PLASMA ELECTROLYTIC OXIDATION (PEO) AT HIGH FREQUENCIES: CHARACTERIZATION AND CONTROL

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Plasma Electrolytic Oxidation

Plasma (enhanced) Anodization

$\text{Al} \rightarrow \text{Al}_2\text{O}_3$

Source: keronite.com
Electrochemical process

\[
2\text{Al}^{3+} + 3\text{O}^2- \rightarrow \text{Al}_2\text{O}_3
\]

\[
2\text{Al}^{3+} + 3\text{OH}^- \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}^+
\]
Time dependent process

![Graph showing RMS Voltage and RMS Current over time.](image-url)
Time dependent process

![Graph showing time-dependent process](image-url)
Time dependent process

![Graph showing time-dependent process with voltage and current data.](image-url)
Time dependent process
Time dependent process

![Graph showing time-dependent process](image_url)
Porous surface

- Aluminum oxide melts and resolidifies on the surface
- Crater-like structures at the center of microdischarge ignition
- Highly porous surface is established during coating

Problem:

Microdischarge energy increases with time and locally destroys the oxide coating
Problem

Electrical parameters
- Current amplitude $I$
- Pulse On-time $T_{on}$
- Pulse Off-time $T_{off}$
- Duty-Cycle $\vartheta$
- Pulsing frequency $f$

Microdischarge behaviour
- Number density $n_{MD}$
- Microdischarge size $A_{MD}$
- Photo Intensity $I_{MD}$
- Time constants $\tau_{On}$
- Lifetime $\tau_{MD}$
- Electron density $n_e$

$T = 1/f$
Experimental Setup

- Electrolyte: dest. water + 2 g/l KOH
- Anode material: Al 6061 alloy (20 · 10 · 2 mm)
- Cathode material: stainless steel (d = 4 mm)
- Generator: Magpuls MP2-30, galvanostatic mode, unipolar (rectangular) pulsing
MD Detection

- Image analysis during process
- Fast algorithm to enable \textit{in situ} measurements
- Threshold filter regarding photo-intensity to create binary image
- MD size, number density and photointensity are calculated
- Time for processing of one image: $t_{tot} < 90 \text{ ms}$
Parameter variation

Standard parameters:
\[ t = 15 \text{ min}; f = 5 \text{ kHz}; \vartheta = 50\%; I = 1 \text{ A} \]
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MD size and MD density can be controlled by changing the duty-cycle and the current density!
Lifetime of MDs (current pulses)

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Lifetime of MDs

• Analysis of current pulses by wavelet transform
• Fitting of wavelet function by translation $b$ and dilation $s$:

$$\Psi_{s,b}(t) = \frac{1}{\sqrt{s}} \Psi \left( \frac{t - b}{s} \right)$$

• Wavelet coefficients (like fourier coefficients):

$$W_\Psi(s, b) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} x(t) \cdot \Psi \left( \frac{t - b}{s} \right) dt$$

Source: towardsdatascience.com
Results wavelet transformation

Lifetime of MDs is in the kHz range! Influence of frequency in this region?
Phase resolved MD dynamics

MDs cannot follow the generator frequency if the pulsing time is shorter than the MD lifetime!
In situ MD control scheme

The diagram illustrates the control scheme involving a microdischarge size, reference variable \( w(t) \), control deviation \( e(t) \), controller (PI, LabView), actuator (Power Supply MP2-30), controlled system (Electrolytic Cell), and measuring unit (CCD-Camera). The duty cycle \( T_{on} \) is manipulated as a variable. Feedback variable \( y_m(t) \) is used for the control algorithm. The raw image from the CCD-Camera is processed through a detection algorithm to determine the microdischarge size, which is then compared to the reference variable to generate the control deviation.
Results MD control (camera)

MD size

$A_{\text{mean}} = 5 \cdot 10^{-3} \text{ mm}^2$

MD number

$A_{\text{mean}} = 5 \cdot 10^{-3} \text{ mm}^2$

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Results MD control (pictures)
Results MD control (OES)
Results MD control (OES)
Results MD control (SEM)

Uncontrolled

Controlled
Conclusion

• MD lifetime is in the range between 6 µs and 1600 µs
• Current density and duty-cycle can adjust the MD number density and size
• Pulsing frequency has to be in the range of the microdischarge lifetime to control microdischarges
• Microdischarge properties can be controlled to distinct values with an *in situ* closed-control loop. By this the microdischarge energy can be controlled indirectly
• Outlook: Further material characterization of produced oxide coatings
Thank you for your attention!

Special thanks to people from: