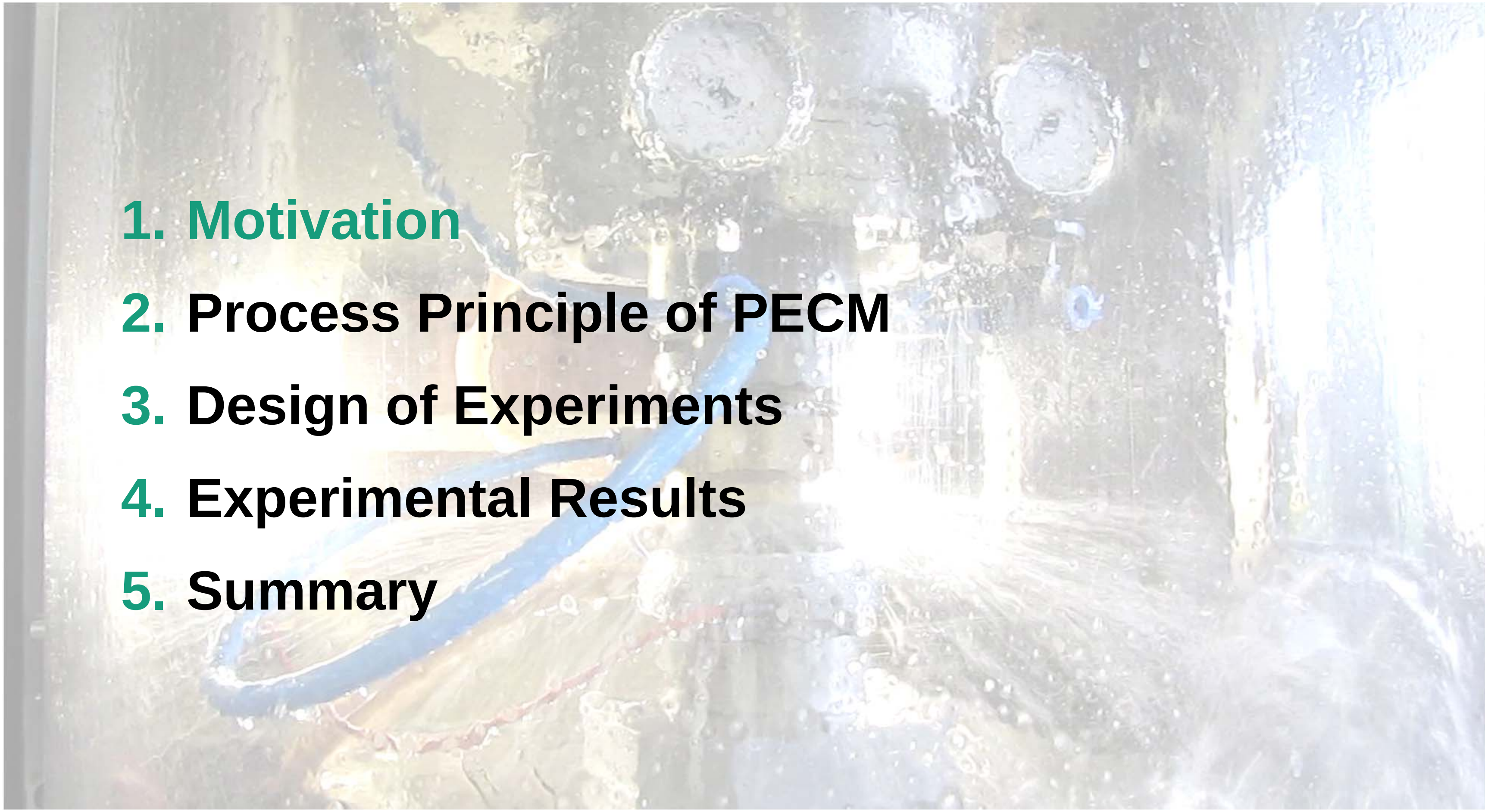


Motivation

Initial situation:

- Requirements on products: sufficient stability, high wear resistance, light weight, …
- Requirements can be achieved by changing the properties of the work-piece material
- Creating new strength materials by:
  - Changing the material composition
  - Changing the production process
  - Using treatment to change the material properties

Complex geometry [TECT Power]

New Materials [Liquidmetal Technologies]

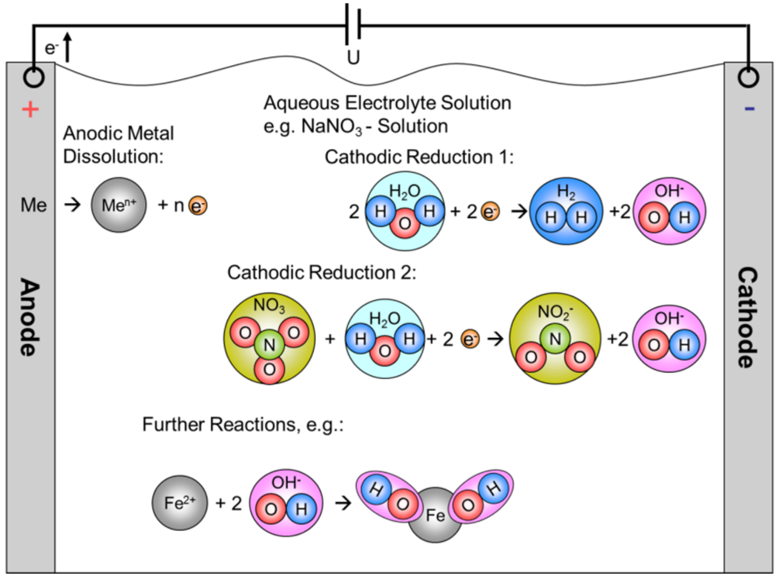
Question:

- How can a high-strength material be machined?

