(PRIN 2022, COD. PROTOCOLLO: 2022H3S28T, CUP MASTER: D53D23005410006) FINANZIATO DALL'UNIONE EUROPEA – NEXT GENERATION EU, PNRR - MISSIONE 4 “ISTRUZIONE E RICERCA” - COMPONENTE C2 INVESTIMENTO 1.1 “FONDO PER IL PROGRAMMA NAZIONALE DI RICERCA E PROGETTI DI RILEVANTE INTERESSE NAZIONALE (PRIN)” D.D. N. 104/2022 “BANDO PRIN 2022”. PE11 Engineering of Metals and alloys.

EUROCORR 2025
Stavanger (NO) | 7-11 Settembre 2025

Producing Plasma Electrolytic Oxidation (PEO) corrosion resistant coatings on aluminium 2024 texturized with a riblet-like surface for aeronautical applications

M. Gamba[1], M. Ormellese[1], A. Cristoforetti[2], M. Fedel[2], A. Brenna[1]

[1] Dipartimento di Chimica, Materiali ed Ingegneria Chimica “Giulio Natta”, Politecnico di Milano
[2] Dipartimento di Ingegneria Industrale, Università di Trento

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Stavanger, Norway
EUROCORR 2025
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Producing Plasma Electrolytic Oxidation (PEO) corrosion resistant coatings on aluminium 2024 texturized with a riblet-like surface for aeronautical applications

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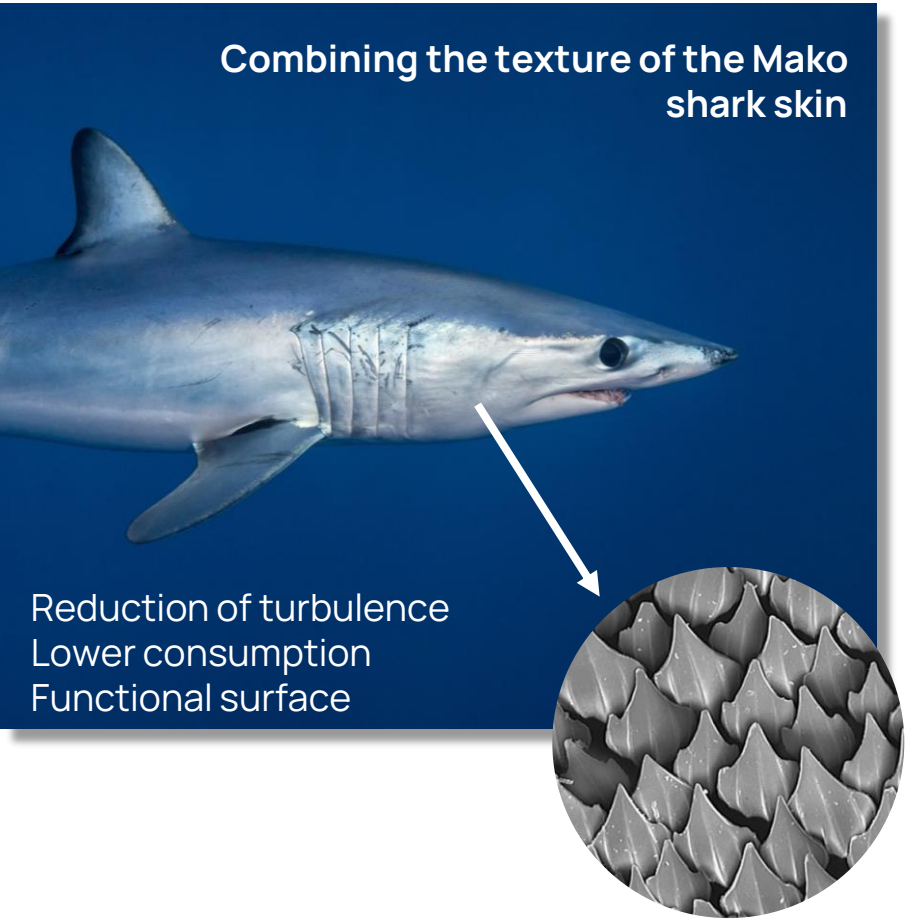
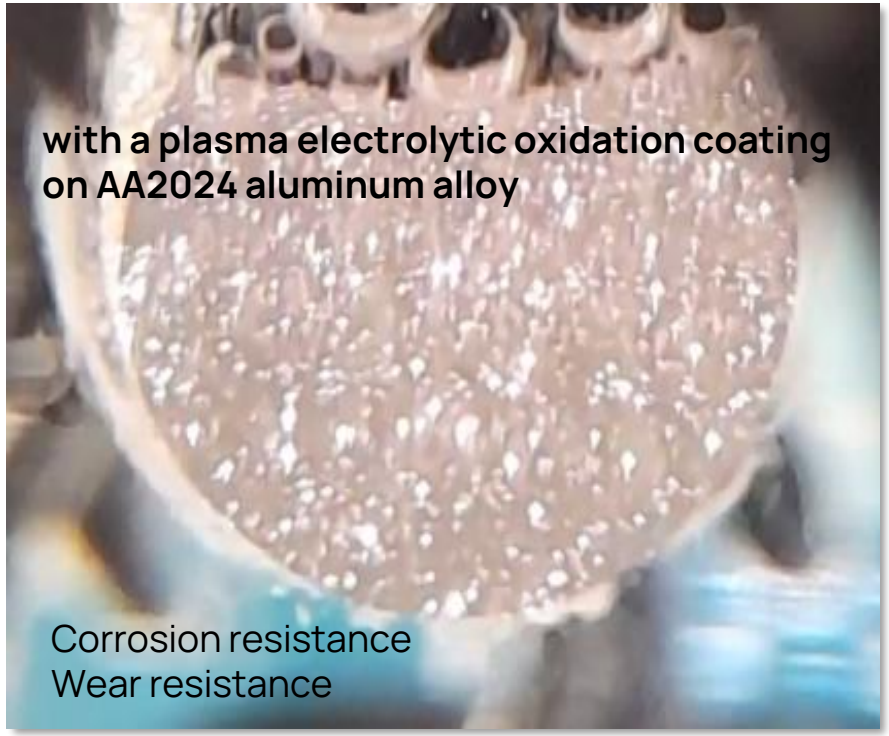
[2] *Dipartimento di Ingegneria Industriale, Università di Trento*

EUROCORR 2025
7 – 11 September 2025 I Stavanger

MAKO: *Biomimetic Corrosion Resistant Aluminium for Aeronautics*

Stavanger, Norway
EUROCORR 2025
7 - 11 September





Project lineup

WP1. Texture optimization

WP2. Texture production

WP3. PEO coating

WP4. Corrosion testing

A. Cristoforetti, PhD
Mastrafjorden B
Wed. 10/09 – 2 pm

The research activity is co-funded by the European Union – Next Generation EU, PNRR - mission 4 “istruzione e ricerca” - D.D. N. 104/2022 “BANDO PRIN 2022”.

Finanziato dall'Unione europea NextGenerationEU

Ministero dell’Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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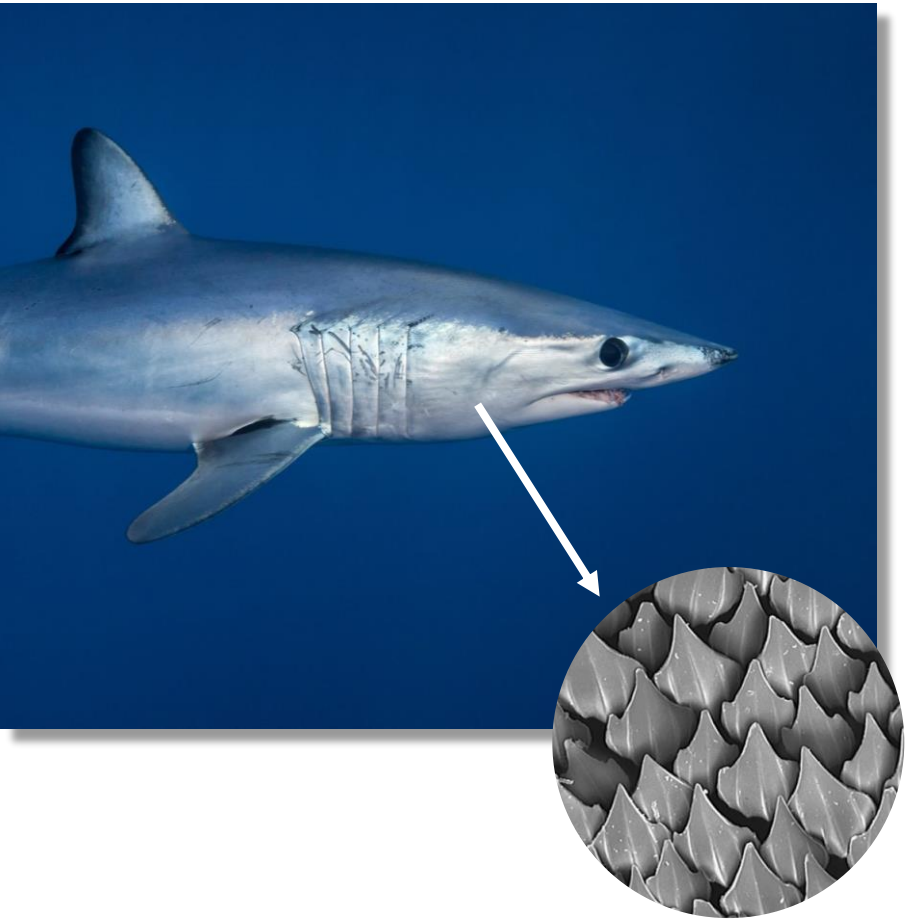
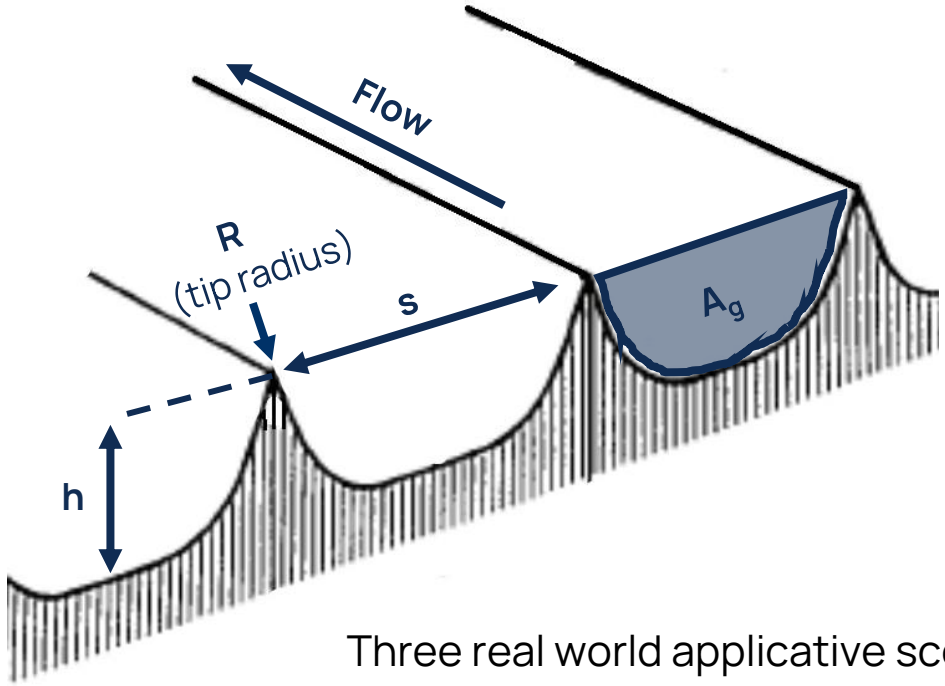
Definition of the biomimetic texture





Three real world applicative scenarios:

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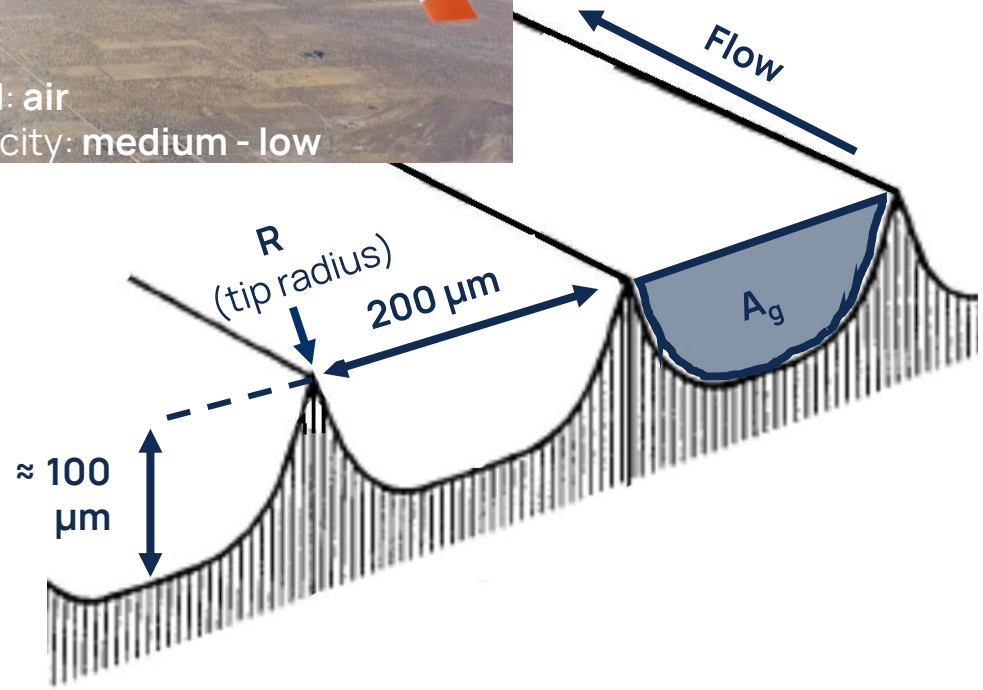
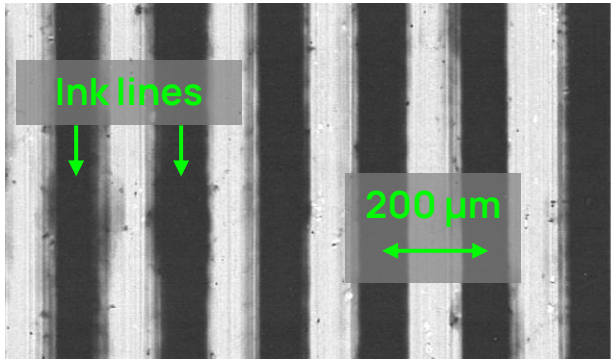
WP1 activities have been developed in in collaboration with prof. Maurizio Quadrio, Department of Aerospace, Politecnico di Milano.

