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TOHOKU UNIVERSITY

CORROSION DAMAGE AND DEGRADATION

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ELyT MaX

SOMMAIRE

1. PART 1. INTRODUCTION OF DAMAGE AND DEGRADATION

2. CORROSION BASIS

3. **CORROSION TESTING, MONITORING, INSPECTION**

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03

- **CORROSION TESTING, MONITORING AND INSPECTION**

CORROSION TESTING IN GENERAL

Main objectives :

- Evaluation and selection of materials or protection methods for specific environment / applications
    - Testing time sufficiently short
    - Test should be reliable
- General information about the behavior of materials in specific environment / applications
- Routine control for materials for acceptance or reclamation
- Investigation of corrosion mechanism (contribution to development of materials and anticorrosion solutions)

CORROSION TESTING IN GENERAL

Corrosion monitoring system characterisitics:

- User friendly. Simple to install, to use, to interpret
- Rugged. Able to withstand the normal use according to environment modifications
- Sensitive to onset of a corrosion problem while providing real time indication
- Accurate. Avoid false positive and négatives indications (intereferences)
- Maintainable. Probes are expected to foul in service. Minimum time in servicing operation is expected (simple and easy to perform)
- Cost effective. Less than the cost of the downtime

CORROSION TESTING IN GENERAL

Tests methods:

- Lab testing
  - Accelerated tests (more aggressive env. higher E, T, P….)
  - model test, tailor-made investigation (more realistic so limited acceleration tests)

- Service and field testing
  - Exposure coupons
  - Test specimes in process environments

- Pilot plant
  - True model for test appropriate design or material selection
  - Complex corrosion conditions

MONITORING AND INSPECTION

Continuous monitoring process plants (Common in petroleum and chemical industries)

One of the most important considerations is the choice of measuring probes positions :

- At abrupt changes in direction flow, pipe diameter, obstructions and irregularities…
- At crevices and areas with stagnant water
- At junctions of dissimilar metals (galvanic corrosion)
- Positions with high local stress, (T,P) fluctuations

➔ Position selection based on process, material, …

Handbook of corrosion engineering. P.R. Roberge (1999)

MONITORING AND INSPECTION

Corrosion rates and distribution not always predicted → be aware of the system evolution at any time

System requiring monitoring often more a less inaccessible for visual inspection

→ Quantitative methods to indicate the corrosion rate or/and the degree of protection

MONITORING TECHNICS

Assessment of corrosion in field conditions is complex.

Direct technique : measured parameters directly affected by the corrosion process

Indirect technique : provide data on parameter that either affect or affected by the corrosivity of the environment (solution, atmosphere, corrosion products…)

These techniques can be intrusive or not

MONITORING TECHNICS

Direct corrosion measurements techniques

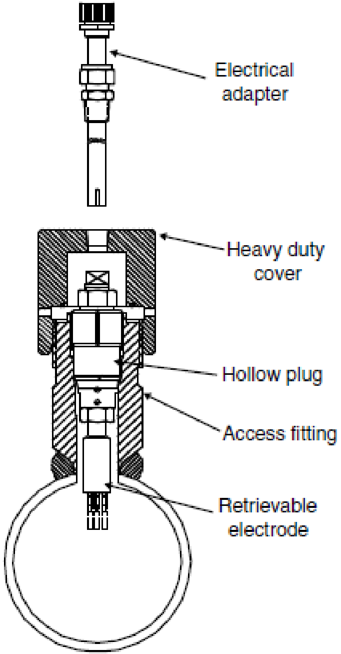
Intrusive

Physical

Electrochemical

Fig. 4.45 Close-up of corrosion sensing elements used for thin-film corrosion monitoring. (Courtesy Kingston Technical Software.)

Mass coupons
Electrical resistance
Visual inspection



Linear polarisation
ZRA (galvanic / same électrodes)
Potiodynamic or galvanodynamic
Electrochemical noise
Impedance spectroscopy

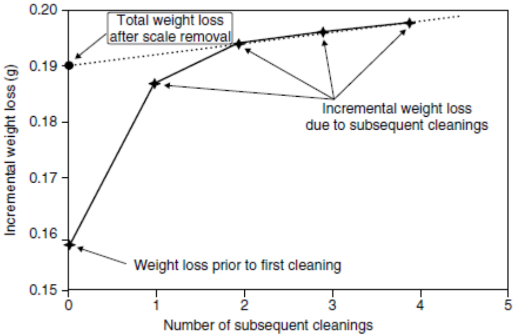


Fig. 4.26. Cleaning procedure of corrosion coupons for weight loss determination yields scale weight, total corrosion weight loss, and error due to cleaning procedure (24, 25).

Corrosion and corrosion control. R.W. Revie, H.H. Uhlig, (2007)

MONITORING TECHNICS (COUPONS OR SENSOR)

Testing Procedure (some of them are standardized):

- Selection and pre-treatment of materials and tests specimens
  - Specimen orientation (rolling direction, texture, surface, welds) → SCC, FC…
  - History of the material and also metallurgy along its volume
  - Specimen geometry
  - Size for reliable weight loss measurements
  -
- Surface preparation
  - Duplicate surface of the component in service (roughness, cleanliness…)
  - Usually necessary to deviate to get reproducible specimens
  - Avoid surface pollution.
  - degreasing
- Measurement of surface area, weighing
- Masking and exposure
- Inspection of specimens after exposure
- Determination of the corrosion rate

{ Oxygen concentration
pH
Salt concentration
Temperature
Humidity
Relative velocity

MONITORING TECHNICS (COUPONS OR SENSOR)

First look on Open circuit potential

Data from polarization curves or electrochemical measurement

recently local electrochemical measurement (µcell, SVET, LEIS) have been developed to discuss microstructure/reactivity

Linear polarization curves or Tafel slope (be aware of the limiting reaction)

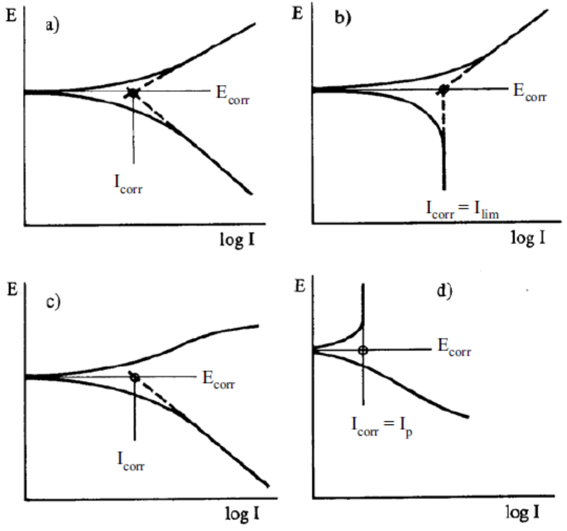
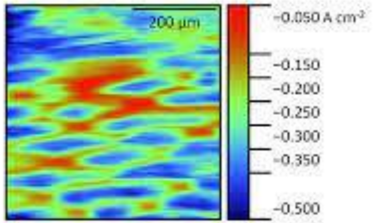


Figure 9.1 Determination of corrosion current density by extrapolation of linear parts of the polarization curves. a) Both the cathodic and the anodic reaction are under activation control (the overvoltage curves are Tafel lines). b) The cathodic reaction is diffusion controlled and the anodic reaction activation controlled. c) The cathodic reaction is activation controlled, the anodic curve is irregular. d) The cathodic curve is irregular, the metal is passive, i.e. the corrosion current equals the passive current.



Biologic.net/topics/svet101-an-introduction-to-the-scanning-vibrating-electrode-technique/
Corrosion and Protection. E Bardal (2004)

MONITORING TECHNICS

Direct corrosion measurements techniques

Non intrusive

Metal loss

U.S.
Eddy current
Radiography
Electrical field mapping

Defect detection

Acoustic emission
Ultrasonics (flaw detection)
Ultrasonics (flaw sizing)

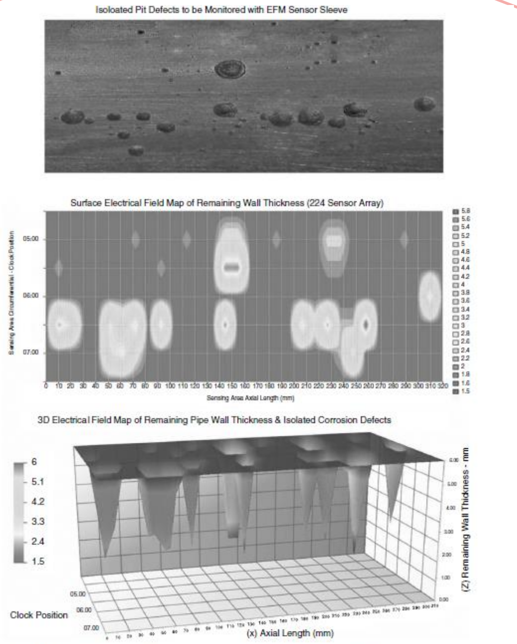


Fig. 4.58 Example of FSM results plotted as a three-dimensional (3D) map obtained on a pitted pipe using a 224 sensor array. (Courtesy of Eric Kubian, PinPoint Corrosion Monitoring Inc.)

Corrosion and corrosion control. R.W. Revie, H.H. Uhlig, (2007)

MONITORING TECHNICS

Indirect corrosion measurements techniques

On line

Corrosion products
Corrosion potential
Water chemistry
Fluid detection
T, P, dewpoint
Fouling
thermography

Off line

Water chemistry
Residual inhibitor (filming, reactant)
Chemical analysis on sample

NON DESTRUCTIVE EVALUATION

Recent improvement in methods for quality control, in-service inspection, development of new methods for diagnostics

NDE techniques → assess the component/system integrity without compromising its performances

Possible to use several inspection techniques (cost, schedule, maintenance…)

Table 5.2. Relative Cost and Requirement Ratings for the Main NDE Techniques

	Cost		Requirement		
	Inspection	Equipment	Skill	Process control	Process variance
Liquid penetrant	Low	Low	High	High	High
Magnetic particle	Low	Moderate	High	High	High
Radiography	Moderate	High	High	High	High
Manual eddy current	Low	Moderate	High	Moderate	Moderate
Automatic eddy current	Moderate	High	Moderate	High	Low
Manual ultrasonic	Low	Moderate	High	Moderate	Moderate
Automatic ultrasonic	Moderate	High	Moderate	High	Low
Manual thermo	Low	High	High	High	Moderate
Automatic thermo	Low	High	Moderate	High	Low

Corrosion and corrosion control. R.W. Revie, H.H. Uhlig, (2007)

NON DESTRUCTIVE EVALUATION

Dominant sources of variance in NDE procedure application

Table 5.1. Dominant Sources of Variance in NDE Procedure Application

	Materials	Equipment	Procedure	Calibration	Criteria	Human factors
Liquid penetrant	X		X			X
Magnetic particle	X	X	X			X
Radiography	X	X	X			X
Manual eddy current		X	X	X	X	X
Automatic eddy current		X	X	X	X	
Manual ultrasonic		X	X	X	X	X
Automatic ultrasonic		X	X	X	X	
Manual thermo—		X	X	X		X
Automatic thermo		X	X	X	X	

Corrosion and corrosion control. R.W. Revie, H.H. Uhlig, (2007)

NON DESTRUCTIVE EVALUATION

Each method is dependent on specific understanding and control of series of parameters

- Material composition (magnetic, nonmagnetic, metallic, …)
- Part size thickness, geometry
- Material condition (heat treatment, grain size, residual stresses)
- Fabrication method (casting, forging, weld, …
- Surface condition (rough, plated, bright, scaled
- Nature or use of the part (critical or not, high or low stress)
- Inspection scanning rate
- Humas factors

04

- **CORROSION PREVENTION**

INTRODUCTION

Five main principle to be applied

- Appropriate material selection
- Change of environment
- Suitable design
- Electrochemical cathodic / anodic protection
- Application of coatings

MATERIAL SELECTION

Component considered with respect of design, manufacture, total geometry

Adjacents components may be compatible → galvanic corrosion

(structural component, insulating…)

➔ Final materials selection result of compromises

Table 10.1 Some natural combinations of environment and material [10.1].