Motivation

Electrochemical Machining - ECM

- Anodic metal dissolution
- No insertion of mechanical stress (tension) into the work-piece
- No thermal influence on the work-piece
- No influence of material's hardness and toughness
- No burrs
- No process-related tool wear
- High surface quality



Scheme of anodic dissolution [nach Klocke]

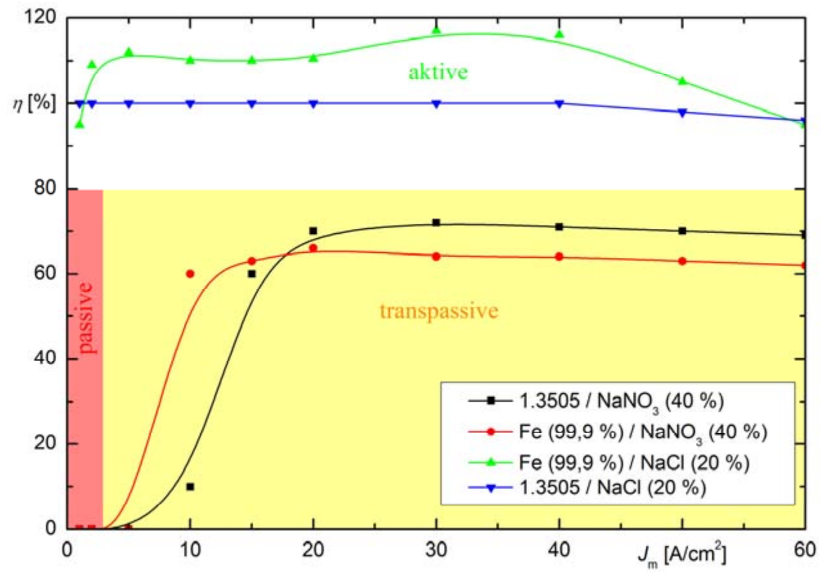
$$\text{Faraday's law :} \quad m = \frac{M}{z_A \cdot F} \cdot Q$$

Motivation

- Knowledge about the material dissolution is necessary:
- Every material has its own characteristic
- Depends on the electrolyte

Does the material's hardness influence the anodic dissolution?

- Study on the influence of the material's hardness in Precise Electrochemical Machining of steel 1.4112
- Carried out with non-tempered, case hardened and hardened work-pieces
- Recording the current efficiency as a function of current density



Current efficiency as function of the current density of the electrochemical dissolution of pure iron and a 1.3505 steel in NaCl and $NaNO_3$ electrolyte [Haisch]

$$\eta = \frac{V_{eff}}{V_{sp}} = \frac{m_{eff}}{m_{sp}} \qquad m_{eff} = \frac{m_a}{Q}$$

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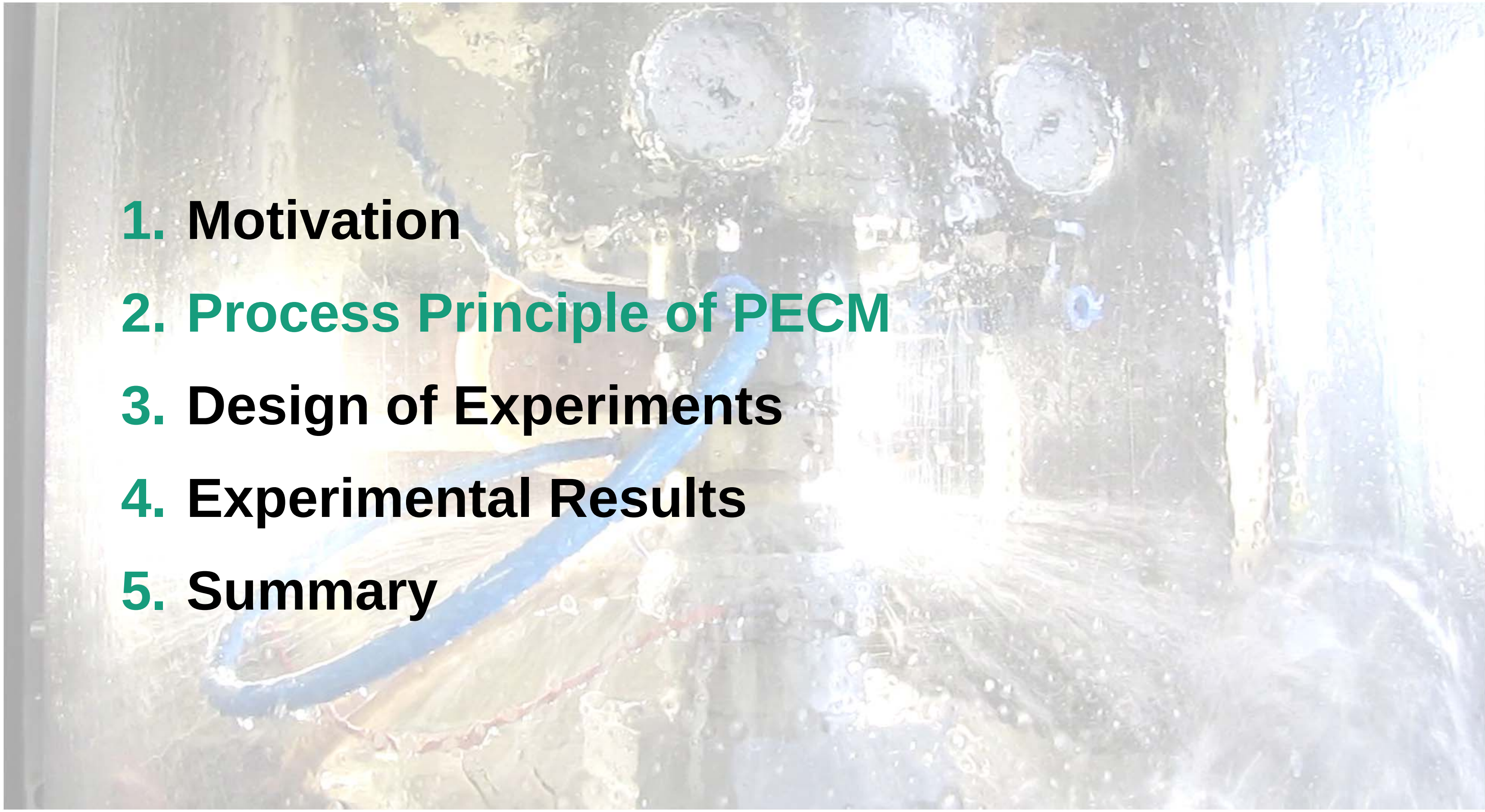


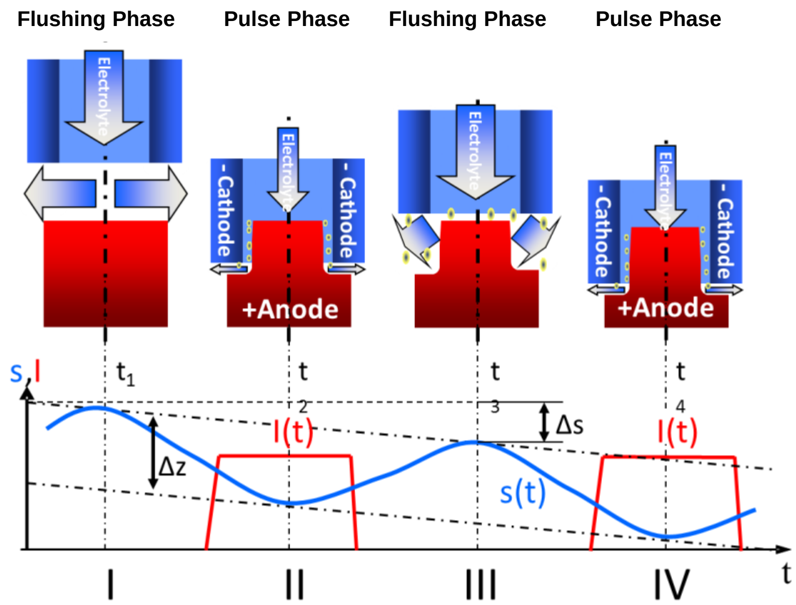
1. Motivation
2. **Process Principle of PECM**
3. Design of Experiments
4. Experimental Results
5. Summary

Process Principle of PECM

Principle:

anodic metal dissolution with **pulsed current and oscillating working gap**

- Localization of the removal area
- Roughing/Finishing/Polishing in a single operation cycle
- Accurate reproduction (± 2 µm)
- Surface quality up to Ra ~ 0.05 µm
- Forming tools, Cutting and punching tools, Microsystems applications



Principle of Pulsed Electrochemical Machining

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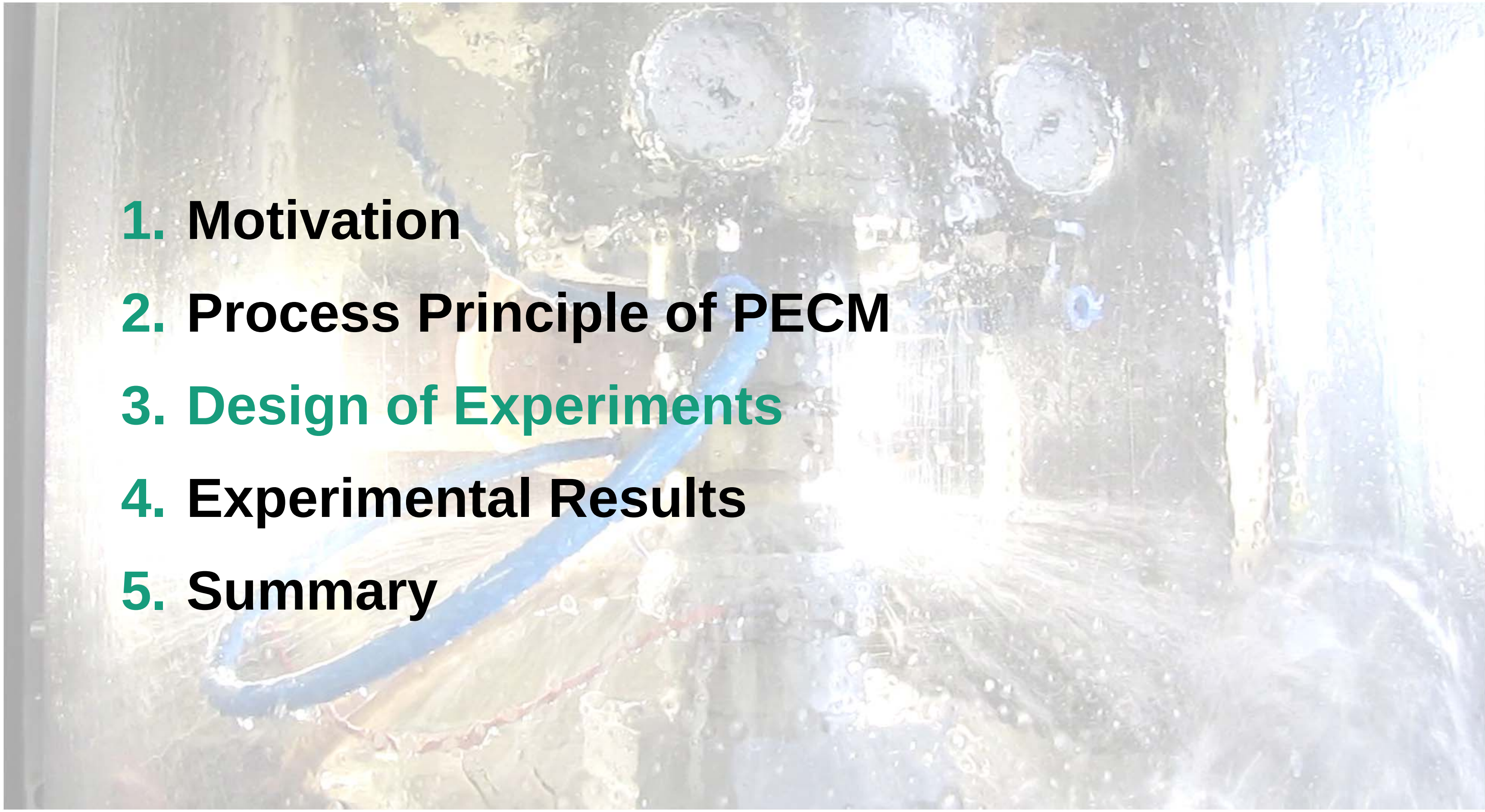

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2. Process Principle of PECM
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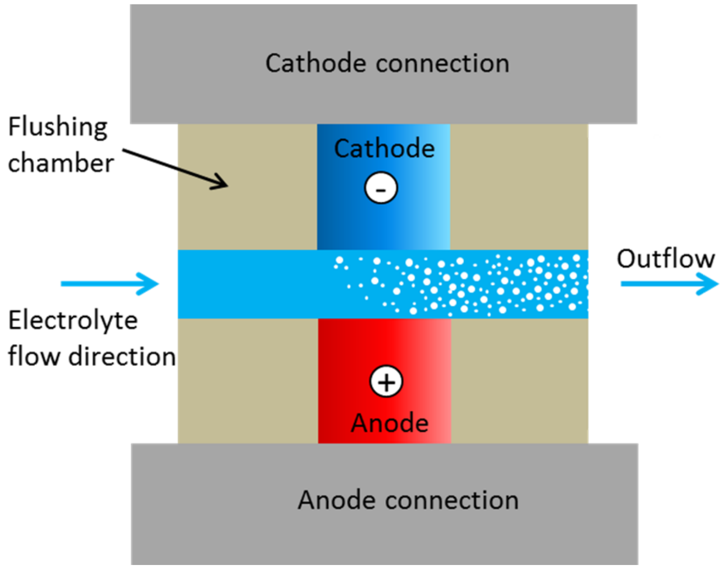
Device System

- Device system for the electrochemical dissolution of metallic materials
- Removal area is supplied with fresh electrolyte using lateral flushing
- Design for implementation into an industrial machine tool like PEMCenter 8000

Requirements on the removal process:

- Frontal removal of the work-piece
- Realisation of a steady state working gap
- Constant electrolyte conditions

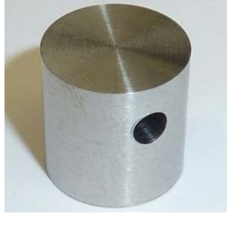


Schematic illustration of the removal device

Device System

Photograph of the experimental setup

- Work-piece size:
  - Ø 12 mm
  - Height 12 mm
- Work-piece average weight (1.4112):
  - ≈ 9.8 g



Work-piece

Process parameters

- Range of the current density:
  5 to 110 A/cm²
- Varied input process parameters:
  - Voltage U
  - Feed rate v_f
  - Working gap a
- Materials:
  - Stainless steel 1.4112
    - non-tempered (320 HV)
    - Case-hardened (620 HV)
    - Hardened (650 HV)
- Process output characteristics:
  - Removal mass m_a

PEM-Center 8000, PEMTec

Experimental parameters

Symbol	*Parameter*	*Value*
	Electrolyte	*Sodium nitrate*
σ	*Electric conductivity*	*66 mS/cm ± 1 mS/cm*
	Workpiece material	*1.4112*
d	*Workpiece diameter*	*12 mm*
A_E	*Electrode surface area*	*1.131 cm²*
f	*Oscillation frequency*	*50 Hz*
t_p	*Pulse duration*	*4 ms*
p_i	*Inlet pressure*	*3 bar*
z_{max}	*Max. travel distance*	*300 µm*
U	*Process voltage*	*5 V – 15 V*
v_f	*Feed rate*	*0.008 mm/min – 0.230 mm/min*
a	*Working gap*	*10 µm – 100 µm*

Measurement Method

- Removal mass m_a
  - Micro balance
    ME614S, Sartorius
  - Before and after machining
  - Measuring error ±28 µg

Micro balance ME614S, Sartorius

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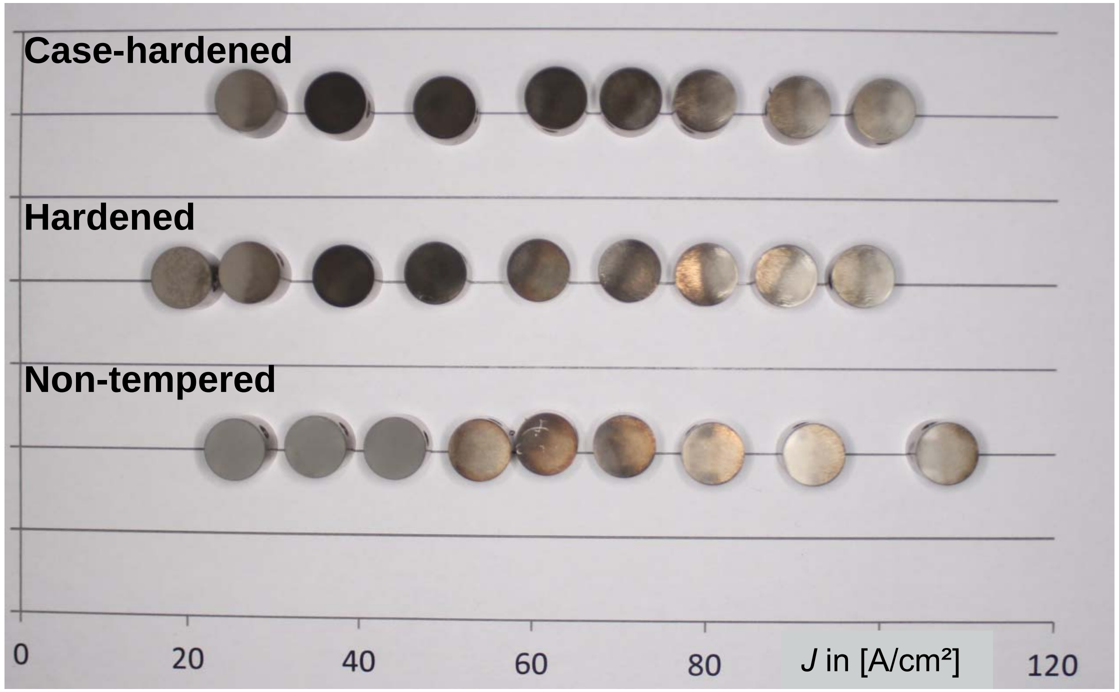
Machining Results



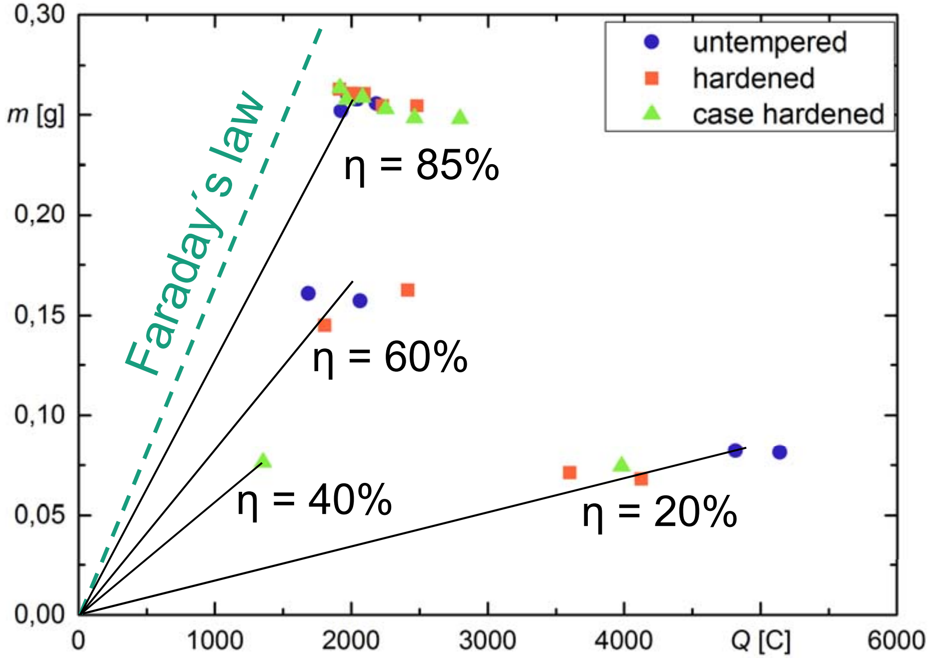
Three different states of heat treatment as a function of the current density of 1.4112

- Feasibility of electrochemical machining of 1.4112 at different states of heat treatment could be demonstrated
- Color and brightness of the surface depends on the current density
- Coloring of hardened and case-hardened 1.4112 is almost equal

Quantification

- Faraday´s law is not achieved
- Equal removal masses at different amounts of electric charge are possible
- The different inclinations of the graphs indicate a variation of current efficiency
  - Smallest current efficiency: 20%
  - Largest current efficiency: 85%

- Not all electric charge is changed into removal mass
- That behavior is similar for the three different states of heat treatment



Removal mass as a function of electric charge transport at different states of heat treatment of 1.4112 under PECM condition

Removal characterization

- Non-tempered 1.4112 shows the following removal characteristics:
  - From 22 A/cm² to 50 A/cm² the current efficiency amounts to 12%
  - From 50 A/cm² to 52 A/cm² the current efficiency increases to 65%
  - From 52 A/cm² to 100 A/cm² the current efficiency increases to 85%
- The removal rate v_a has the same behavior as the current efficiency
- The removal characteristic depends on the current density

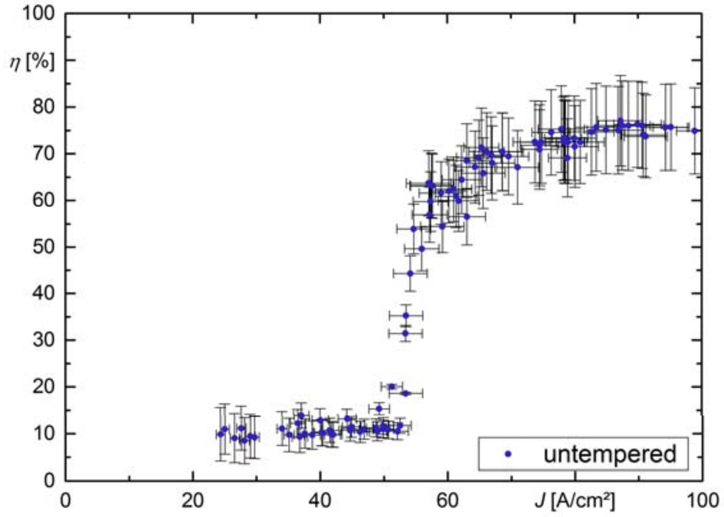


Fig.: Current efficiency as a function of current density *J* at different working gaps a of non-tempered *1.4112*