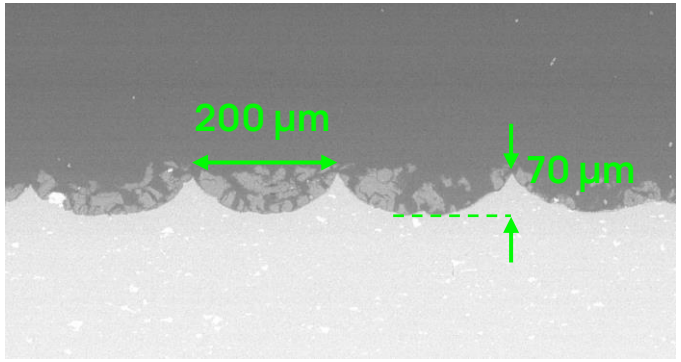
Biomimetic texture production on AA2024



Riblets are produced by
electrochemical micromachining (TMEMM)



Inkjet printing of a **dielectric mask**
UV curing

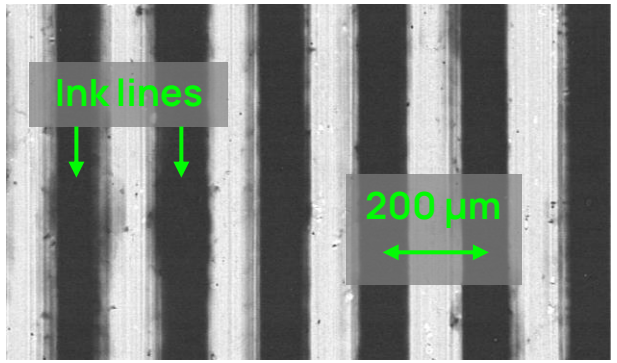


Electrochemical etching
DC or DC pulsed
in $NaNO_3$ 1,17 mol/L

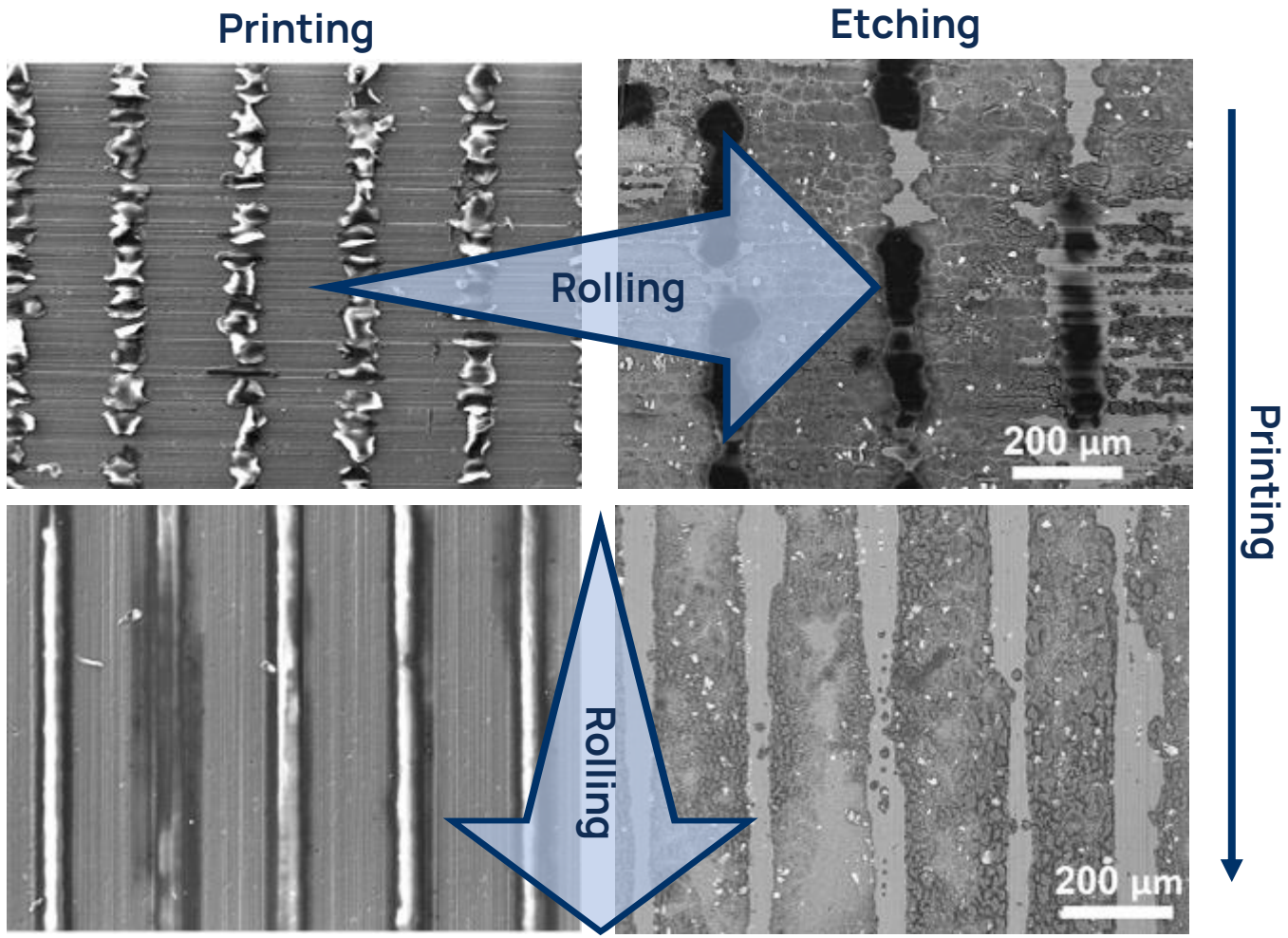
- Effect of the **rolling direction**
- Effect of etching **time and current**
- Effect of **mask thickness**

Biomimetic texture production: *Rolling direction*

Riblets are produced by **electrochemical micromachining** (TMEMM)

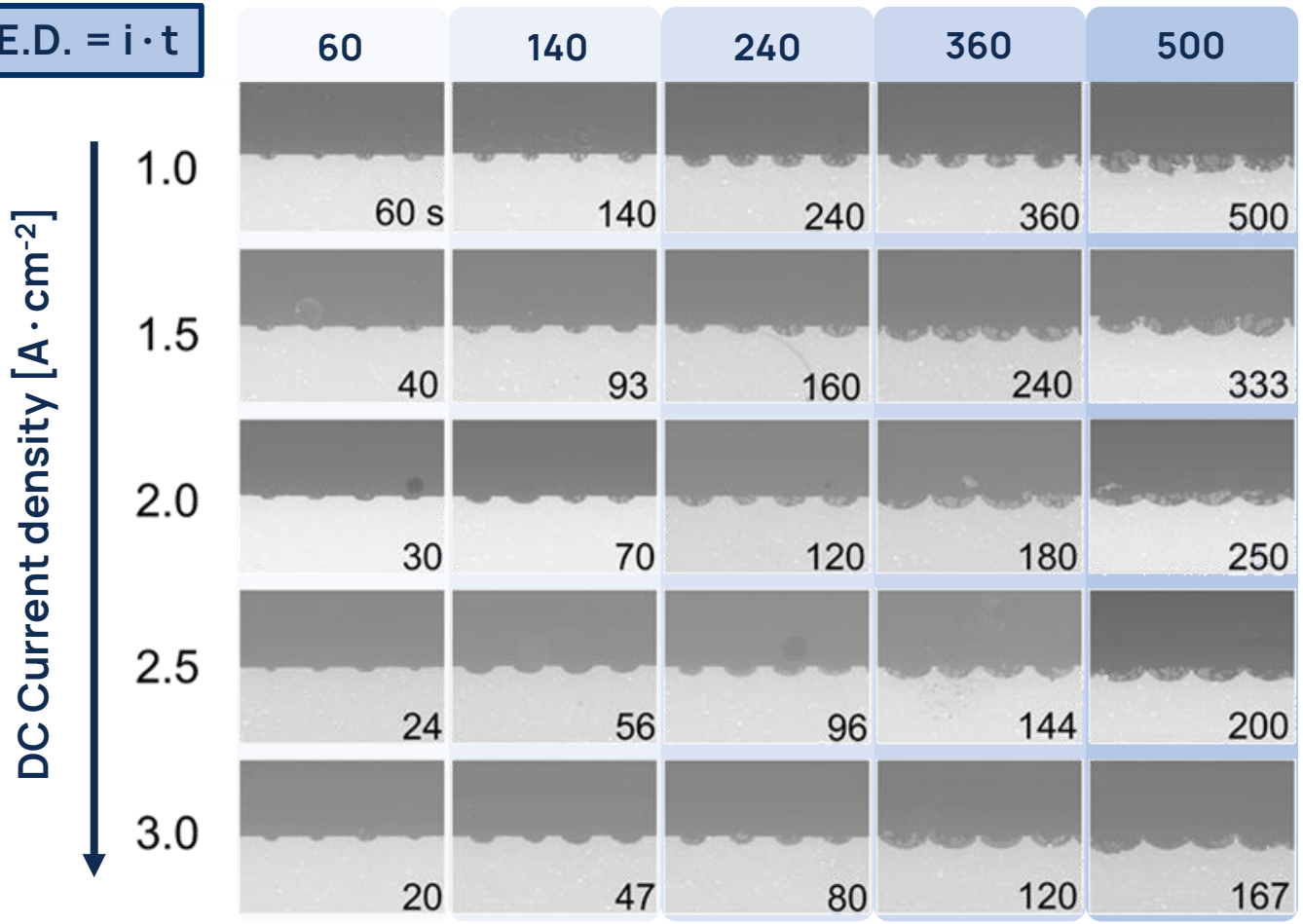


Inkjet printing of a **dielectric mask**
UV curing



Biomimetic texture production: *Etching current and time*

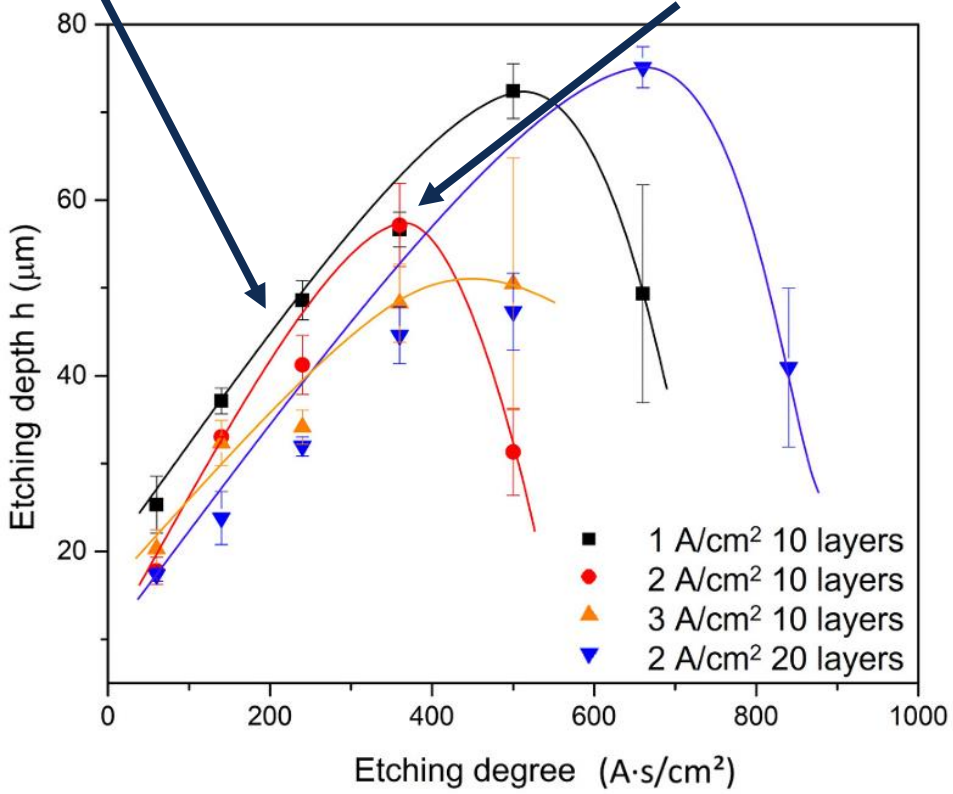
E.D. = i · t



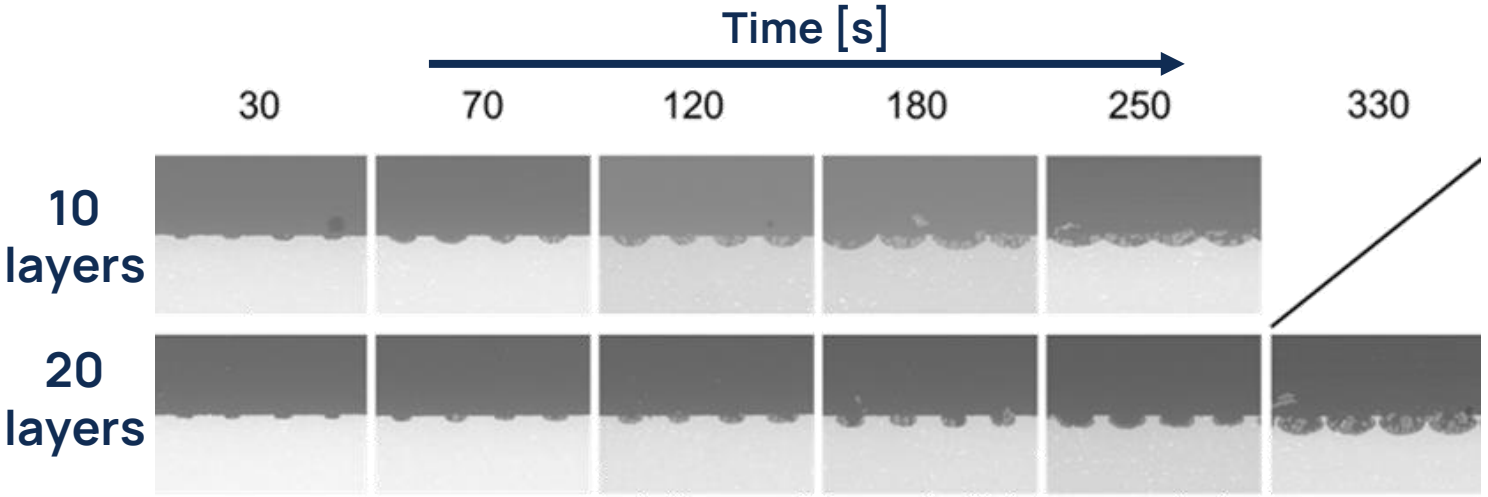
in $NaNO_3$ **1,17 mol/L**

Etching degree
Control on the riblets depth

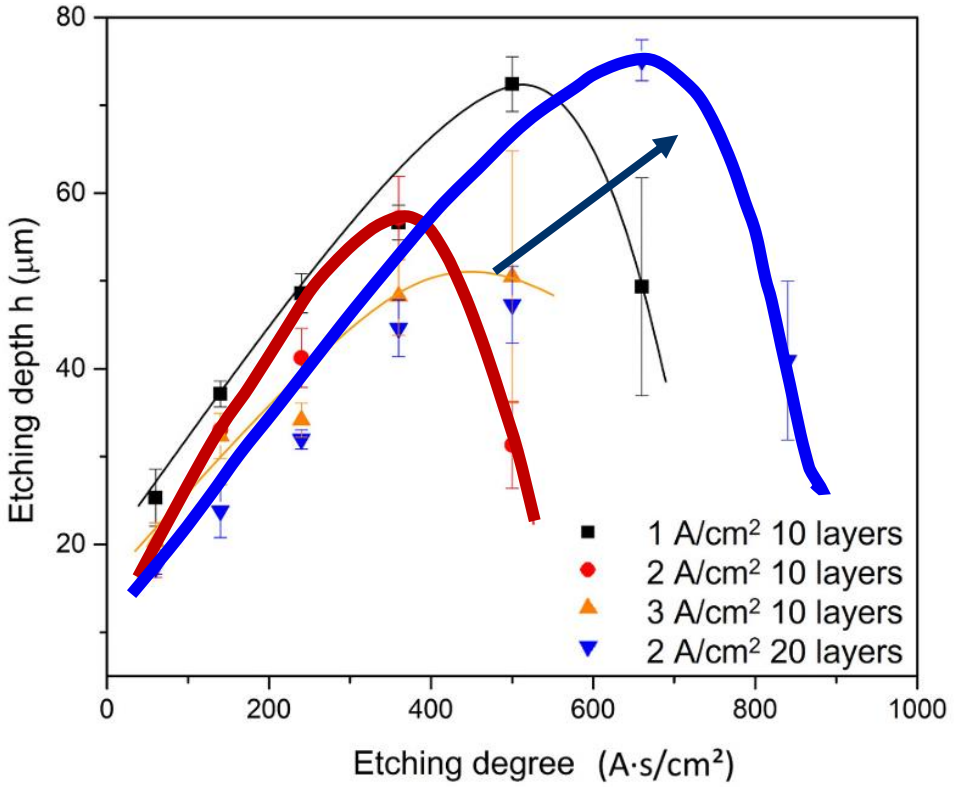
Current density
Control on the maximum depth achievable