Environment	Material
Nitric acid	Stainless steels
Caustic solutions	Nickel and nickel alloys
Hydrofluoric acid	Monel
Hot hydrochloric acid	Hastelloys (Chlorimets)
Dilute sulphuric acid	Lead
Non-staining atmospheric exposure	Aluminium
Distilled water	Tin
Hot, strongly oxidizing solutions	Titanium
Ultimate resistance	Tantalum
Concentrated sulphuric acid	Steel

Check lists including :

- risk of corrosion
- condition affecting each form of corrosion
- possibility in corrosion form changing
- possibility in corrosion protection application method
- environmental condition …

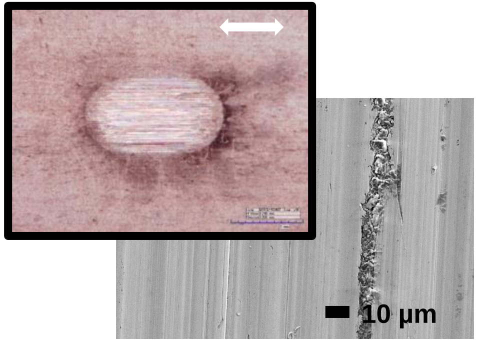
Non metallic materials may be also considered (polymer, ceramic…)

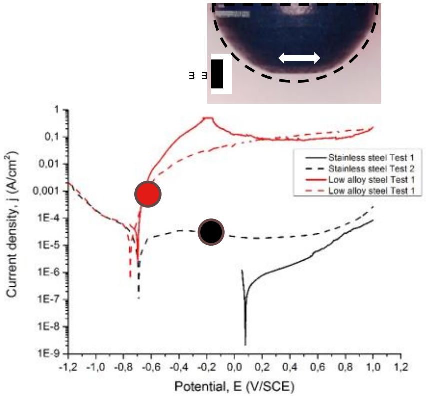
Corrosion and Protection. E Bardal (2004)

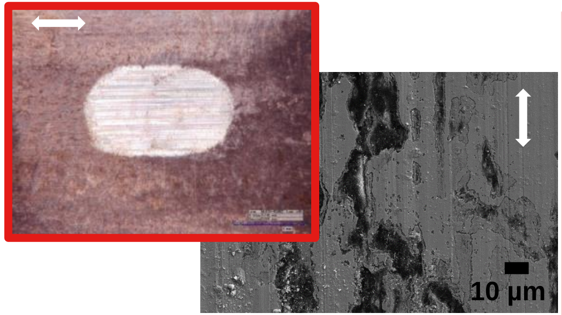
MATERIAL SELECTION (EXAMPLE)

Carbon steel or stainless steel againts tribocorrosion in carbonate media

Stainless steel







Carbone Steel

$Fe\ (s) \rightarrow Fe^{2+}\ (aq) + 2e^-$
$Cr\ (s) \rightarrow Cr^{3+}\ (aq) + 3e^-$
$Fe^{2+} + \mathbf{Cr^{3+}} + CO_3^{2-} \rightarrow \mathbf{[Fe, Cr]CO_3}$

$Fe\ (s) \rightarrow Fe^{2+}\ (aq) + 2e^-$
$Fe^{2+}\ (aq) + CO_3^{2-} \rightarrow FeCO_3$

Total wear volume
$(0.19 \pm 0.02)\ \times 10^{-4}\ mm^3.N^{-1}.m^{-1}$

Total wear volume
$(0.18 \pm 0.02)\ \times 10^{-4}\ mm^3.N^{-1}.m^{-1}$

Different material but repassivation behaviour similar (carbonate solution effect)
Wear volume identical + polymer pin deformation
Risk of pitting in the case of DSS and general dissolution for CS.

CHANGE OF ENVIRONMENT

Not always possible !!!

To reduce corrosion rates:

- Decreasing or increasing the temperature
- Decreasing or increasing the flow velocity
- Decreasing or increasing the content of oxygen or aggressiveness species
- Adding inhibitor

Corrosion and Protection. E Bardal (2004)

SUITABLE DESIGN

Majority of corrosion forms affected by the geometry (galvanic, crevice, erosion…)

Here some general guidelines

- Design with sufficient corrosion allowance
- Component easy to replace
- Easy drainage for atmospheric corrosion
- Avoid hot / cold spot
- Minimize the consequences of corrosion on surroundings
- Drive corrosion to less critical parts
- Avoid sharp edges and irregularities
- …

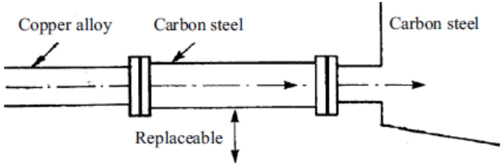


Figure 10.6 The part with highest corrosion rate should be easy to replace.

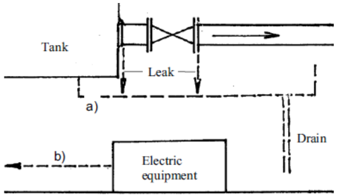


Figure 10.9 Avoiding serious damage due to leakage by a) using a tray for collecting drips or b) moving sensitive equipment to a safer possition.

Corrosion and Protection. E Bardal (2004)

CATHODIC PROTECTION

Cathodic protection :

- Impress an external current to force the electrode to move down its immune region (general corrosion)
- Or below its corrosion pitting/crevice potential

External current produced :

- Less noble material (sacrificial electrode → galvanic coupling)
- External current source

Potential selection avoid : cathodic disbanding (coating) or Hydrogen embrittlement

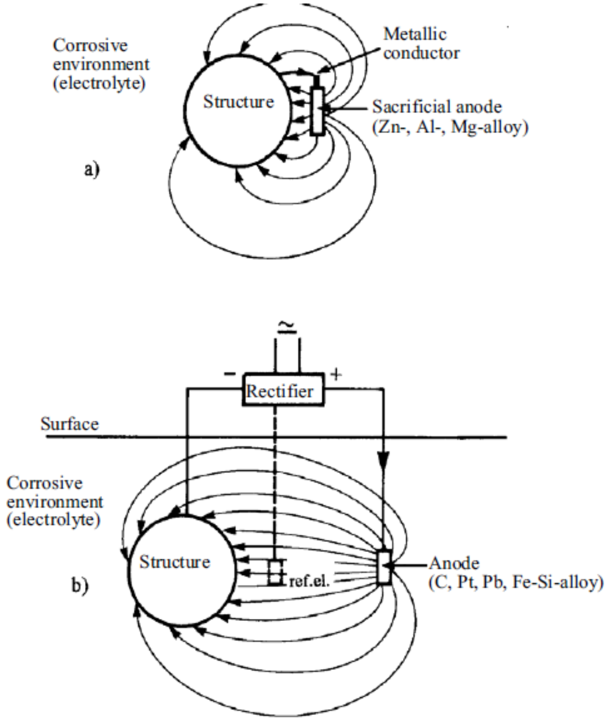


Figure 10.13 Cathodic protection by a) sacrificial anodes and b) impressed current.