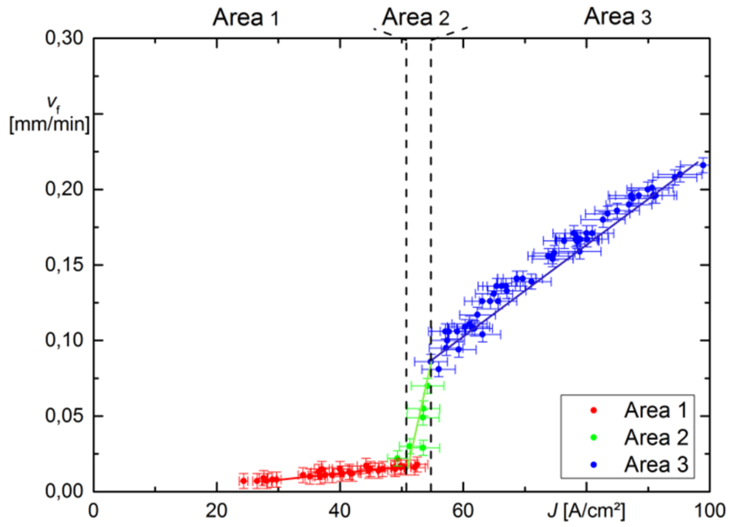


Fig.: Removal rate v_a as a function of current density *J* at different working gaps a of non-tempered *1.4112*

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Removal characterization

- Hardened 1.4112 shows the following removal characteristics:
  - From 20 A/cm² to 38 A/cm² the current efficiency increases to 20%
  - From 38 A/cm² to 40 A/cm² the current efficiency increases to 55%
  - From 40 A/cm² to 100 A/cm² the current efficiency increases to 80%
- The removal rate v_a has the same behavior as the current efficiency
- The removal characteristic depends on the current density

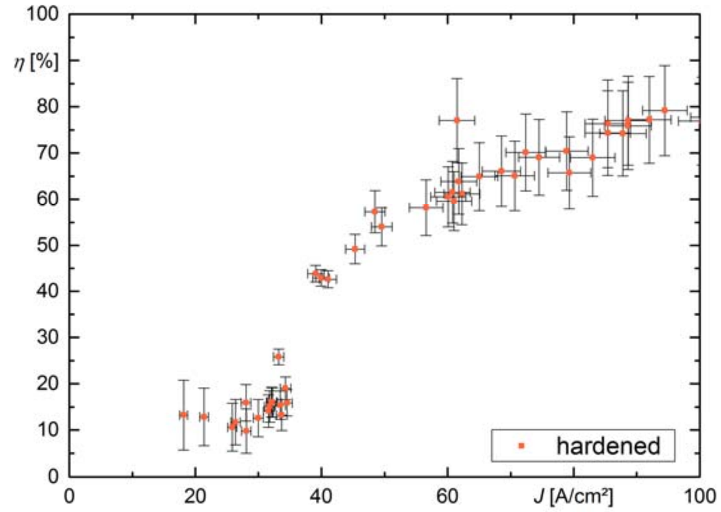

Fig.: Current efficiency as a function of current density *J* at different working gaps a of hardened *1.4112*

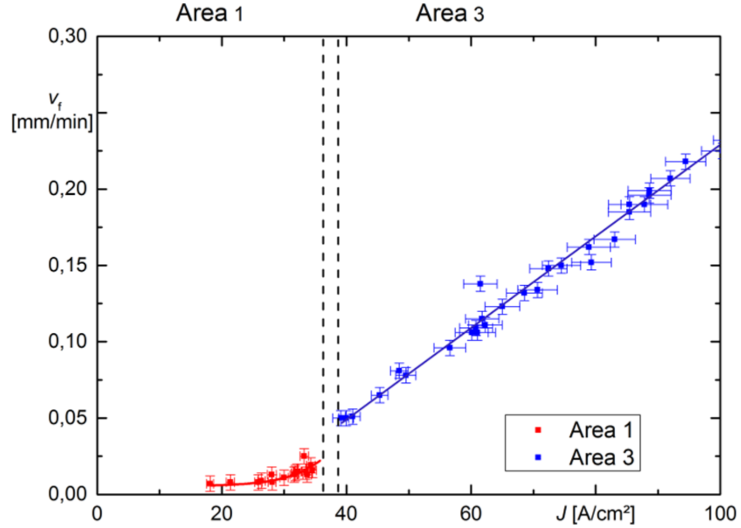

Fig.: Removal rate v_a as a function of current density *J* at different working gaps a of hardened *1.4112*

Removal characterization

- Case hardened 1.4112 shows the following removal characteristics:
  - From 26 A/cm² to 32 A/cm² the current efficiency increases to 15%
  - From 32 A/cm² to 35 A/cm² the current efficiency increases to 35%
  - From 35 A/cm² to 100 A/cm² the current efficiency increases to 80%

- The removal rate v_a has the same behavior as the current efficiency
- The removal characteristic depends on the current density