Biomimetic texture production: *Dielectric mask thickness*



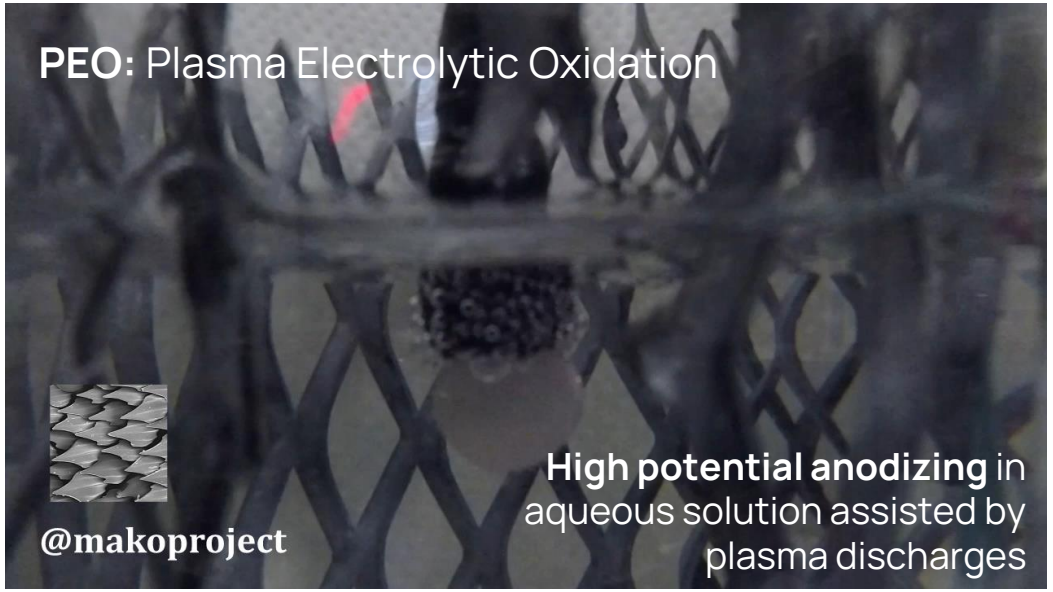
2 A · cm^{-2} in $NaNO_3$ **1,17 mol/L**



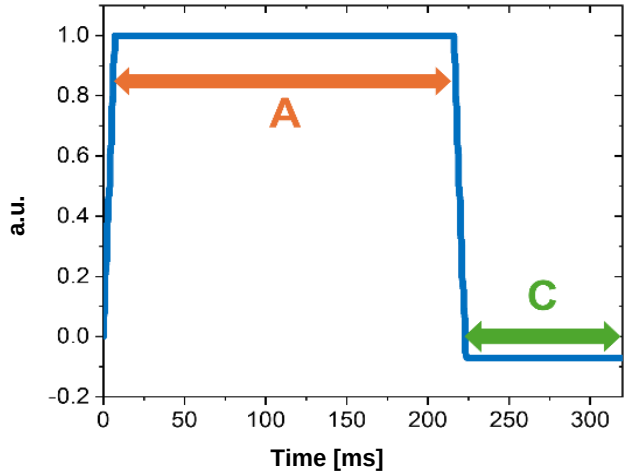
Mask thickness increase

- Delaying effect
- Maximum etching depth increase

PEO coating optimization



AC PEO in **potential control** with square waves 60-40-7
Frequency 1000 Hz, Duration 14', Max. voltage 350 V_{rms}

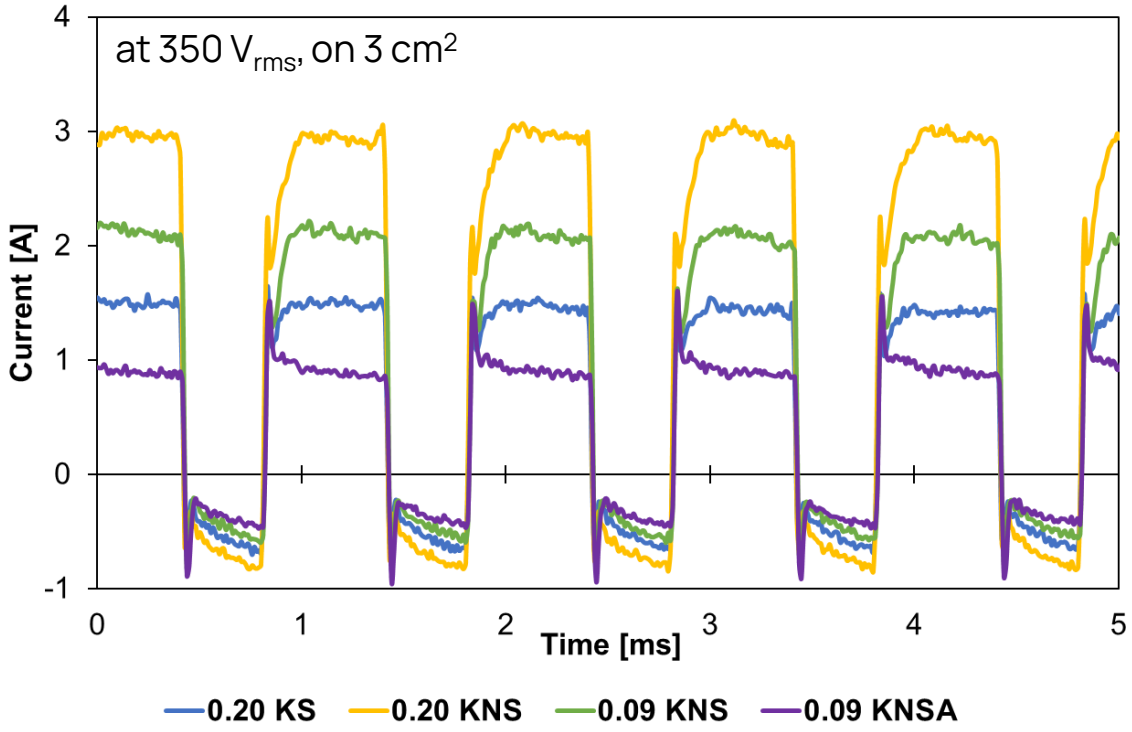


60% anodic
40% cathodic
7% cathodic vs anodic peak

- Definition of the electrical input
- Effect of electrolyte composition
  - Sodium silicate (Na_2SiO_3)
  - **Cationic component (Na^+ e K^+)**
  - **Alkalinity (OH^-)**
  - **Organic acids (CH_3COOH)**
- Application of a pore sealing post-treatment

PEO coating optimization: *Anodizing current*

Electrolyte	OH^- [mol/L]	KOH [mol/L]	NaOH [mol/L]	Na_2SiO_3 [g/L]	CH_3COOH [g/L]
0.20 KS	0.20	0.20	-	10	-
0.20 KNS	0.20	0.04	**0.16**	10	-
0.09 KNS	**0.09**	**0.014**	**0.076**	10	-
0.09 KNSA	0.09	0.014	0.076	10	**10**



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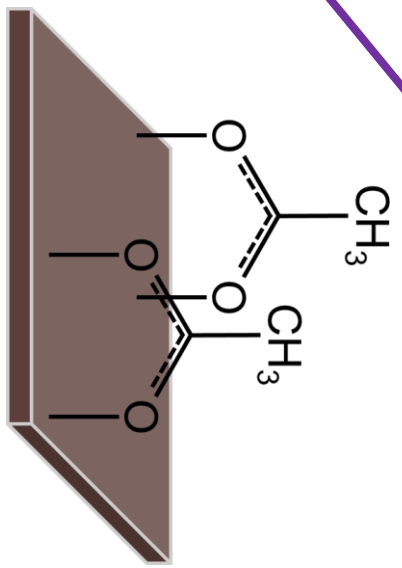
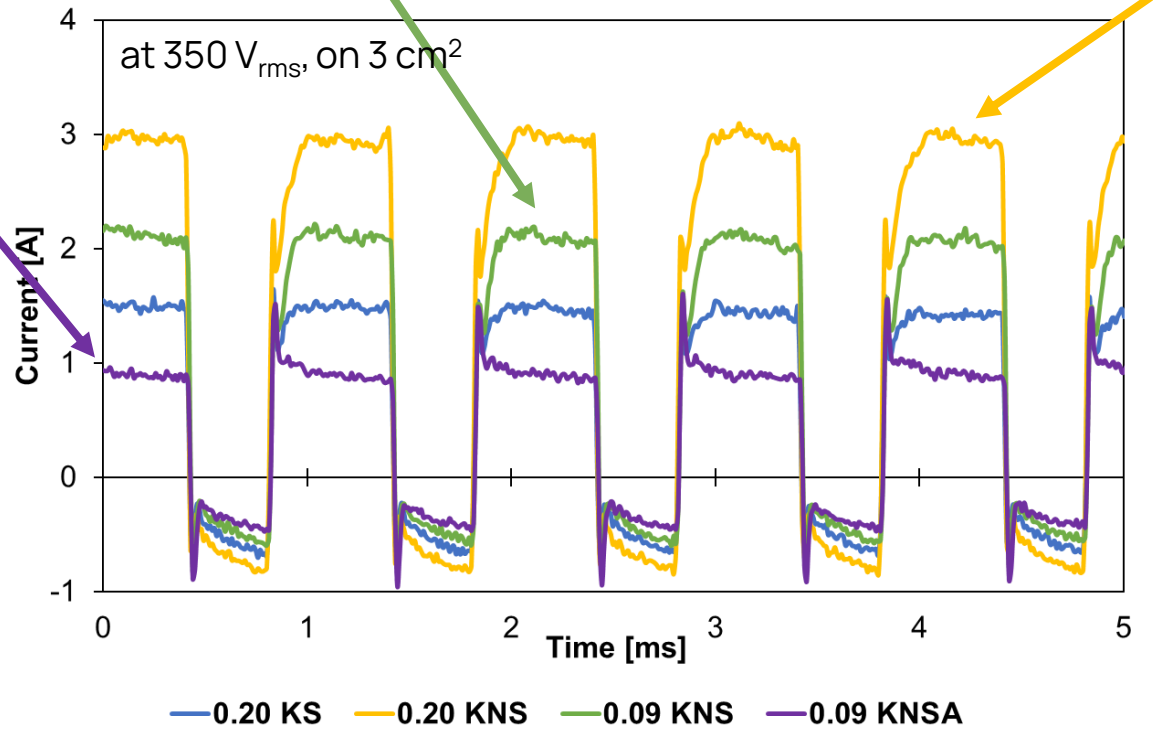
PEO coating optimization: *Anodizing current/2*

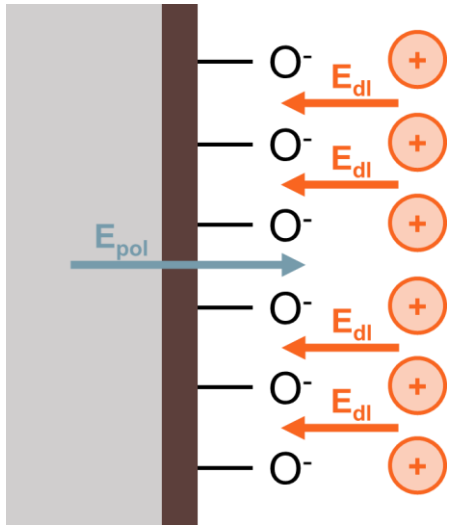
ACETIC ACID EFFECT



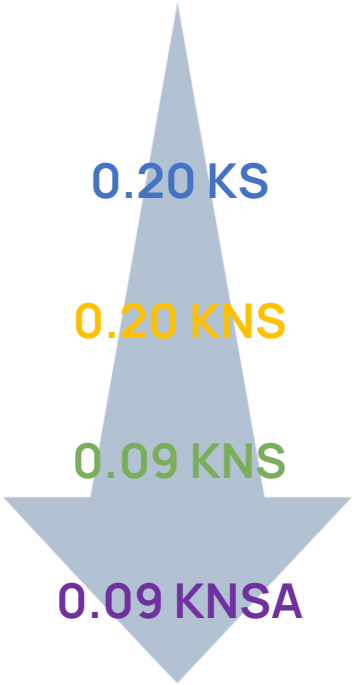
CONDUCTIVITY EFFECT



DOUBLE LAYER EFFECT



Large discharges



Small discharges

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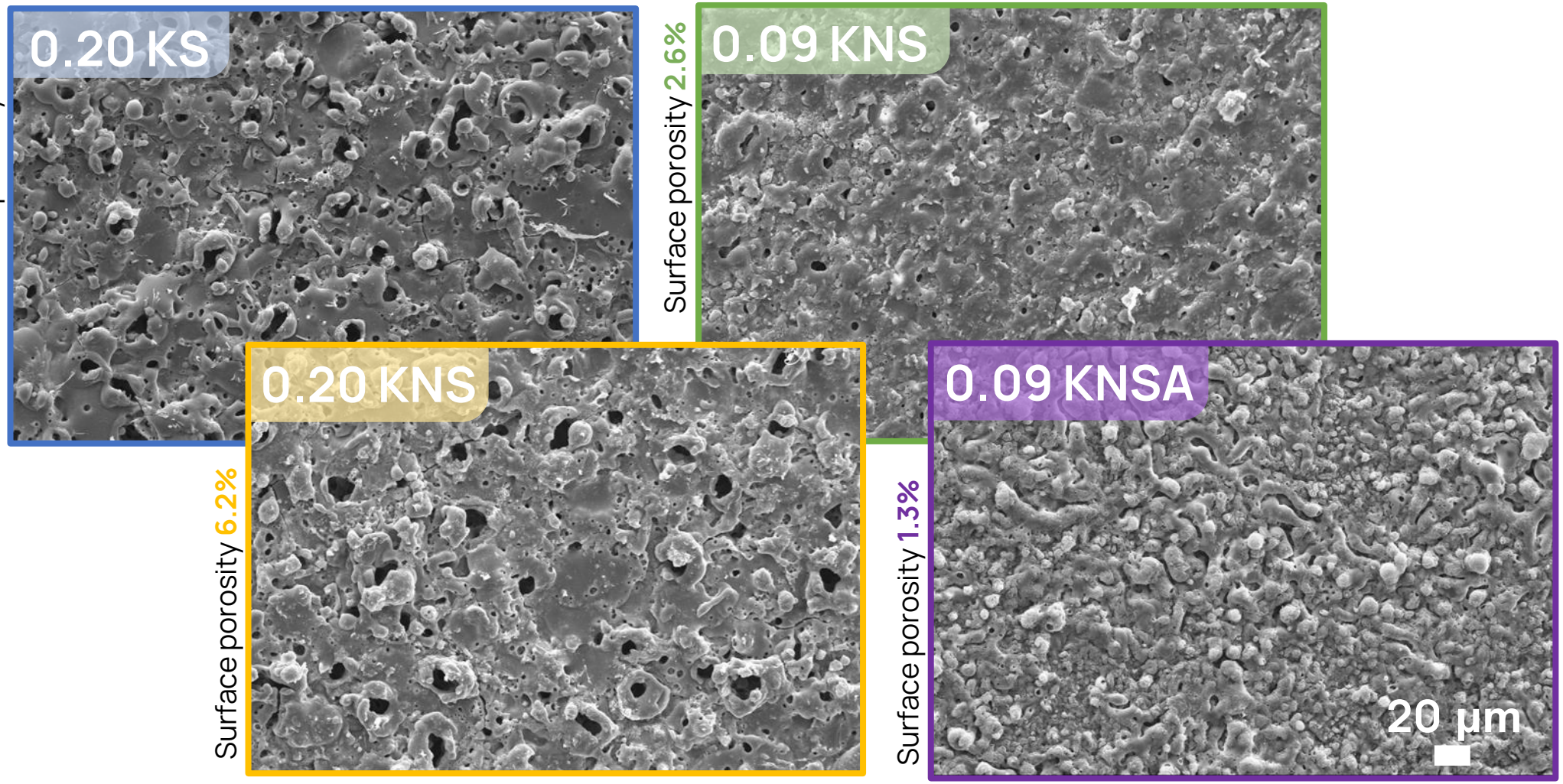
PEO coating optimization: *Morphology and microstructure*