Corrosion and Protection. E Bardal (2004)

COATING

Coating acts on either :

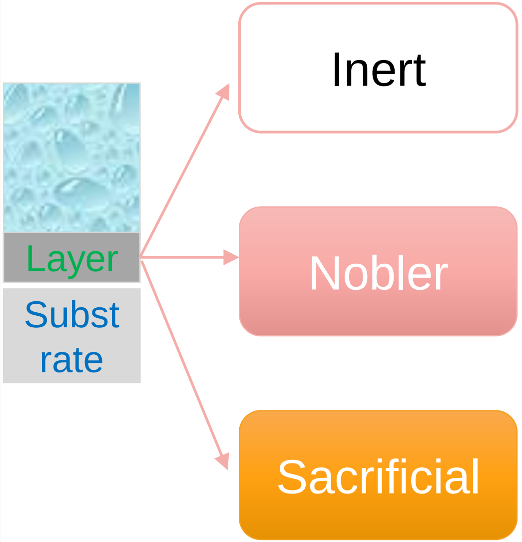
- Barrier effect
- Cathodic protection
- Inhibition / passivation including anodic protection

Coating can be

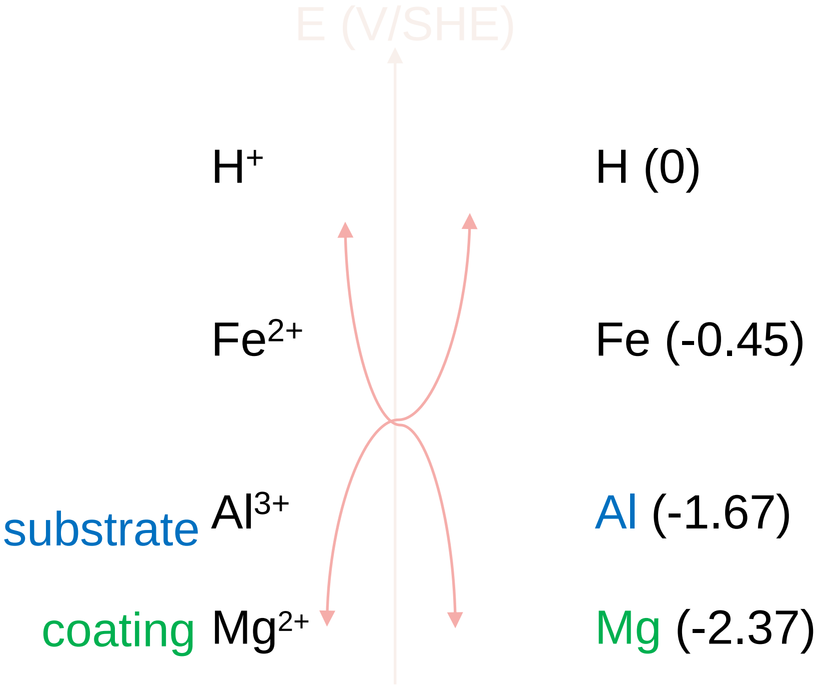
- Metallic
- Inorganics (oxides, nitrides, borides)
- Organics (epoxy resign, paints,

Corrosion and Protection. E Bardal (2004)

INTRODCTION



-Lower potential than the covered material
-Dissolution of coating protect substrate



Fe protected
Dissolution of Al or Mg coating : thickness decrease

TOWARD APPLICATION CASE

Cold spray for ductile metals: plastic deformation of particles to create hydrodynamic shear instability that bonds particles between them

Geometry of particles is also a key point : spherical particles undergo higher level of plastic deformation than flattened shapes even if they have lower in-flight velocity

Co deposition is used to go out some limitations (wear resistance)

Coating with metallurgical heterogeneties (dual phase microstructure)

TOWARD APPLICATION CASE

SiC size

Ratio SiC/Al5056

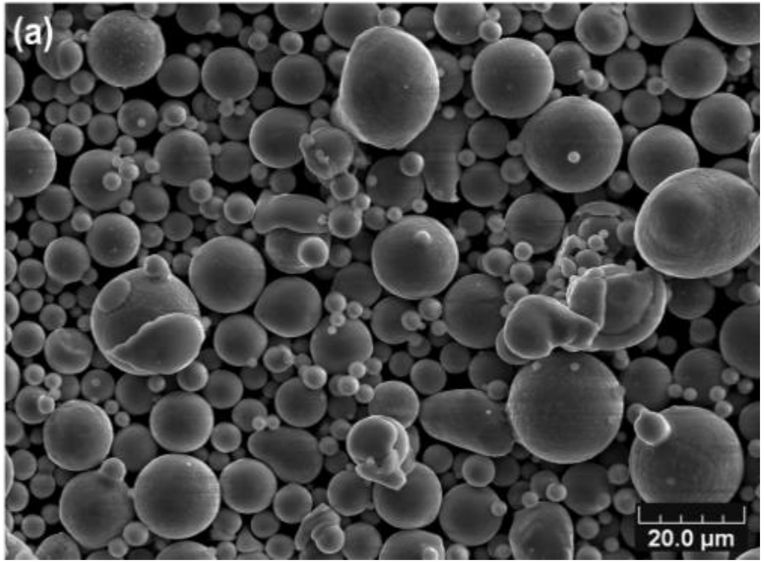
Best corrosion performances

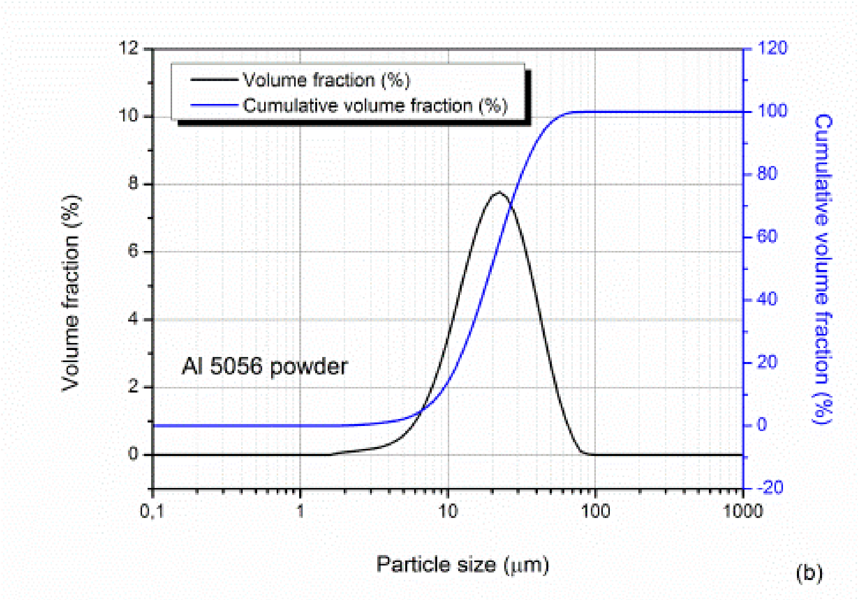
- metallurgical description of powders
- Coating crystallography
  Roughness
  Composition
  Porosity

Al5056-SiC coating // Aluminum substrate

POWDERS

Al5056 powder (coating matrix)



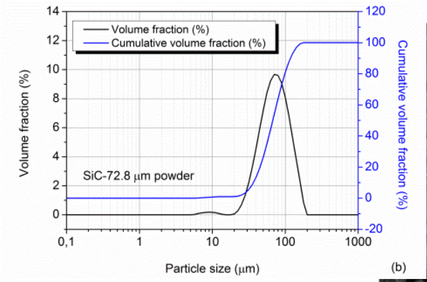


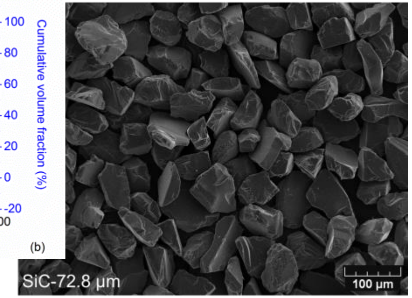
Spherical geometry with size distribution around 20 µm
FCC crystallographic structure
No oxide detected by XRD (native oxide only)

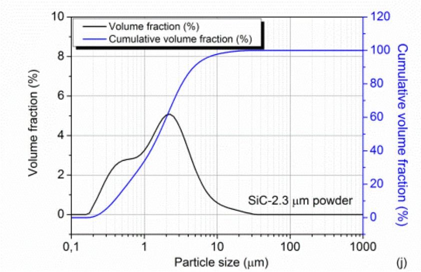
POWDERS

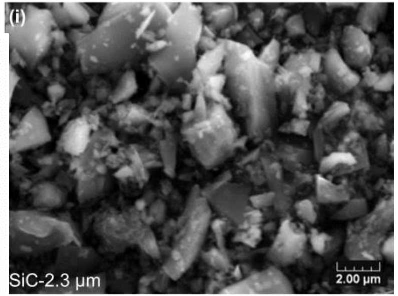
SiC particles with Volumic fraction (0%, 15%, 30% and 60% volumic)

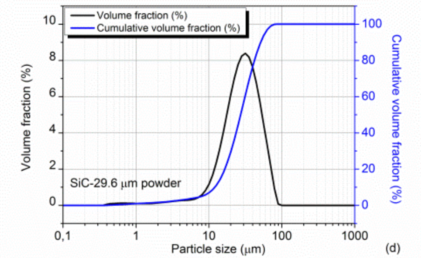
From ~70 µm to ~3 µm !

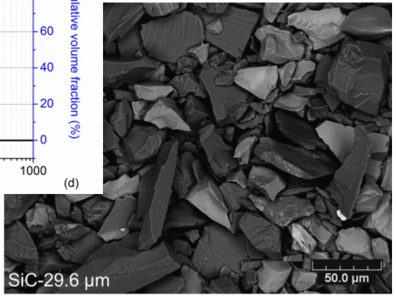


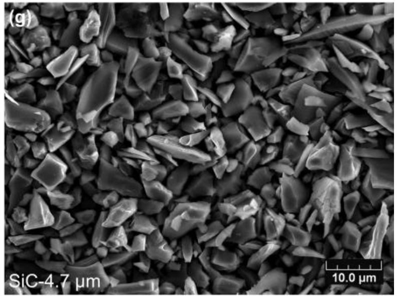


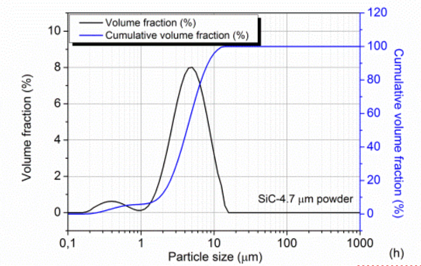










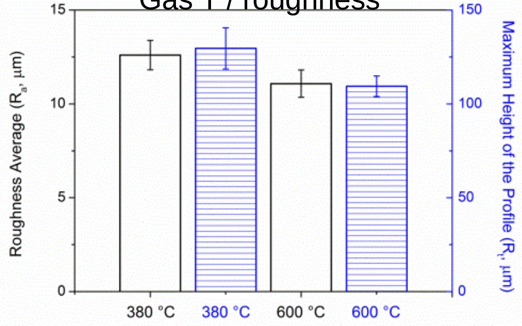


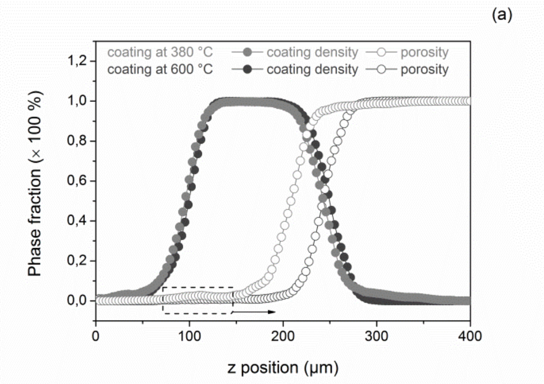
DEPOSITION

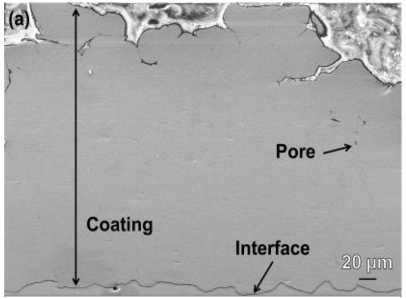
Al substrate with blend coating : Al5056 + SiC particles

Co deposition parameters optimization in PhD Thesis of Y. Wang (INSA Lyon 2015)

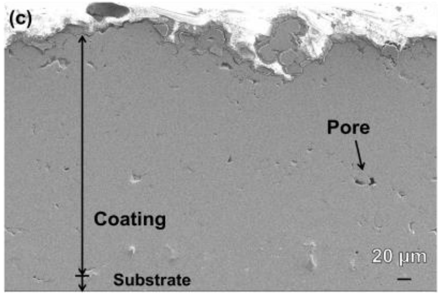
Gas T / roughness



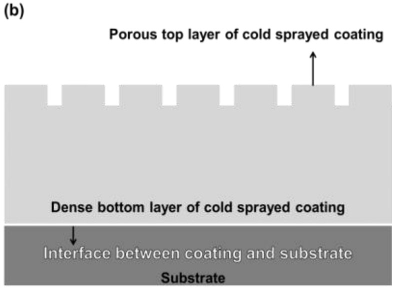


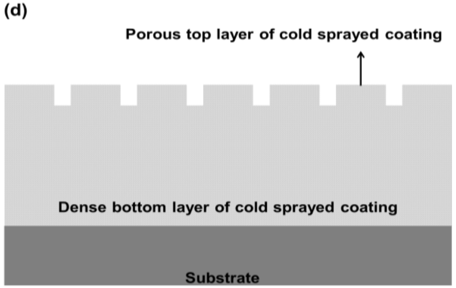


Microstructure 380°C



Microstructure 600°C

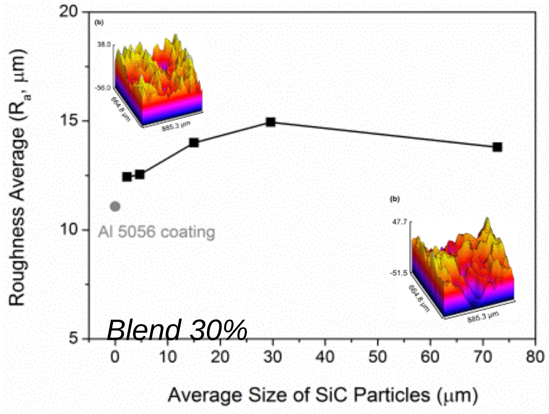


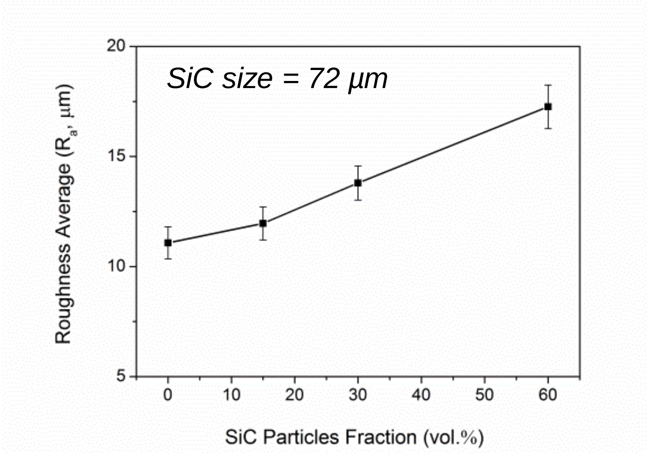


SURFACE ROUGHNESS

SiC size

Ratio SiC/Al5056





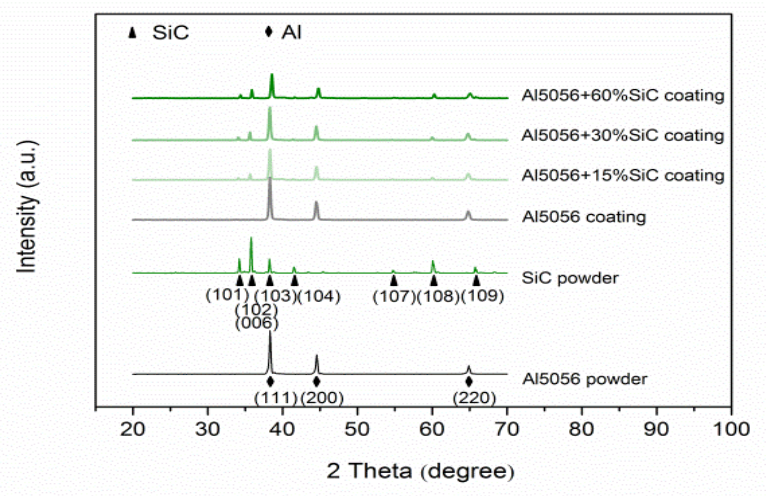
Roughness linearly increases with SiC fraction