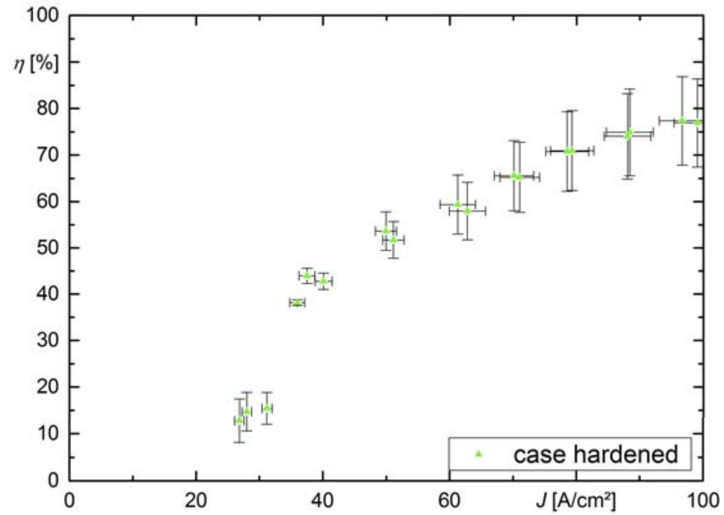

Fig.: Current efficiency as a function of current density *J* at different working gaps a of case hardend *1.4112*

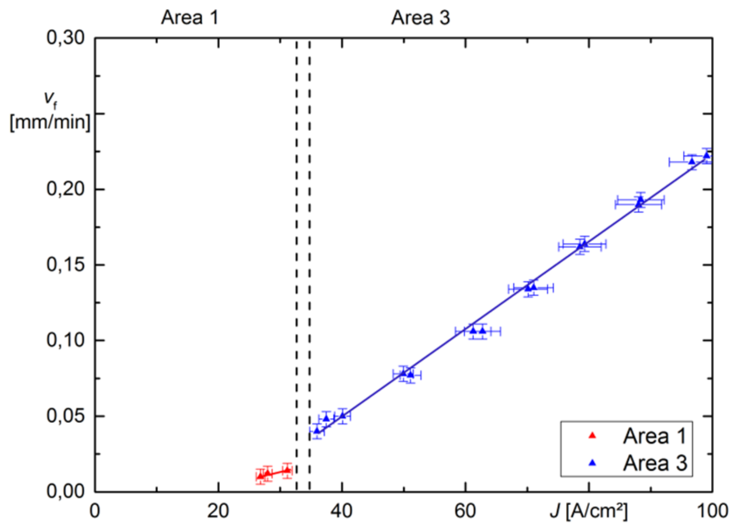

Fig.: Removal rate v_a as a function of current density *J* at different working gaps a of case hardend *1.4112*

Removal characterization

- Hardened and case hardened 1.4112 have an almost equal removal characteristic
- Different removal characteristic for non-tempered 1.4112 up to a current density of 52 A/cm²
- Equal removal characteristic for non-tempered 1.4112 at a current density exceeding 52 A/cm²

- At low current densities the removal of 1.4112 depends on the heat treatment
  - The heat treatment improves the removal rate
- At higher current densities exceeding 52 A/cm² the removal process is independent from the hardness

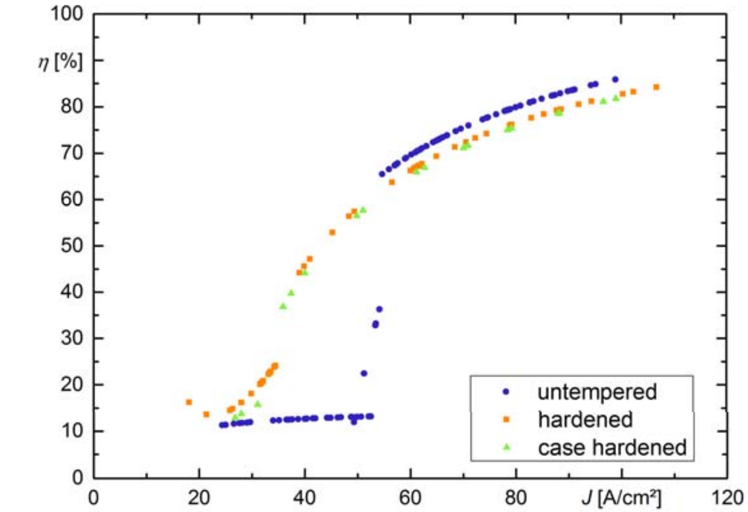

Fig.: Current efficiency as a function of current density *J* of differently heat-treated 1.4112 under PECM condition

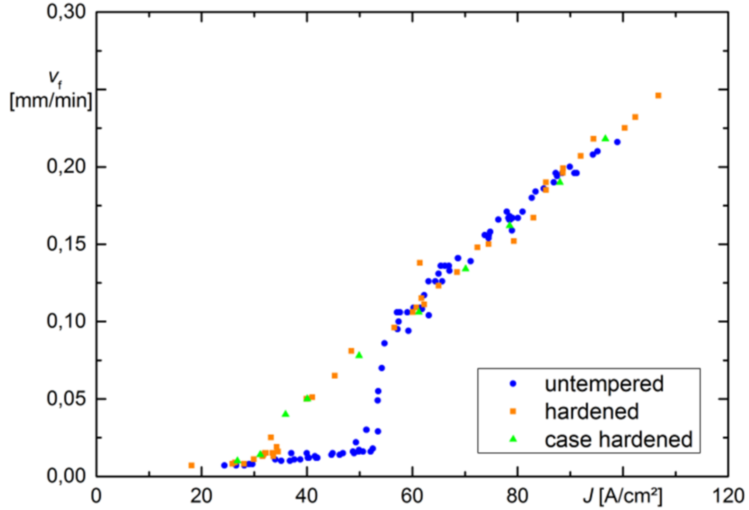

Fig.: Removal rate v_a as a function of current density *J* of differently heat-treated 1.4112 under PECM conditions