Large discharges
Large pores

0.20 KS

0.20 KNS

0.09 KNS

0.09 KNSA

Small discharges
Small pores

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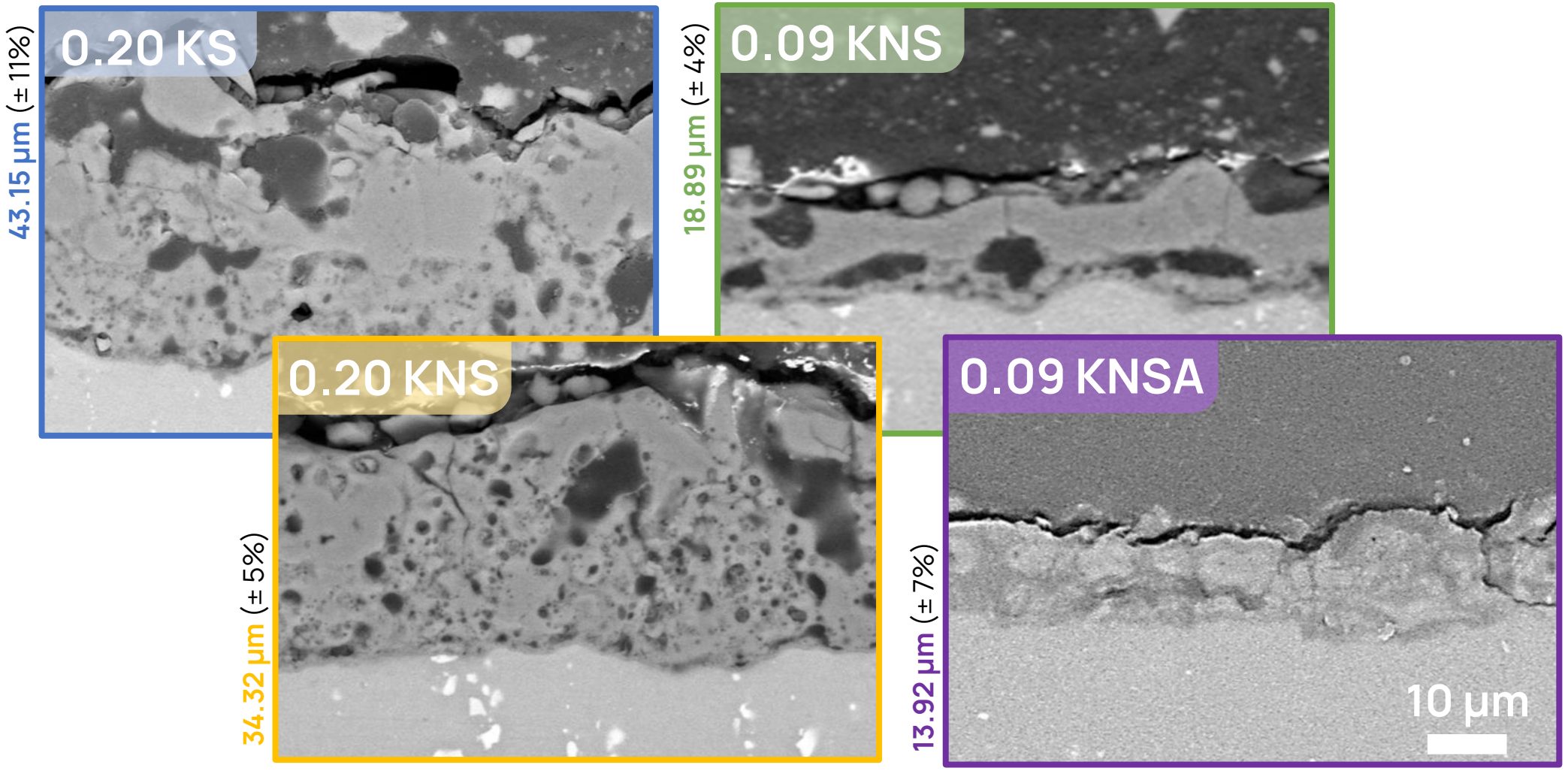
PEO coating optimization: *Morphology and microstructure/2*



Large discharges
Large pores

0.20 KS

0.20 KNS

0.09 KNS

0.09 KNSA

Small discharges
Small pores

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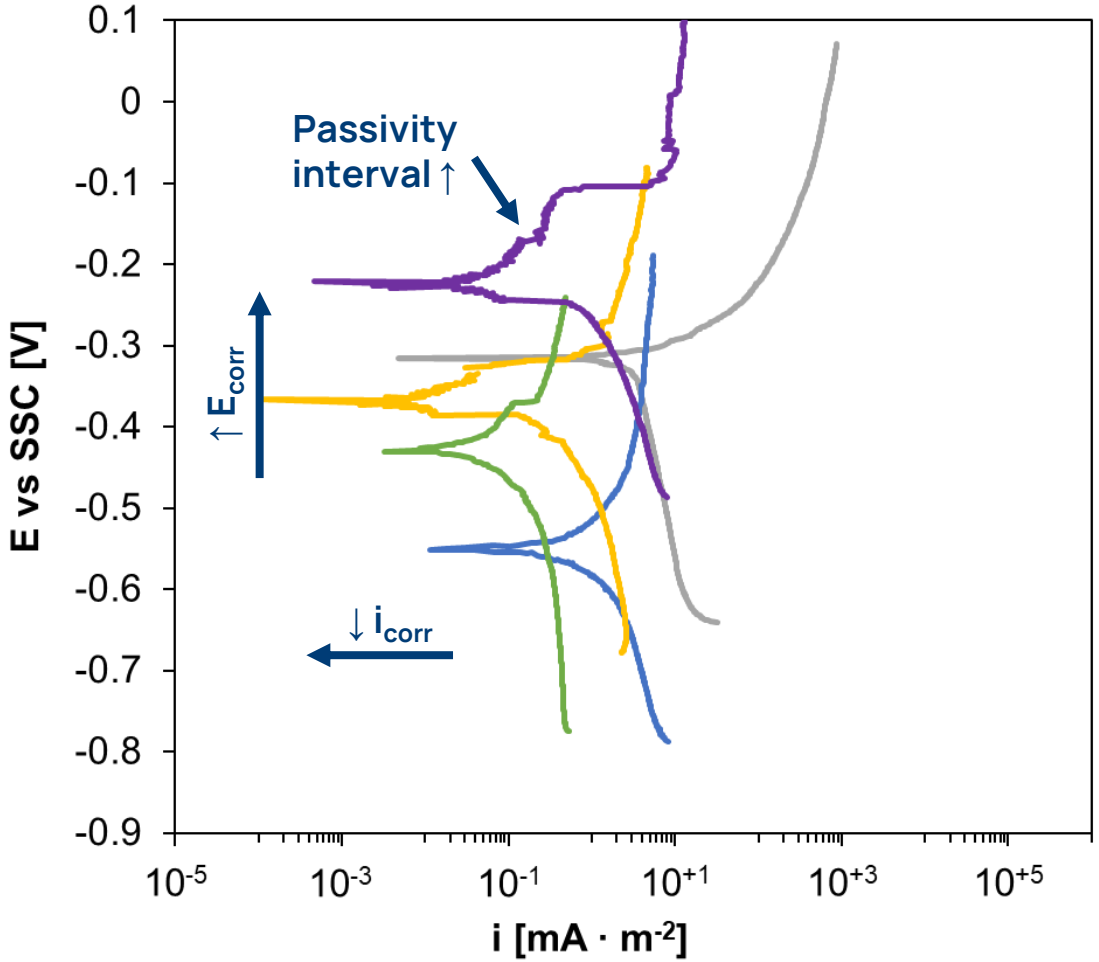
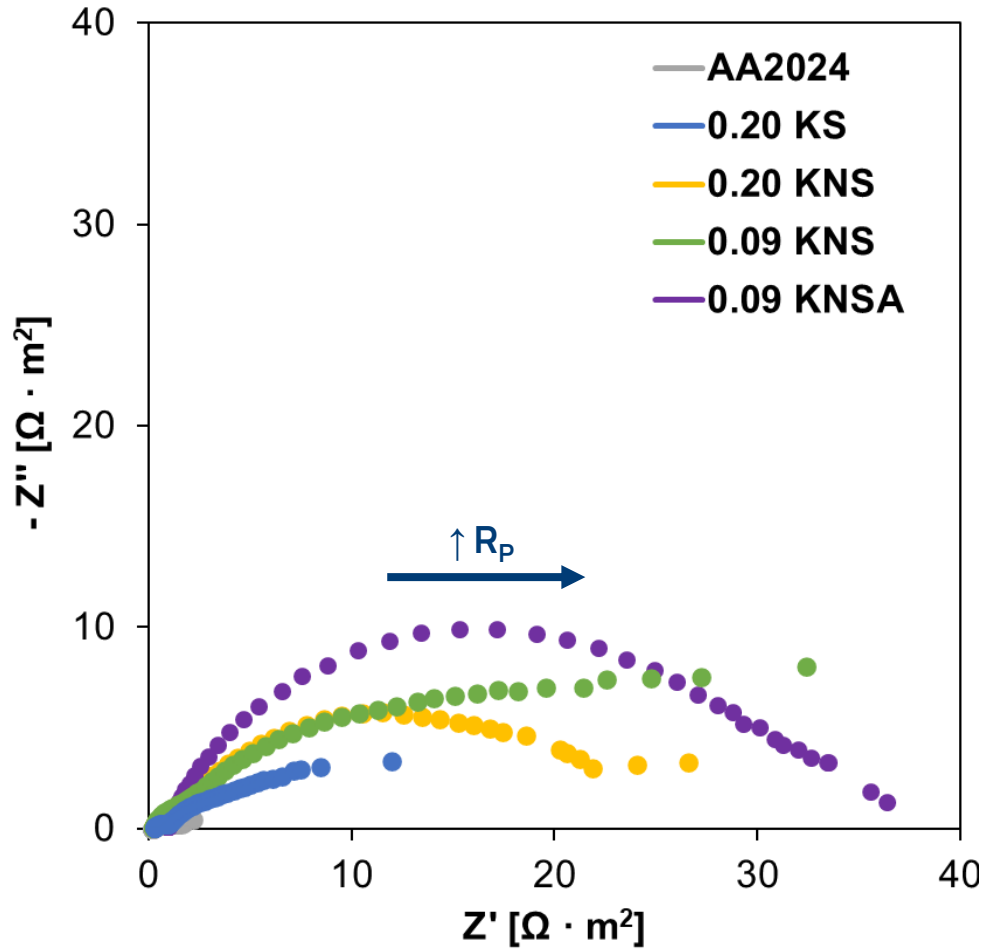
PEO coating optimization: *Corrosion Resistance*

20 ppm Cl^- (≈ freshwater), 1h immersion





Large discharges
Large pores
Low protection

0.20 KS

0.20 KNS

0.09 KNS

0.09 KNSA

Small discharges
Small pores
High protection

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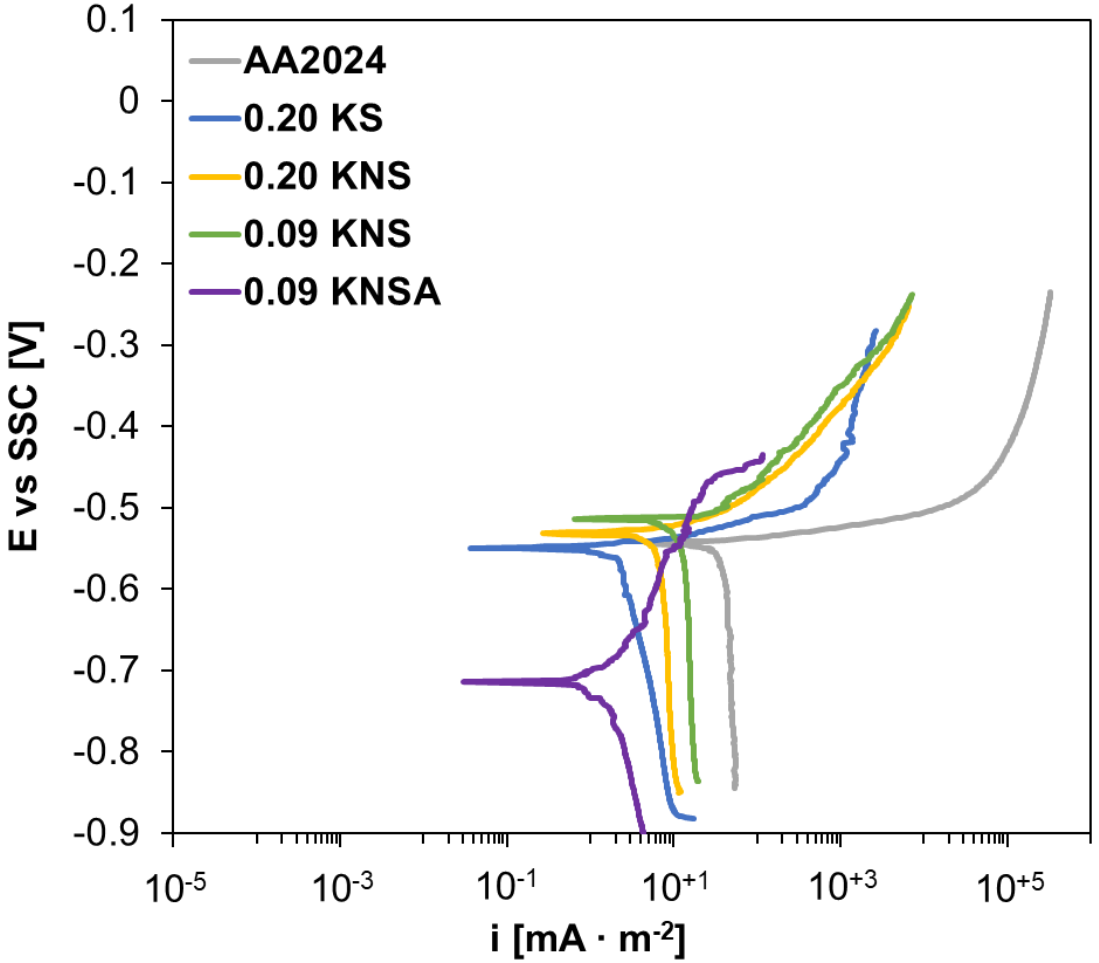
PEO coating optimization: *Corrosion Resistance/2*

20k ppm Cl^- (≈ seawater), 1h immersion



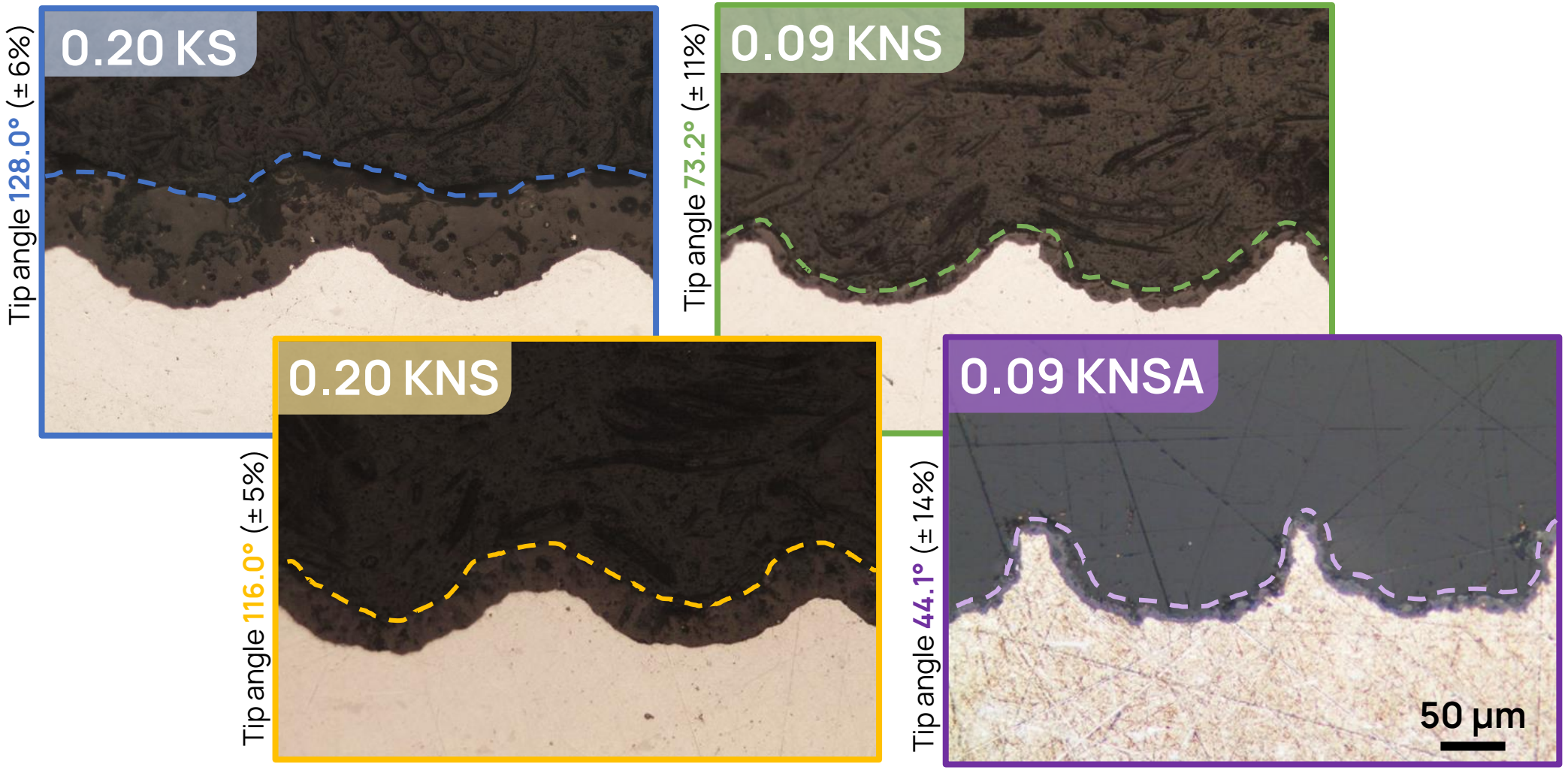
All performances **closer each other**

Almost the **same ranking** as in freshwater

Coated surfaces still behaving **much better than AA2024**

REQUIREMENT FOR **ADDITIONAL PROTECTION STRATEGIES**

PEO coating of biomimetic textures



Large discharges
Large pores
Low protection
Texture inaccuracy

0.20 KS

0.20 KNS

0.09 KNS

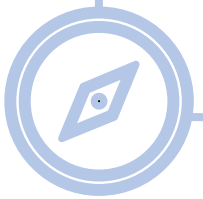
0.09 KNSA

Small discharges
Small pores
High protection
Texture accuracy

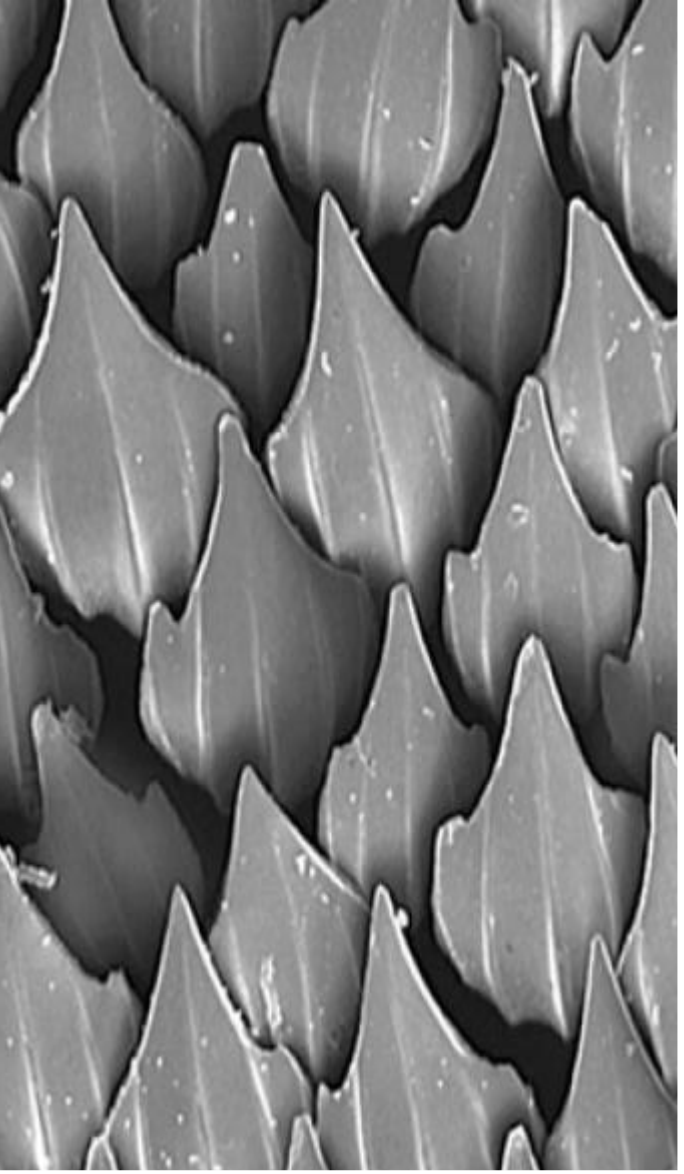
Conclusions / Future developments

- **TMEMM** proved to be effective at **reproducing the biomimetic texture** on AA2024.
- The desired texture parameters were achieved by acting on **etching degree** and **mask thickness**.
- Corrosion resistance of a PEO coating depends more on its **porosity** than on its thickness.
- PEO coating porosity may be controlled by reducing the **plasma discharge intensity**.
- PEO reproduces the substrate biomimetic texture with an accuracy depending on the electrolyte.

- Enhancing corrosion resistance with a pore-sealing post-treatment.
- Addressing long-term corrosion resistance (accelerated/natural exposure).
- Studying the texture effect on PEO coating corrosion resistance.



A. Cristoforetti, PhD
Mastrafjorden B
Wed. 10/09 – 2 pm



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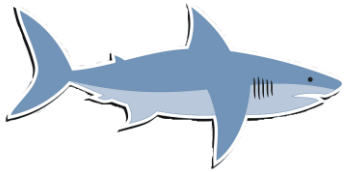
EUROCORR 2025
7 - 11 September

Thank you!

Follow the shark!



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polilapp.chem.polimi.it

The research activity is co-funded by the European Union – Next Generation EU, PNRR - mission 4 “istruzione e ricerca” - D.D. N. 104/2022 “BANDO PRIN 2022”.

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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Stavanger, Norway
EUROCORR 2025
7 - 11 September

Corrosion Resistance of PEO-Coated Biomimetic Textured AA2024 Aluminum Alloy

A. Cristoforetti[2], M. Gamba[1], A. Brenna[1], M. Ormellese[1], M. Fedel[2]

[1] Dipartimento di Chimica, Materiali ed Ingegneria Chimica "Giulio Natta", Politecnico di Milano
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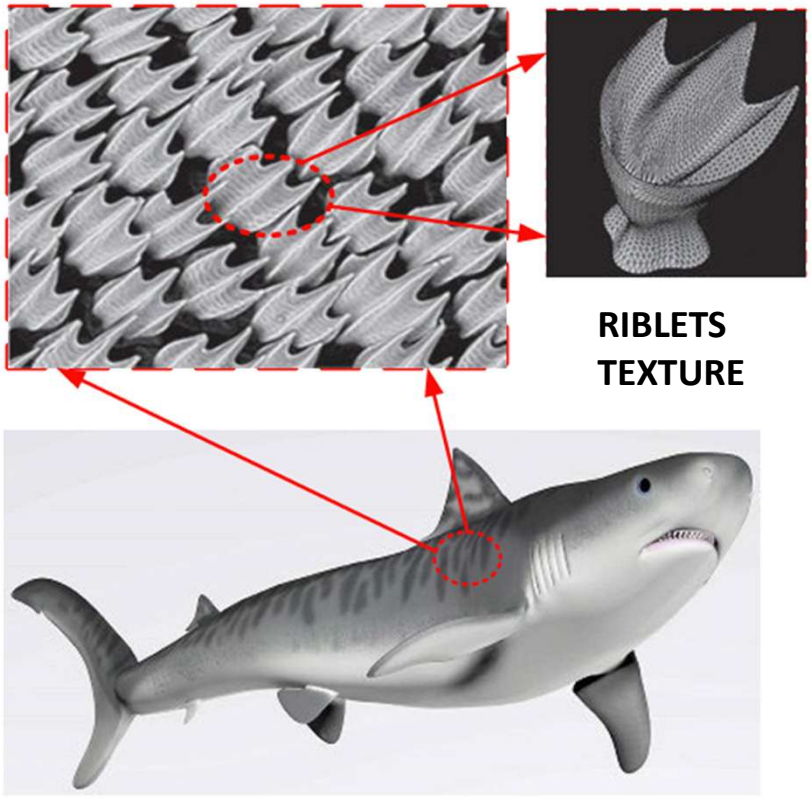


RIBLETS TEXTURE

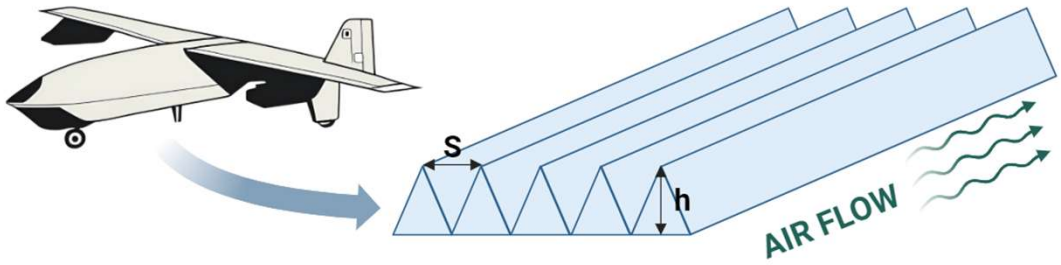
BIOMIMICRY: MAKO SHARK SCALE PROFILE

↓

REDUCTION OF AERODYNAMIC DRAG

↓

REDUCTION IN CO_2 EMISSIONS



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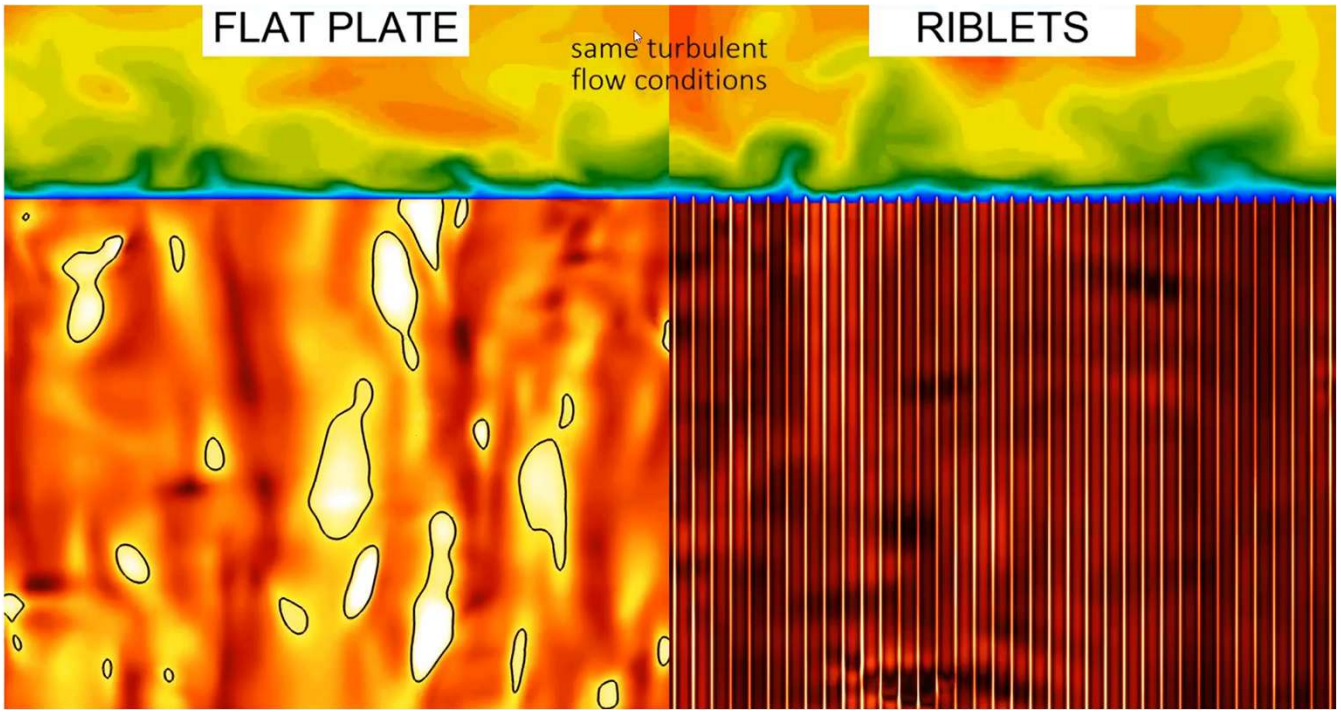
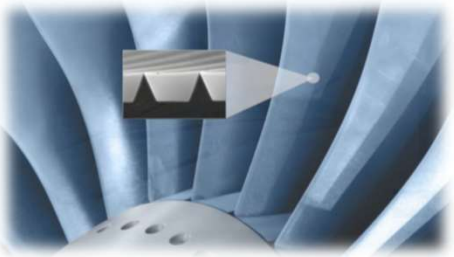
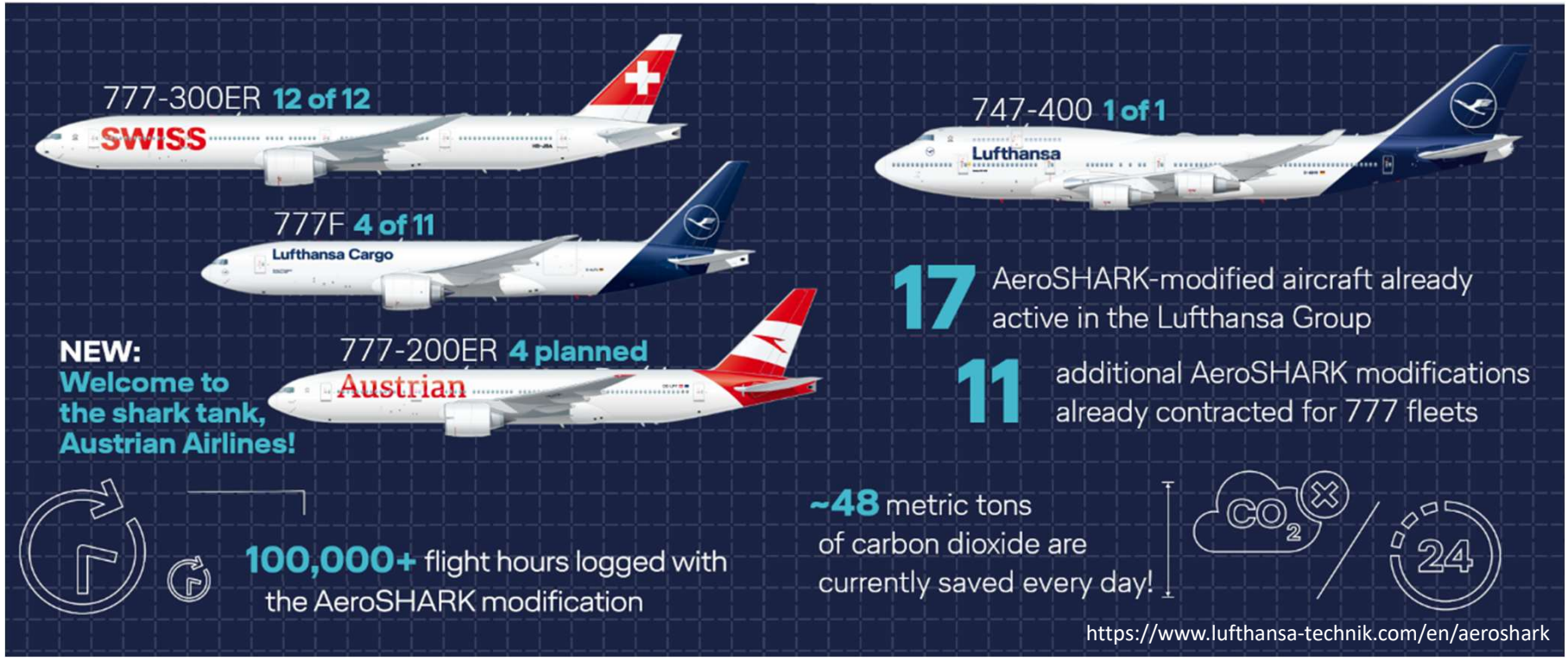




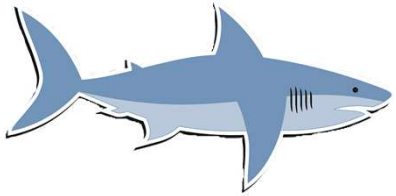
https://www.bionicsurface.com/

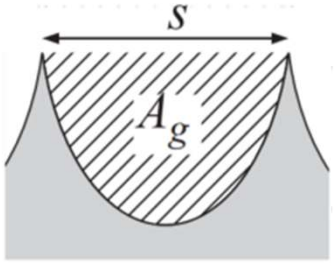


APPLICATION OF POLYMER FILMS → WEAR → MAINTENANCE COSTS

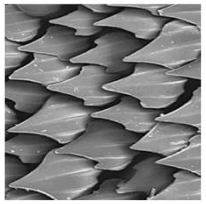
MAKO PROJECT ROADMAP

WP1
Definition of the Biomimetic Texture





WP2
Texture Fabrication via Electrochemical Etching (TMEMM)



UNITRENTO

WP3
PEO Treatment of Textured Surfaces

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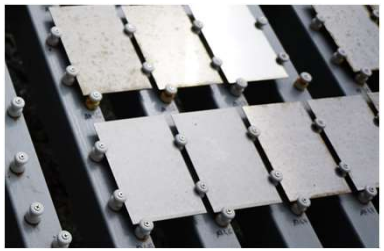
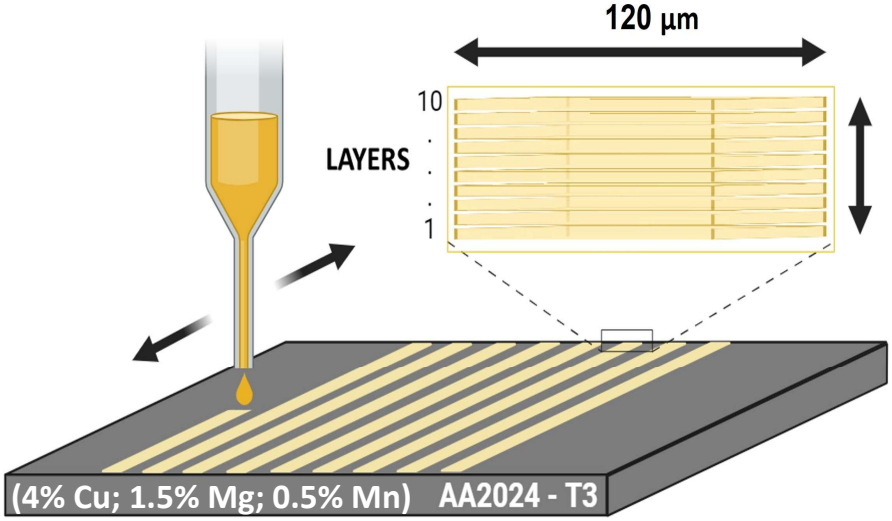
WP4
Evaluation of Corrosion Resistance



TEXTURING BY TMEMM

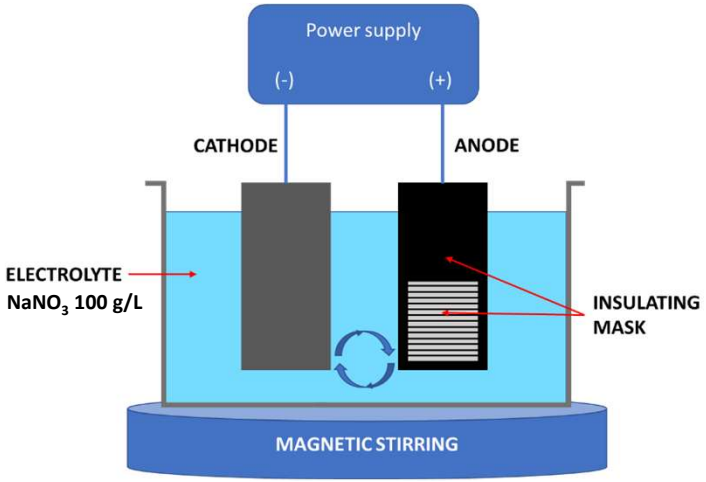
Through Mask Electrochemical Micromaching

STEP 1: inkjet printing - polymeric mask



→ CERADROP F-Series (MGI group) inkjet printer

STEP 2: anodic polarization – texture



→ 180 s galvanostatic polarization set at 2 A/cm^2

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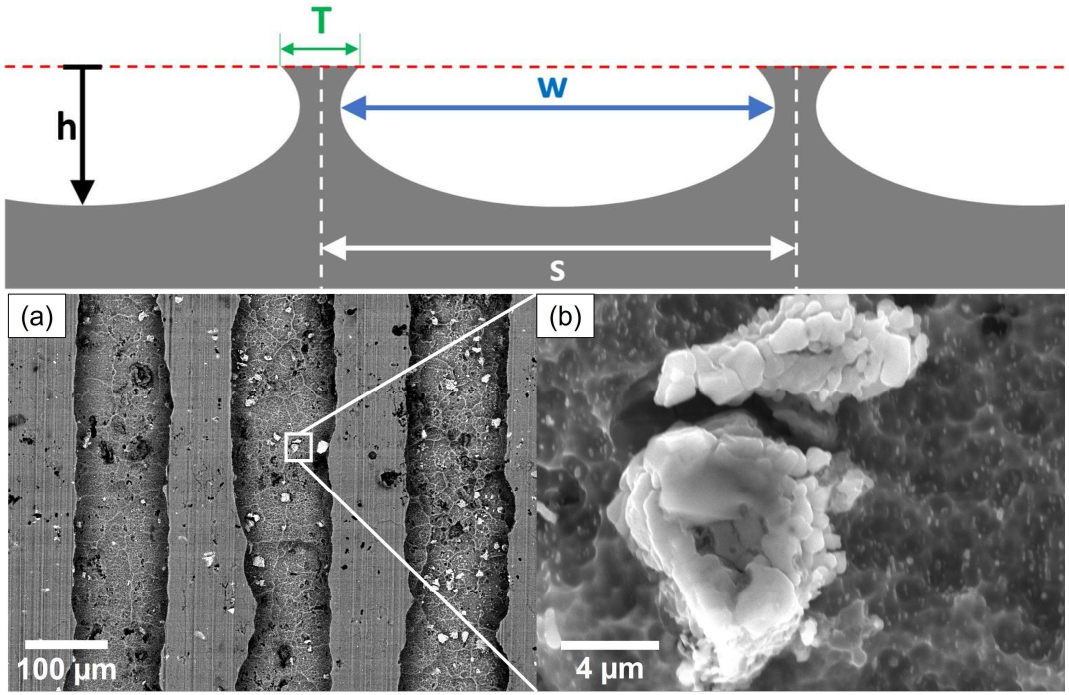
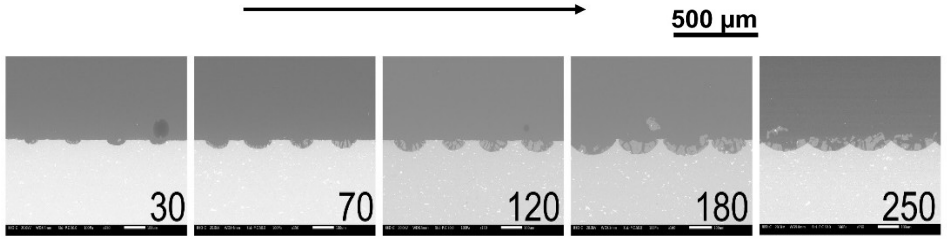
POST-TEXTURING SURFACE



- **AA2024-T3** is prone to **localized corrosion**, with no stable passive region due to Cu-rich IMPs.
- The partial removal of IMPs could yield benefits for subsequent anodizing coatings.



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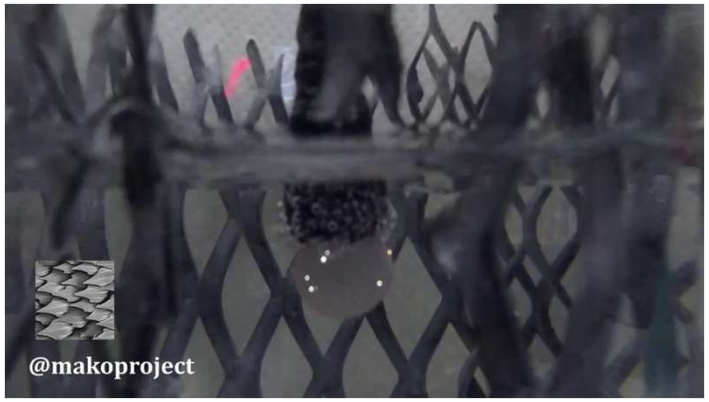
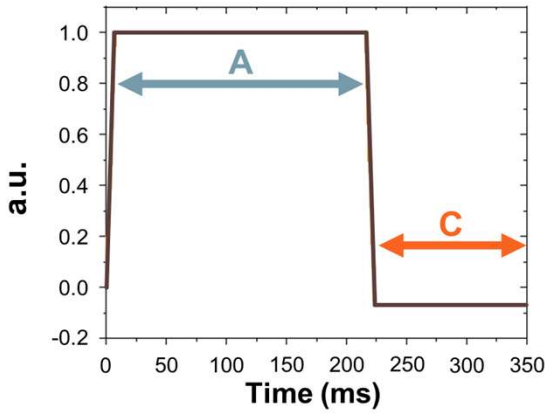
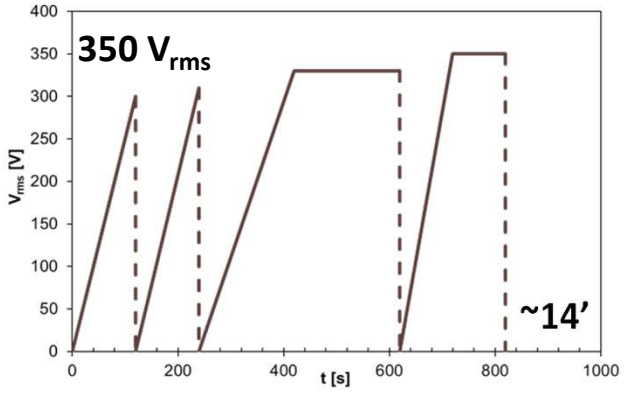
PEO PROCESS

- Silicate-alkaline with glycerin for reducing splash-out
- The addition of acetic acid (AA) was considered



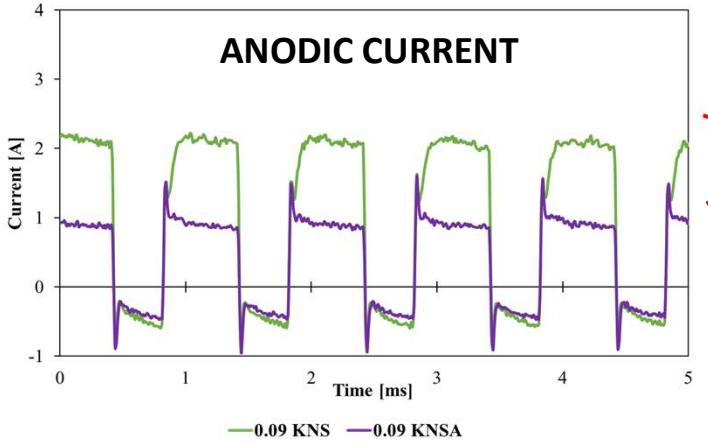
INPUT WAVEFORM





MULTISTEP INPUT CYCLE

ANODIC CURRENT



+AA

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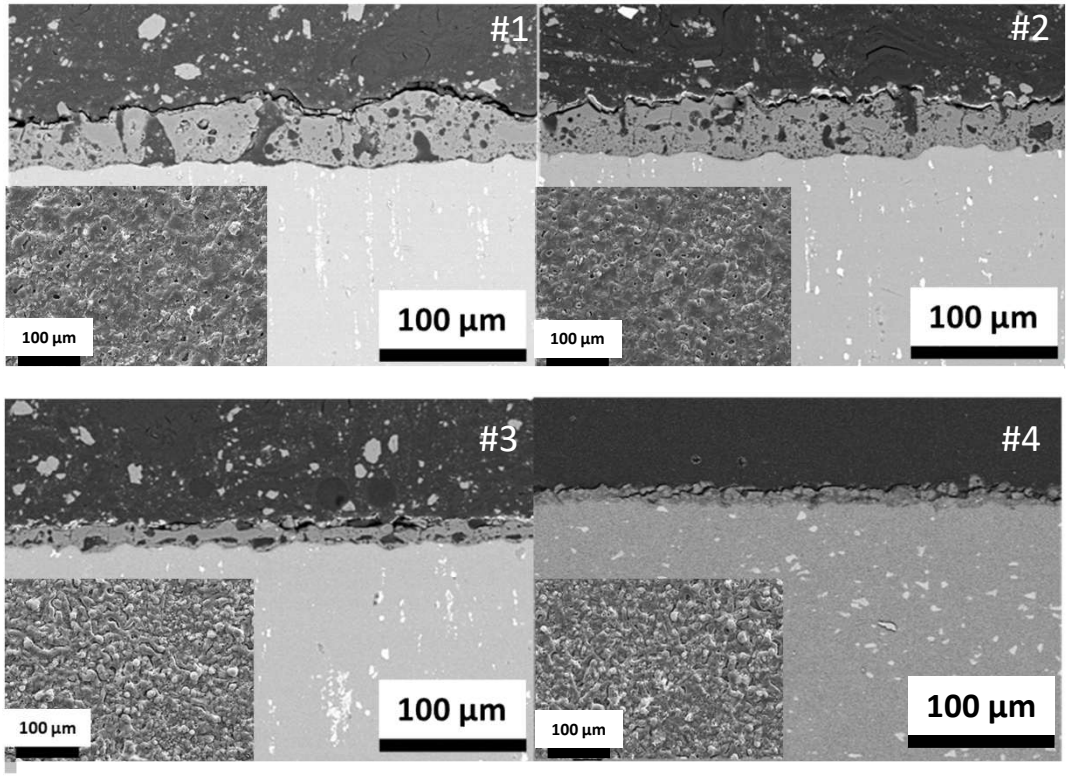
PEO-COATED SAMPLES

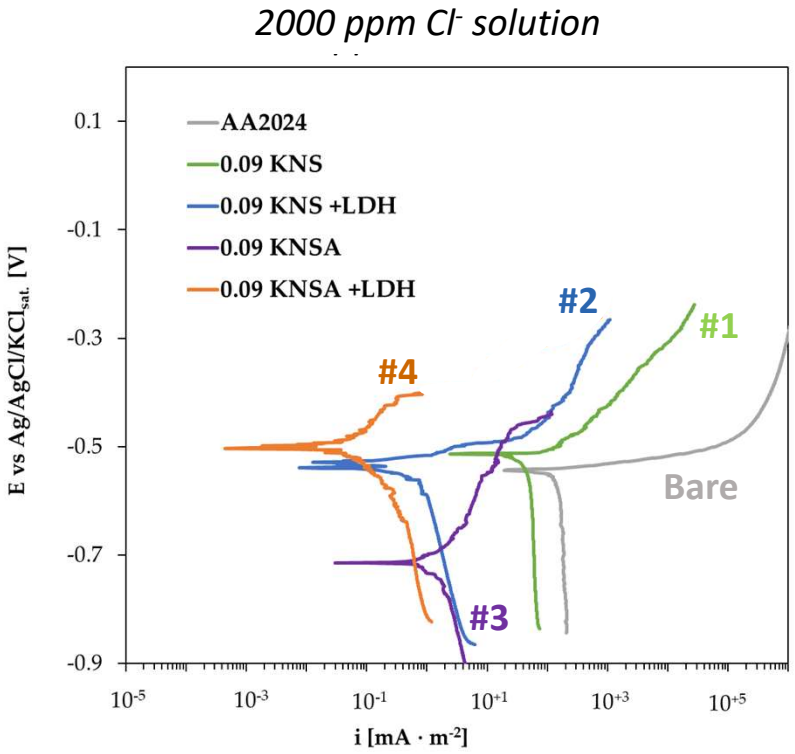
	Name	PEO electrolyte OH^- [mol/L]	KOH [mol/L]	NaOH [mol/L]	CH_3COOH [g/L]	Na_2SiO_3 [g/L]	Glycerin [g/L]	Sealing ZnAl-LDH	Thickness [µm]
#1	0.09 KNS	0.09	0.014	0.076	-	10	10	-	19 ± 1
#2	0.09 KNS+LDH	0.09	0.014	0.076	-	10	10	90°C 15 min	19 ± 1
#3	0.09 KNSA	0.09	0.014	0.076	10	10	10	-	14 ± 1
#4	0.09 KNSA+LDH	0.09	0.014	0.076	10	10	10	90°C 15 min	14 ± 1

+AA

AIM

- Identify the best-performing coating formulation: contour, durability performances
- Compare the corrosion resistance of PEO coatings: textured vs. flat surfaces


#1
#2
#3
#4
100 µm


2000 ppm Cl- solution
AA2024
0.09 KNS
0.09 KNS +LDH
0.09 KNSA
0.09 KNSA +LDH
#1
#2
#3
#4
Bare
E vs Ag/AgCl/KCl$_{sat.}$ [V]
i [mA · m^{-2}]
0.1
-0.1
-0.3
-0.5
-0.7
-0.9
10^{-5}
10^{-3}
10^{-1}
10^{+1}
10^{+3}
10^{+5}

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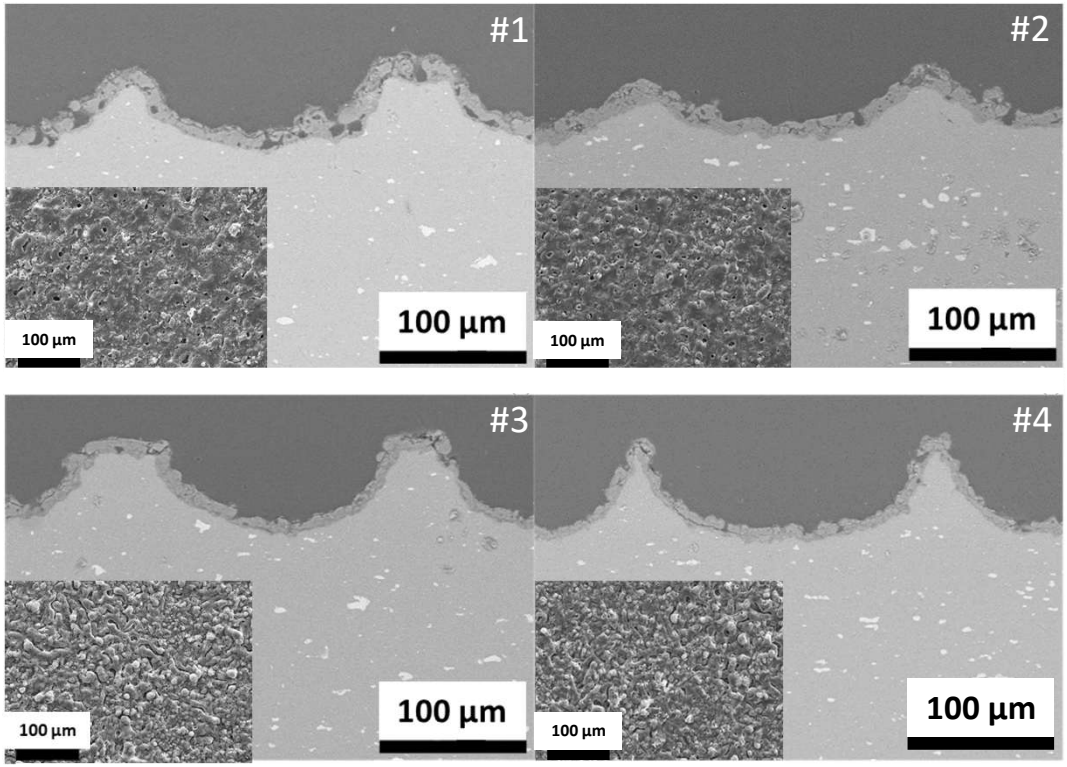
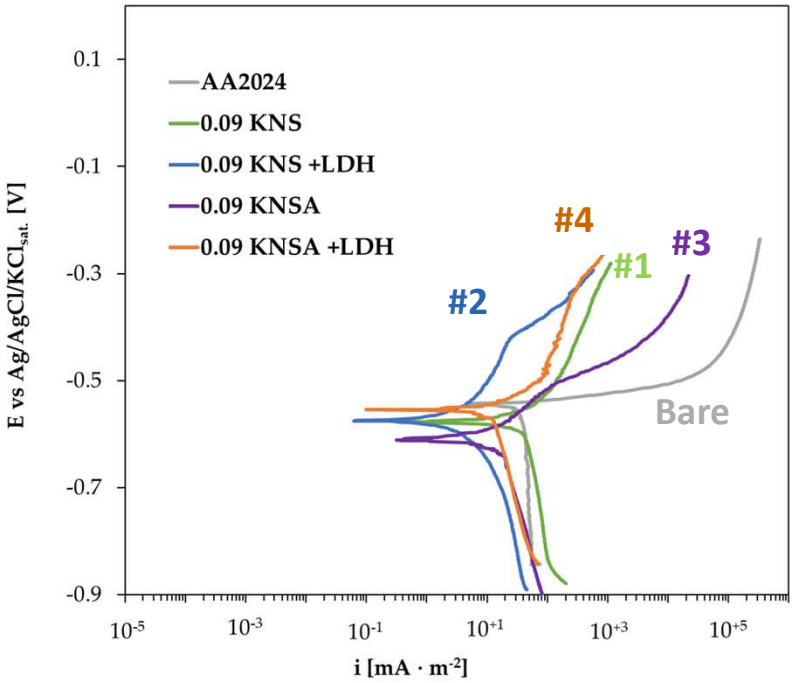


2000 ppm Cl^- solution



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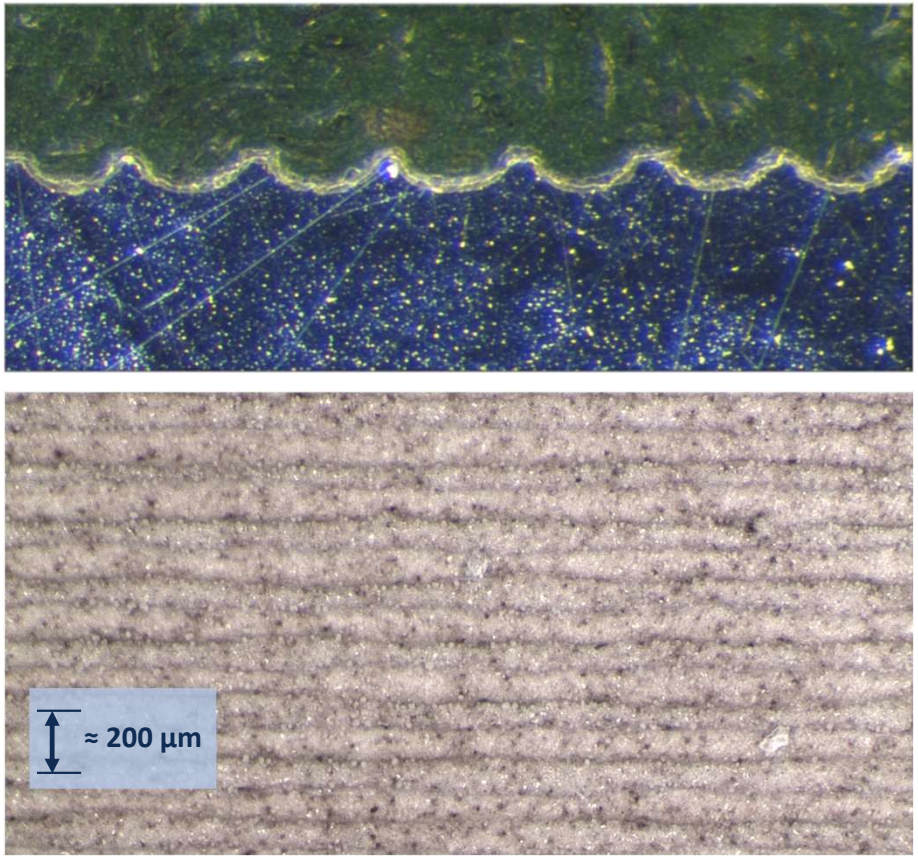
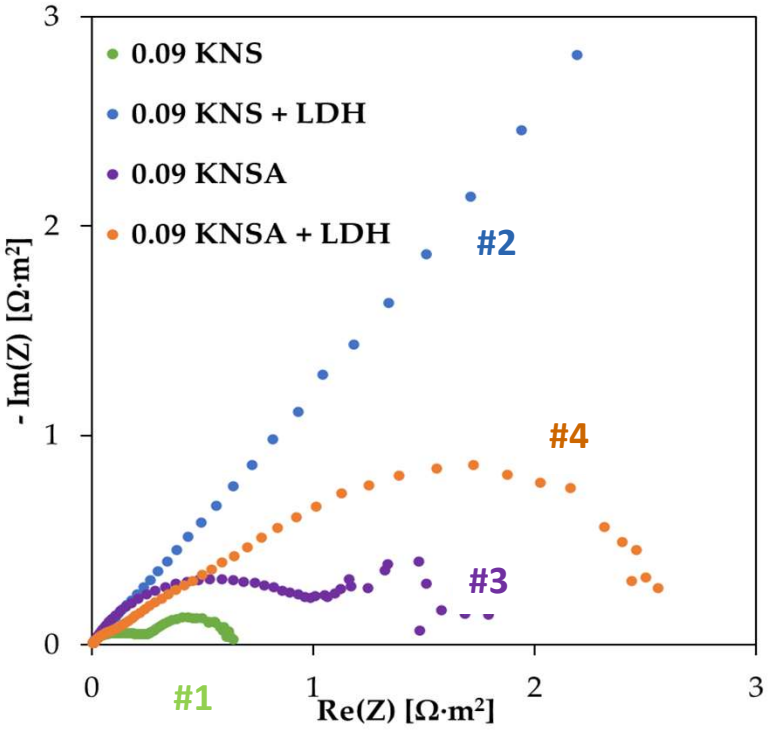