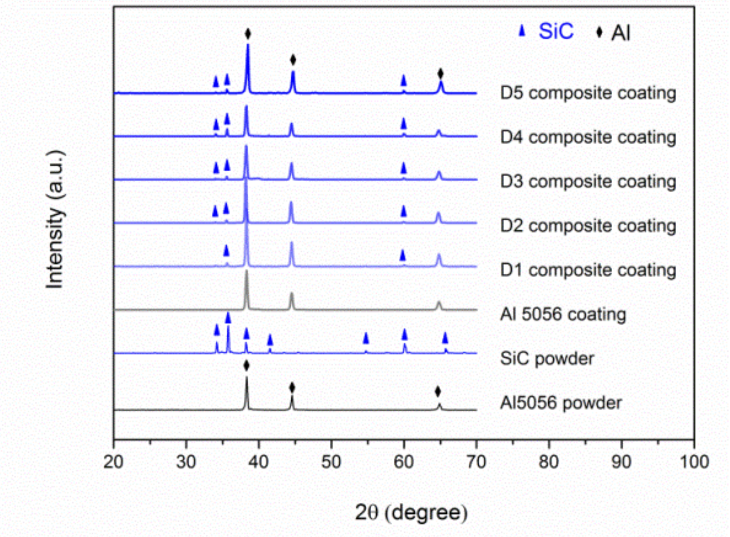
Maximum roughness for SiC θ=30µm

SURFACE ROUGHNESS

SiC size

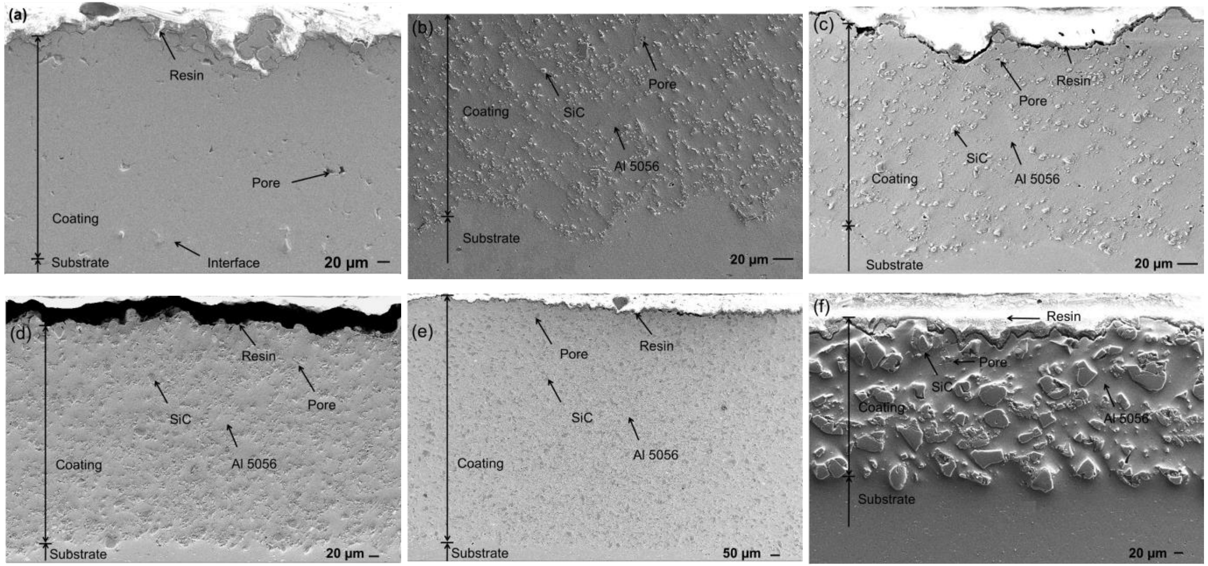
Ratio SiC/Al5056

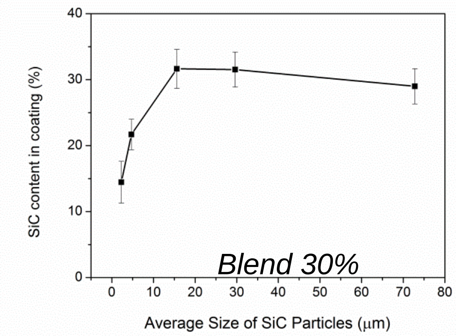




No oxides microstructures
Quantification of SiC

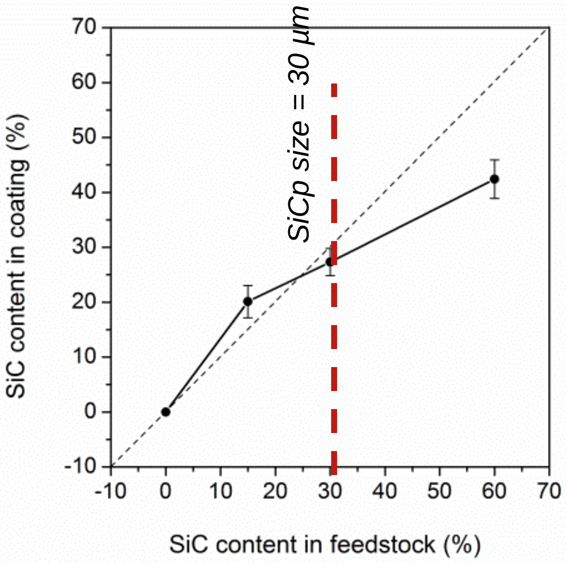
COATING COMPOSITION MICROSTRUCTURE

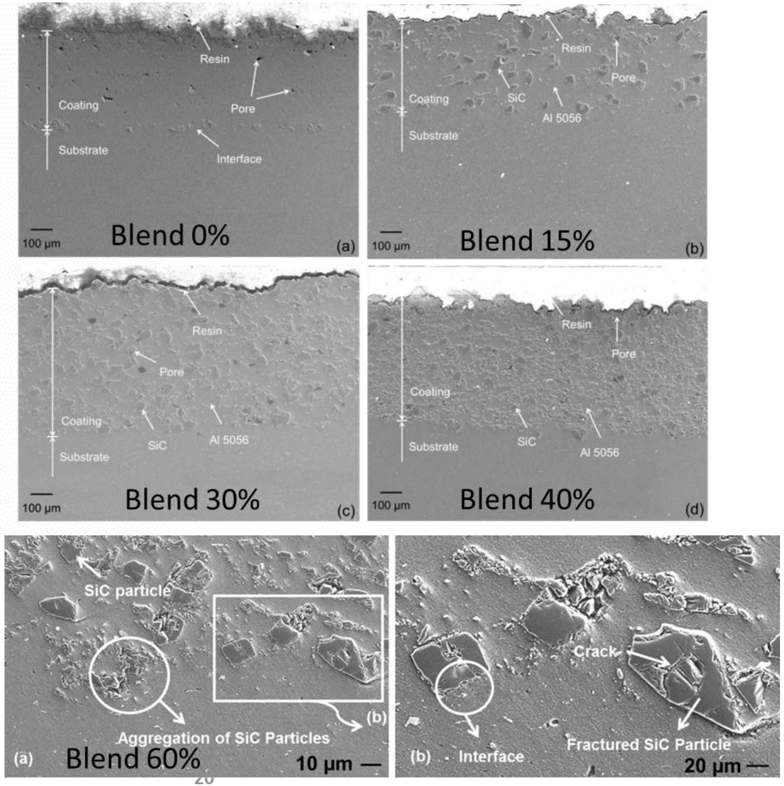




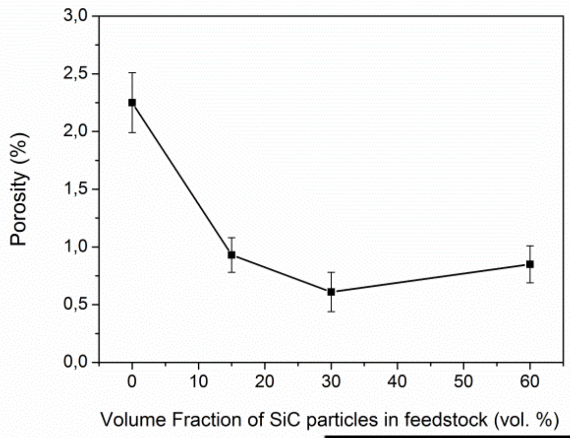
SiC content = SiC blend for SiC size > 20 µm

