Development of Electrochemical Machining (ECM) for Tungsten

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Contents:

- Motivation for electrochemical machining (ECM)
- Electrochemistry of tungsten
- ECM of tungsten
  - S-ECM
  - C-ECM
- Conclusions and recommendations
Motivation for Electrochemical Processing (ECM) of Tungsten
Typical defects and failures in W parts by conventional machining

Primary machining defects
- Smooth surfaces
- No defects from machining
- No sharp edges

Conventional machining is expensive
- Innovative soft machining methods required

Secondary failures, growing under HHF load

Crack growth at machining defect

Post HHF analyses of mock-up EFREMOV. Machining defect caused failure Mock up # 4
Electrochemical Reactins of Tungsten
W dissolution: EC oxidation

<table>
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<th>Basic Investigation</th>
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<td>Anodic reaction</td>
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<td>W-dissolution</td>
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<tr>
<th>pH</th>
<th>i / mAcm</th>
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<td>7</td>
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System: W / TCEE / Pt
v = 1 mV/s, 1000 U/min, d = 16 mm
ECM for 3-D structuring | M-ECM => S-ECM + C-ECM

M-ECM

- Mask processing
- UV lithography
- Electrochemical Etching
- Structured workpiece

M-ECM without resist masks = S-ECM

C-ECM

- Cathode = ECM working tool
- Agitation by microstep-motor

MAIN DIFFERING FEATURES

<table>
<thead>
<tr>
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<th>M-ECM, S-ECM</th>
<th>C-ECM</th>
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<tr>
<td>Technique</td>
<td>Conventional installation</td>
<td>Complex facility</td>
</tr>
<tr>
<td>Parameters</td>
<td>Current x time = charge</td>
<td>Charge + distance + step rate + convection</td>
</tr>
<tr>
<td>Cathode</td>
<td>passive counter electrode</td>
<td>active shaping component (by step motor)</td>
</tr>
<tr>
<td>Tool design</td>
<td>2-dim. mask (positive)</td>
<td>3-dim. electrode (negative)</td>
</tr>
<tr>
<td>Transformation</td>
<td>+2-dim → +3-dim resp. +0-dim</td>
<td>-3-dim → +3-dim</td>
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ECM Requirements
- Electrolyte development
- M-ECM: anode mask process
- C-ECM: cathode tool

ECM Advantages
- No cracks by ECM process
- Surface polishing
- Residue-free metal removal

M-ECM for Slot array:
- Cathode = ECM working tool, negative image vertically mobile
- Tool design: 2-dim. mask (positive)
ECM of W towards W/refractory-alloys

Dissolution ability of W-alloys by ECM electrolyte

\[ i = f(pH) \]

System: \( \text{Me} / 1,25 \text{ M N-NH}_3 / \text{Pt} \)
\( \text{Me} = \text{W}, \text{Wla10}, \text{Mo}, \text{Ta}, \text{Al} \)

Mo improves machinability / dissolution rate
Stable oxide forming elements (Ta) are less favorable for the electrolyte N-NH3
Electrochemistry of tungsten
Investigation and development of ECM electrolytes

Electrochemical investigations: Potentiostatic Linear Scanning Voltammetry

W + 2 H₂O + 2 OH⁻ → WO₄²⁻ + 6 H⁺ + 6 e⁻

pH = 11
pH = 10
pH = 9
pH = 8
pH = 7
pH = 6
pH = 5
pH = 4
pH = 3
pH = 1

W + 3 H₂O → WO₃ + 6 H⁺ + 6 e⁻

W → W³⁺ + 3 e⁻

Does not take place !!!
Electrochemical Tungsten Processing S-ECM

S-ECM of surfaces
...on EDM-cut rod pieces

W as machined

![Image of W as machined](image)

S-ECM 15 min, 400 mA/cm^2

![Image of S-ECM processed W](image)
Electro-chemical tungsten processing S-ECM

S-ECM of surfaces
Single crystal pieces

Mechanical mirror polishing

Wittmann'sche Etching structures

Wittmann'sche Etching structures rough, without any reflection
Plain, partial reflection
Plain, black = total reflection

S-ECM, rising current densities
elaboration on z-orientation
Effect on sc-orientation: parameters of S-ECM mirror polishing
on one orientation cannot be applied unchanged to other orientation
C-ECM of tungsten
Impact of pulse current effects

HF-Pulses in ECM of tungsten
Dependencies of measures from frequency
Extrapolation to HF = 0

Development of techniques to generate high HF currents
C-ECM of tungsten
Fabrication of 3-dim demonstrators

TOOLS

Demonstrators: Generated W-structures

Tool

Parallel grooved structure

Angled structures

Cathode tool
Cathodic potential: no corrosion + mechanically contactless - no pressure
Working tool (every material, every design, every current) without any chemical, electrochemical, thermal, mechanical abrasion
Anodic dissolution by ECM

Parameter dependencies
Smaller distance tool – work piece

Quality improvement
W → WL 10, WTaMoX

Higher frequency of pulsed DC power

Mobility control / reduction
Conductivity of electrolyte
Development of C-ECM tool for shaping of micro-structured workpieces: e.g. Castellation:
6-fold star,
Projected depth 6 mm, width 0.1 mm;
aspect ratio = 60

Design of cathode tool and facility for castellation-shaping

Castellation cathode tool: first prototype (brass foils)
C-ECM
European Patent EP 467

Mitteilung gemäß Regel 71 (3) EPÜ
Hiermit wird Ihnen mitgeteilt, dass die Prüfungsabteilung beabsichtigt, ein europäisches Patent auf der Grundlage der oben genannten europäischen Patentanmeldung in der nachstehend angegebenen Fassung zu erteilen:

In der Fassung für die Vertragsstaaten:
AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HU IE IS IT LI LT LU LV MC NL PL PT RO SE SI SK TR
Conclusions

Electro-Chemical Machining (ECM) of tungsten:

- W can be successfully machined by ECM without chemical passivation
- Three ECM branches selected for special applications (S-ECM, C-ECM M-ECM)
- ECM shows strong dependency on DC pulse frequency and gap distance
- High frequency technology in DC pulses is required for good accuracy
- S-ECM can polish and optimize fine structured surfaces
- Demonstrators fabricated by S-ECM and C-EC

General statement:

- ECM is a well investigated technology for tungsten
- Achievements (work progress) in agreement with work plan
- ECM has an established status for industrial W-shaping
- Achieved technical status allows it to industrial scale, AND/OR....
- Achieved patent EP 467 allows commercial exploitation
Open questions

Actual and future work:

- Accuracy improvement by high frequency (> 10 kHz range)
- Analyses of conductivity impact on long range dissolution suppression
- Application of not symmetrically pulse pause ratios of DC profiles
- Investigations of new non-aqueous electrolyte systems (e.g. EMIM, IL)
- Analyses of ECM application to W-Ta by improved electrolytes

Response / needs from discussions with industry

- Testing of newest electro-mechanical tools and forced flow
- Electrolyte regeneration
- Integration of industries into ECM of W under patent application