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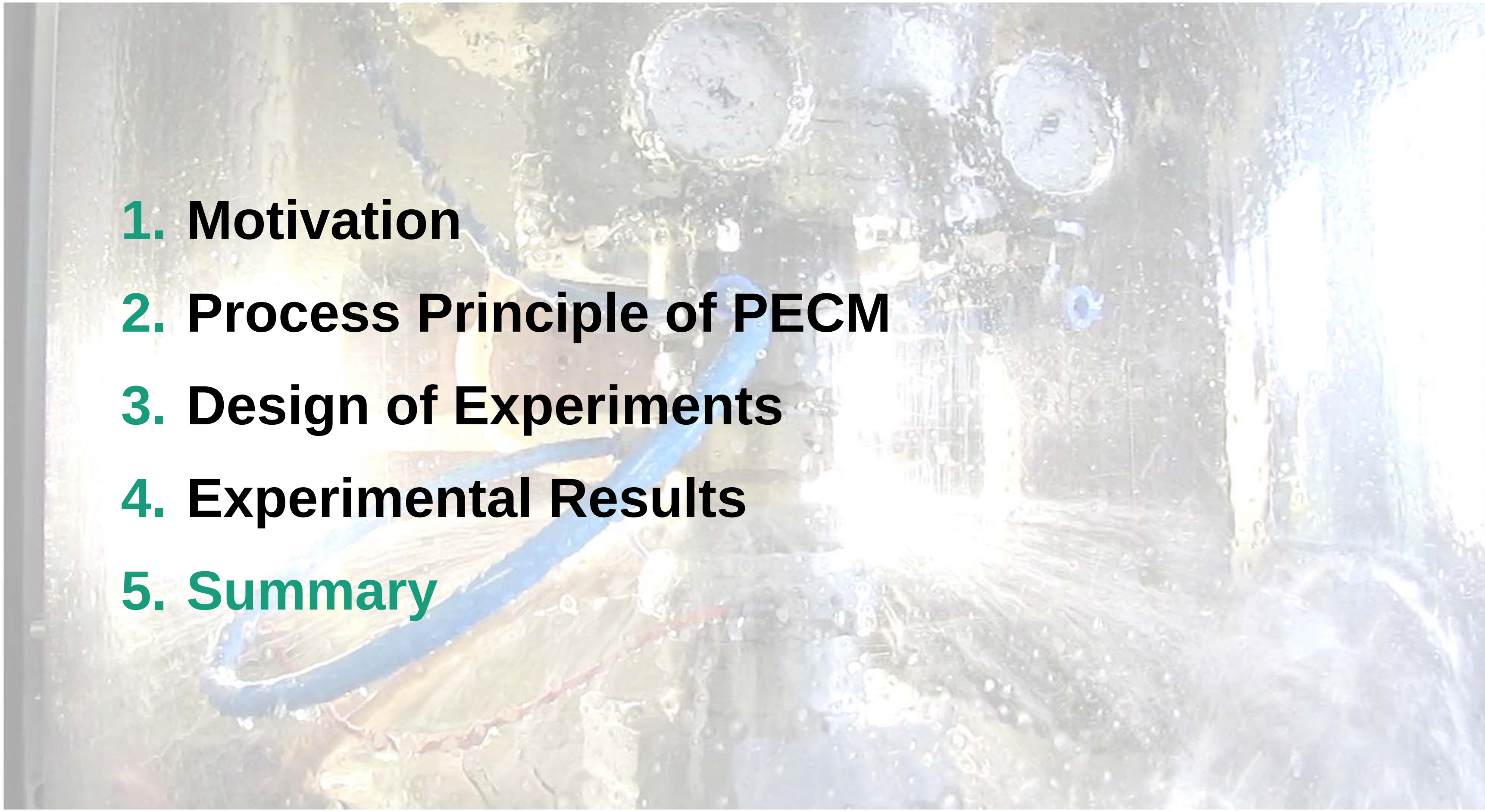
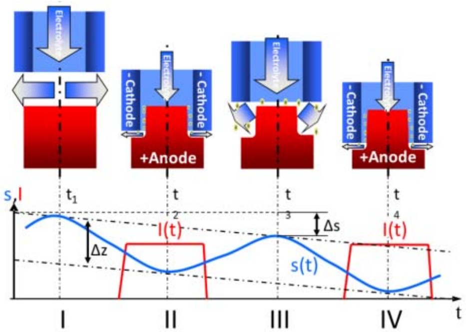
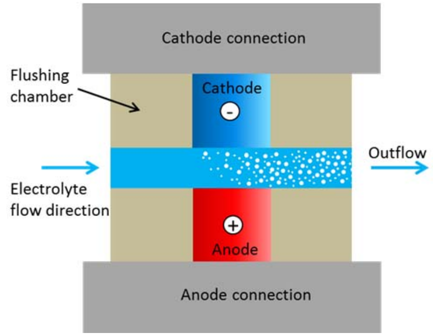


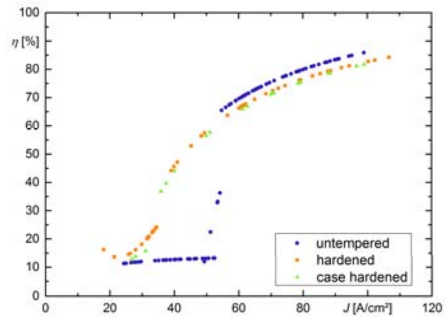
Summary

- Anodic dissolution of stainless steel 1.4112 at three different states of heat treatment under PECM conditions was presented
- The removal of the differently heat-treated materials is characterized by different as well as equal sections
- At current densities below 52 A/cm² the current efficiency depends on the heat treatment
- In this case the heat treatment improves the removal rate

- ECM process can depend on the heat treatment of the metal material
- ECM can be used to machine hardened metal materials







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