2000 ppm Cl^- solution



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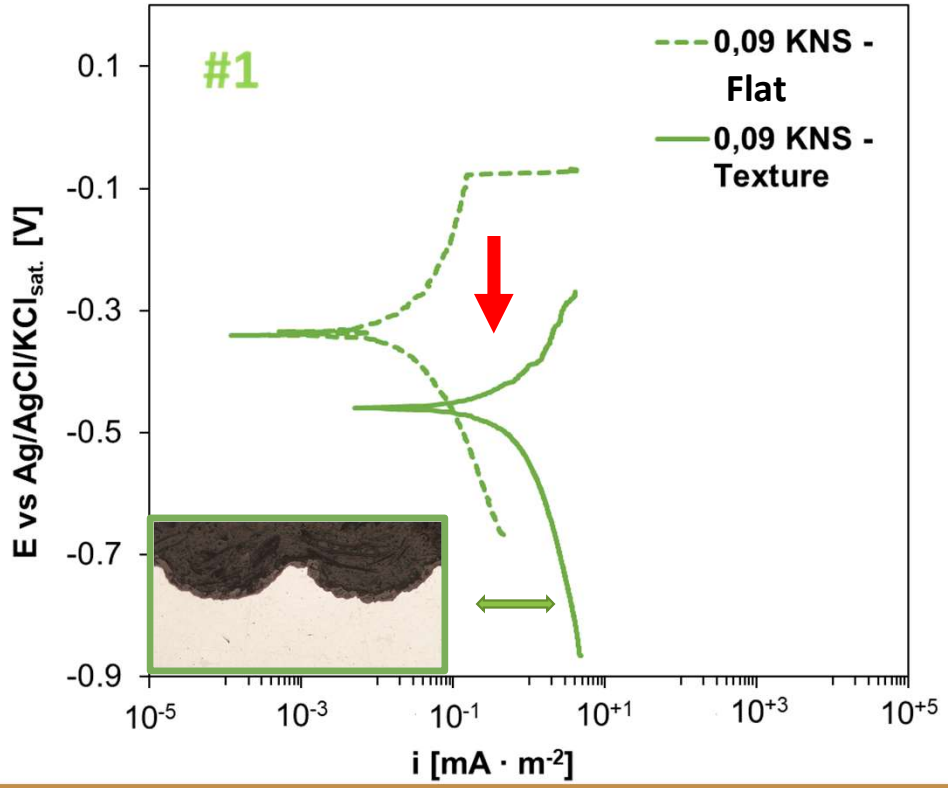
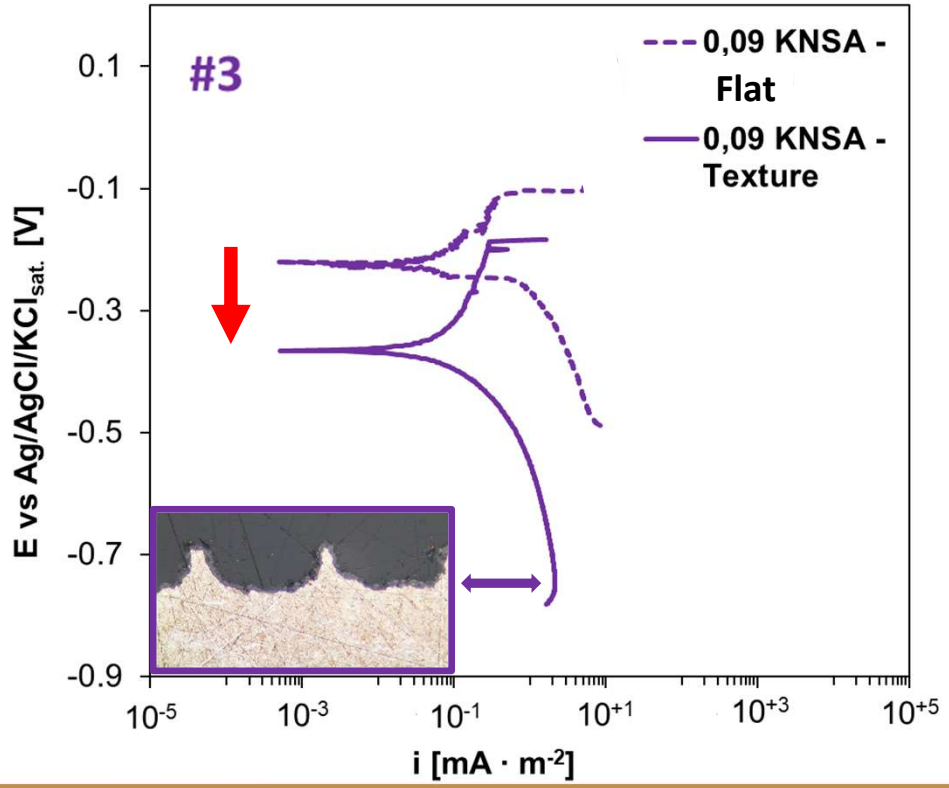
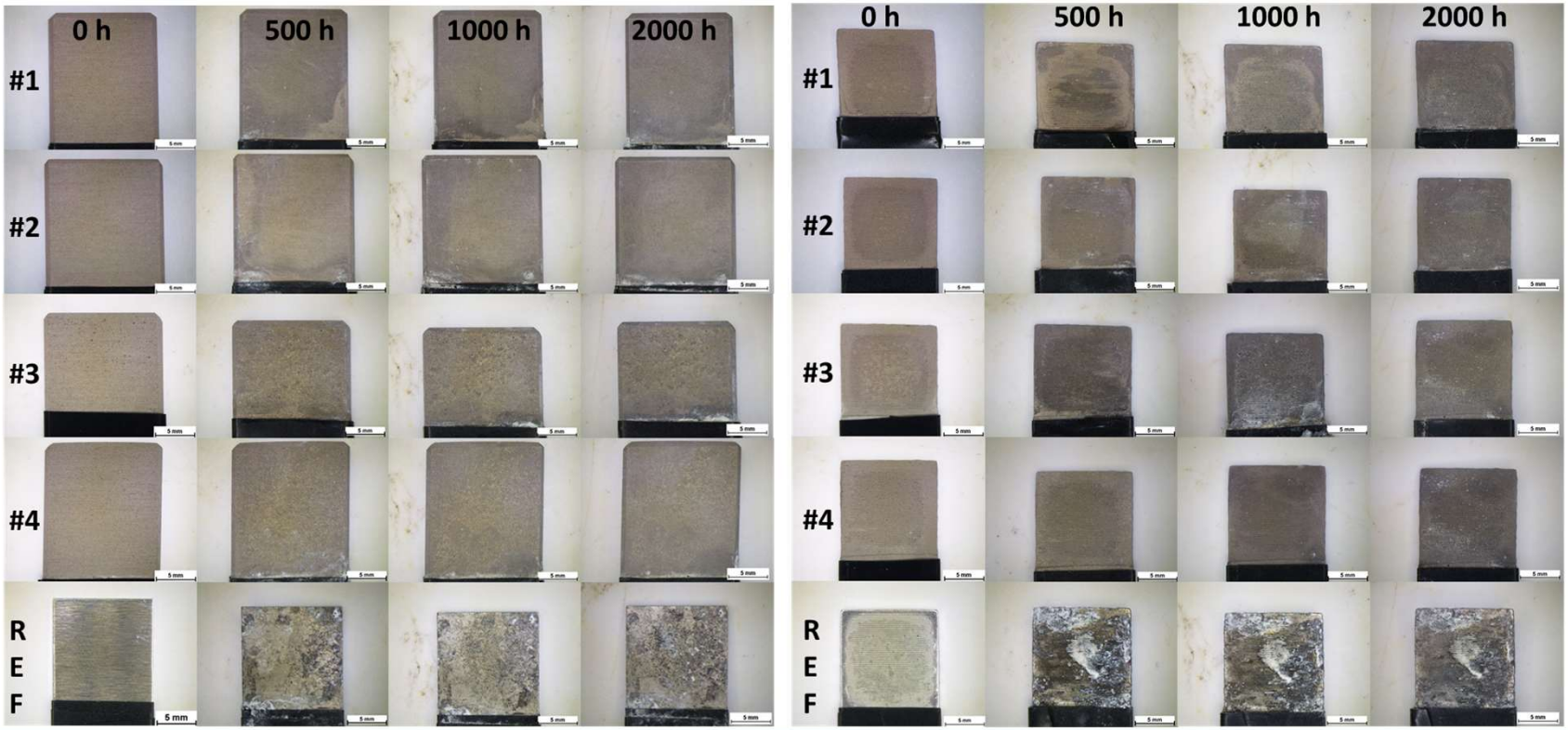
20 ppm Cl^- solution





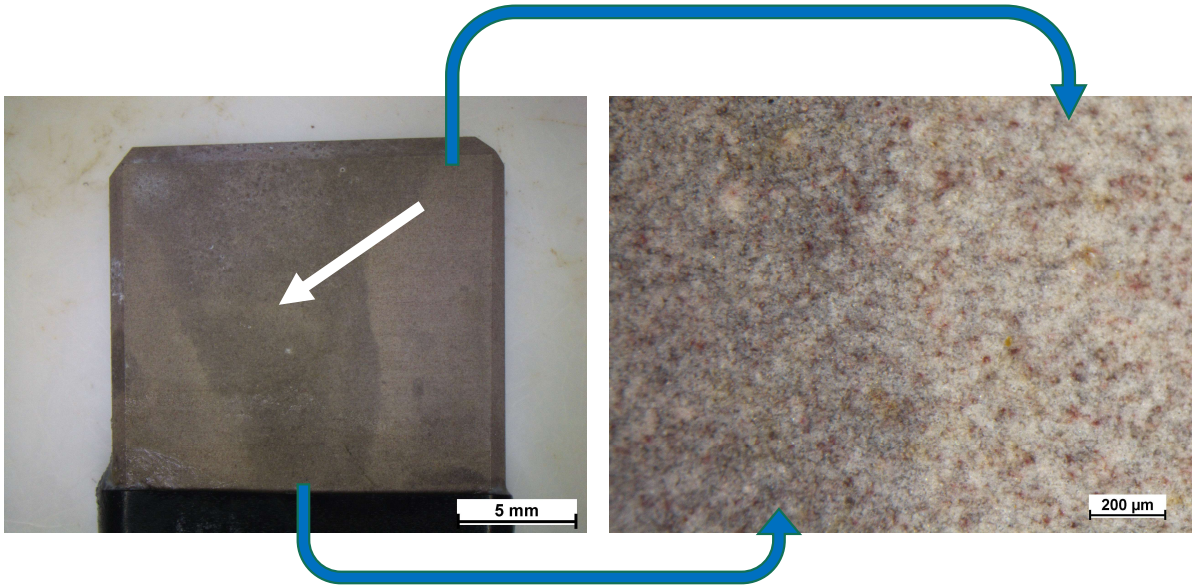
NEUTRAL SALT SPRAY (ASTM B117)



NEUTRAL SALT SPRAY – COATING FAILURE

Oxides formation

darkened areas



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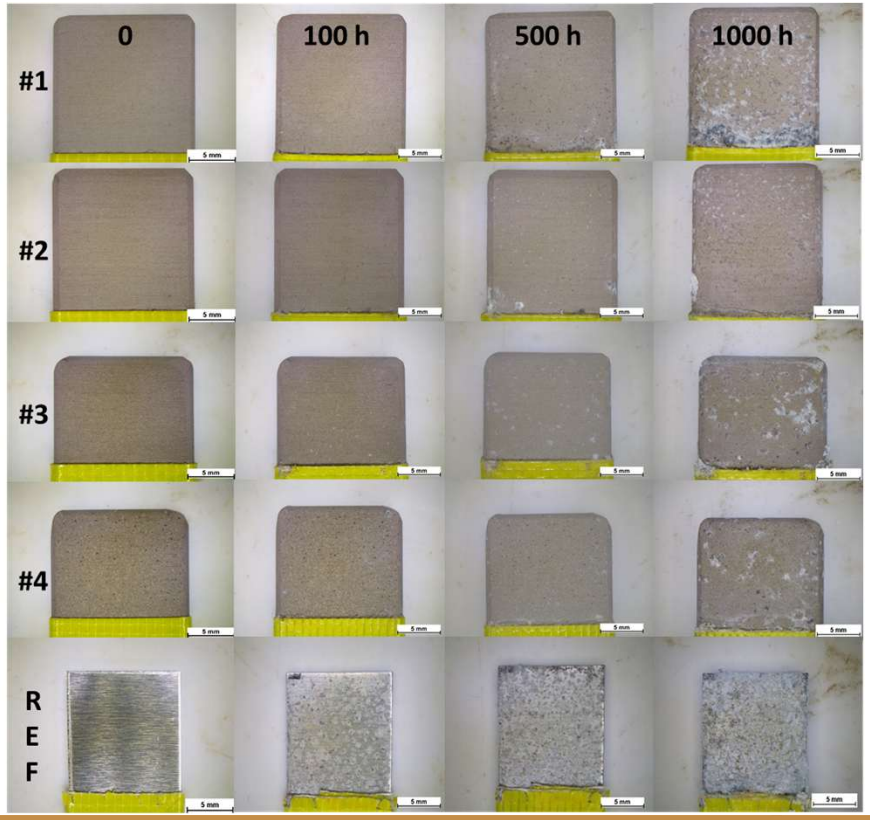
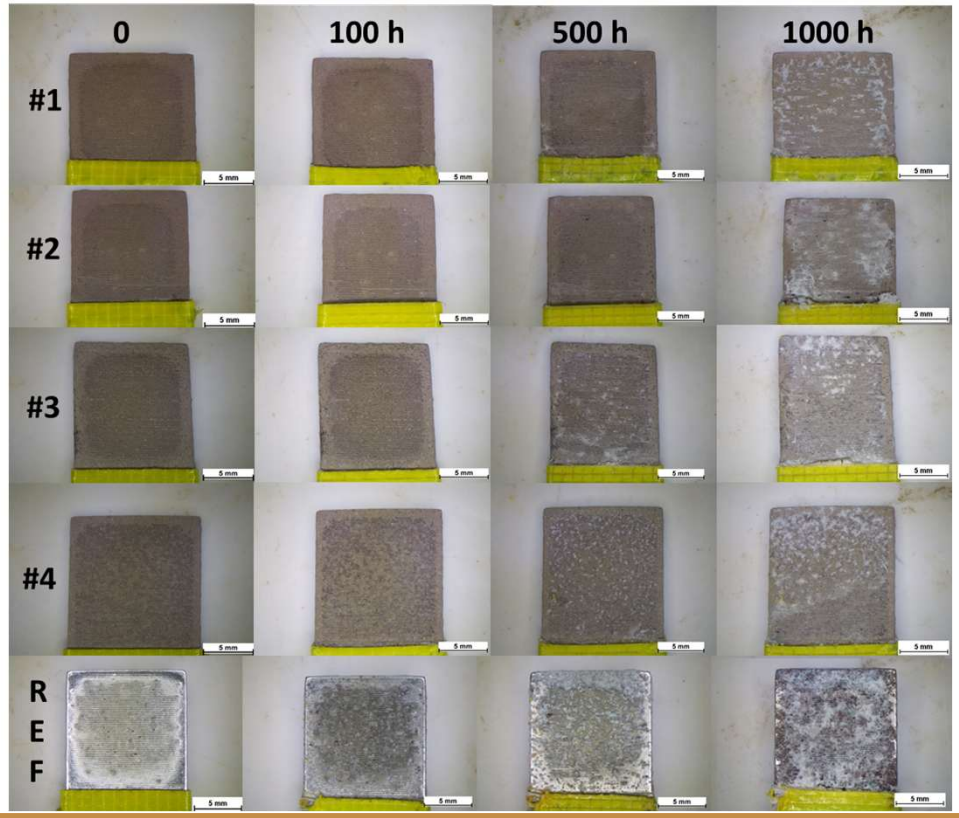
DILUTE ELECTROLYTE CYCLIC FOG/DRY TEST





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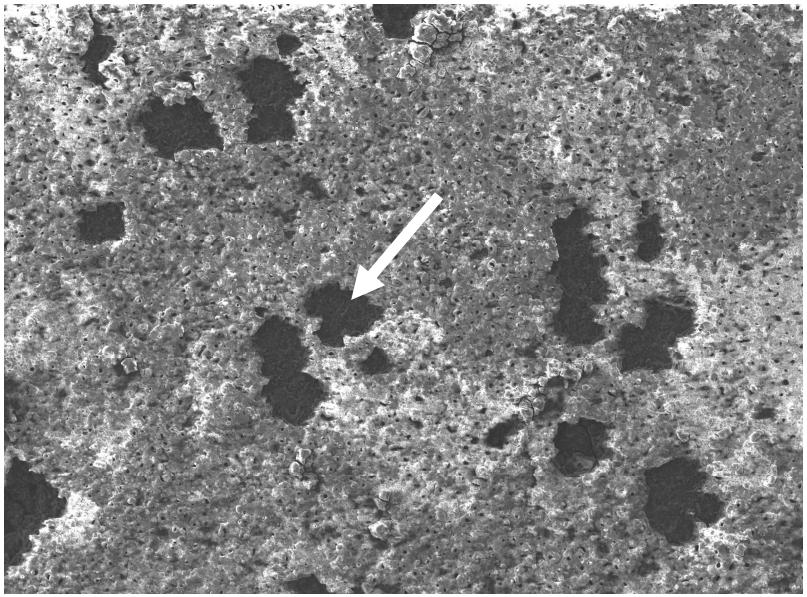
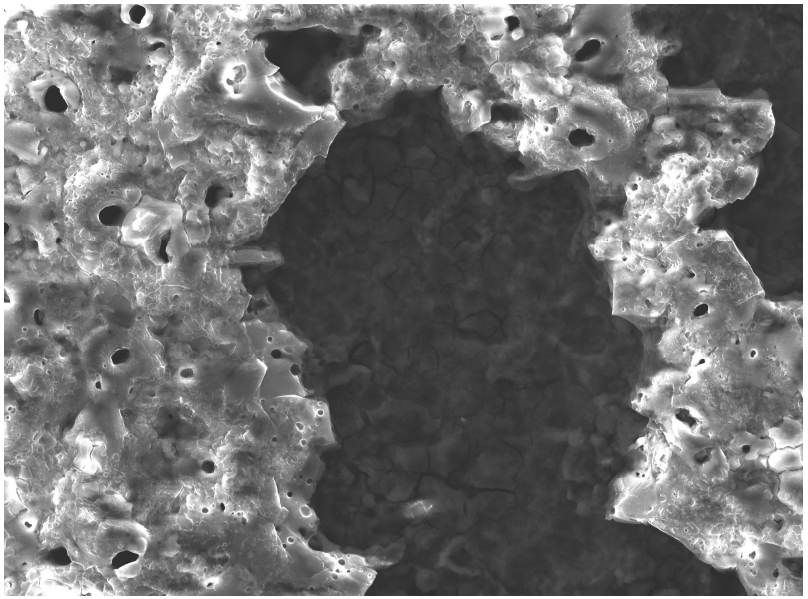
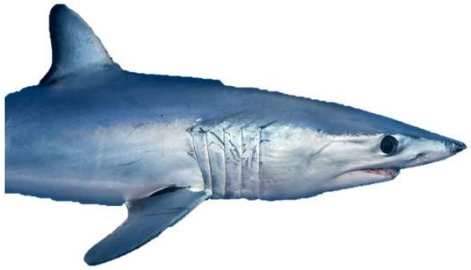
DILUTE ELECTROLYTE CYCLIC FOG/DRY TEST – COATING FAILURE





REMARKS



- **TMEMM** is an efficient method for aluminum alloys surface **texturing**
- The **PEO** coating accurately conforms to the **riblet profile**, while maintaining a **uniform thickness** along its surface
- The **PEO** coating enhances the **corrosion resistance**
  - ✓ The addition of **acetic acid** to the anodizing bath, combined with **LDH-based sealing**, further enhances the durability performance of the coated system
  - ✓ Greater **degradation** under dilute electrolyte **dry/fog cyclic test** than in salt spray.

Exploring the Corrosion Resistance and Microstructural Evolution of Textured Aluminum Alloys using TMEMM

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[2] Dipartimento di Ingegneria Industrale, Università di Trento

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