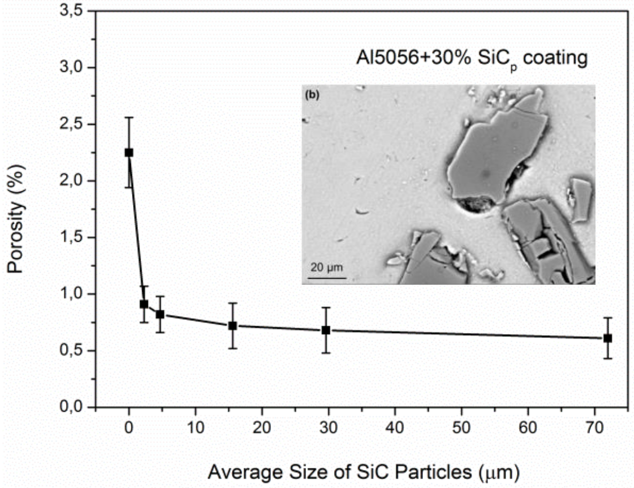
COATING COMPOSITION MICROSTRUCTURE

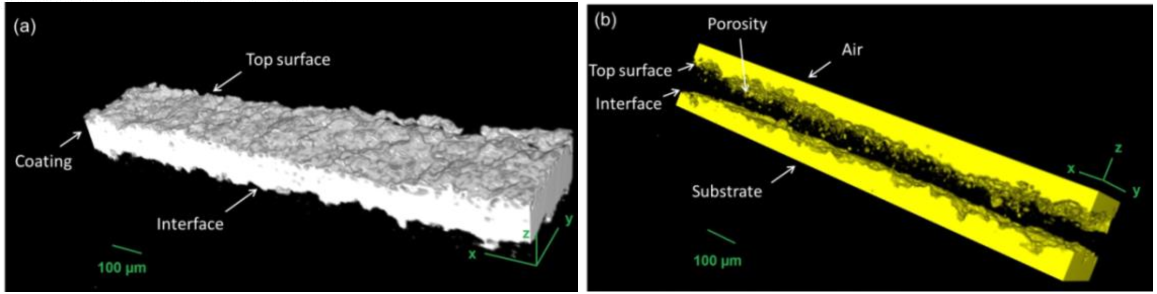




COATING POROSITY







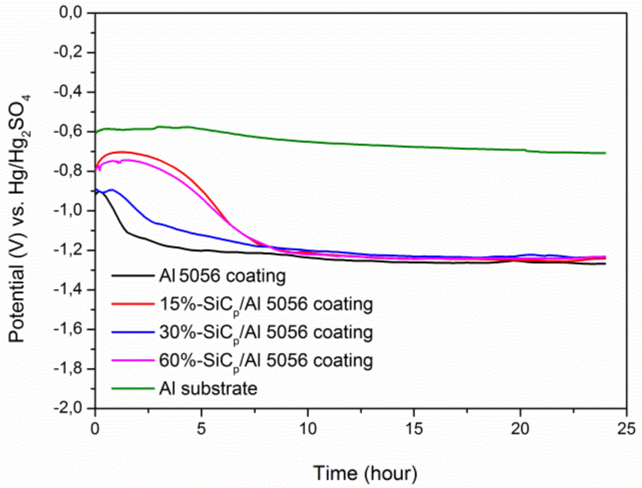
Porosity decrease with SiC
Minimum porosity with SiC 30%
No connected pores

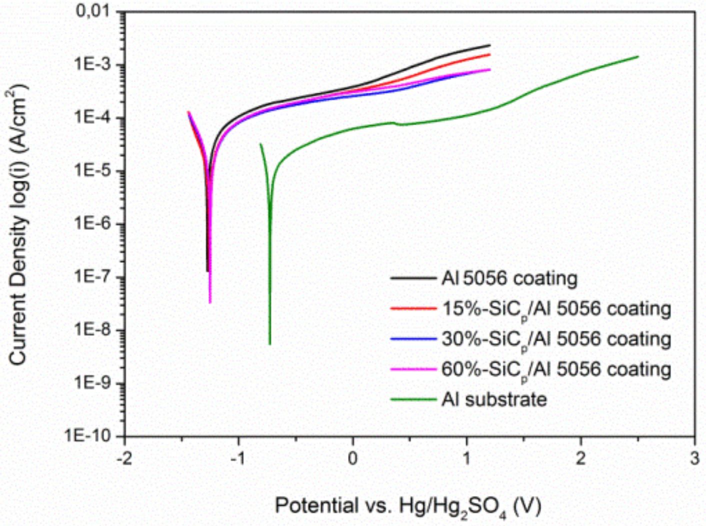
COATING SUM-UP

- Dense aluminum coatings with process gas temperature of 380 °C and 600 °C.
- Pores are micro-sized and non-connected in cold sprayed aluminum coatings.
- Higher gas temperature results in lower surface roughness, lower porosity and better adhesion to substrate.
- Addition of SiC particles in aluminum iimproves surface roughness.
- Addition of SiC particles reduces porosity.
- Addition of SiC particles results in better adhesion.
- Porosity of cold sprayed aluminum based composited coatings decreases with SiC size.

30%-SiCp/Al 5056 composite coating shows the lowest porosity and good compromize

COATING CORROSION





Coatings more cathodic (sacrificial)

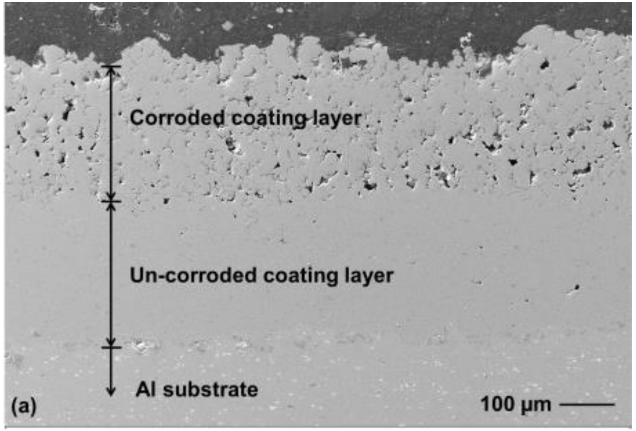
No influence of SiC % (size and content)

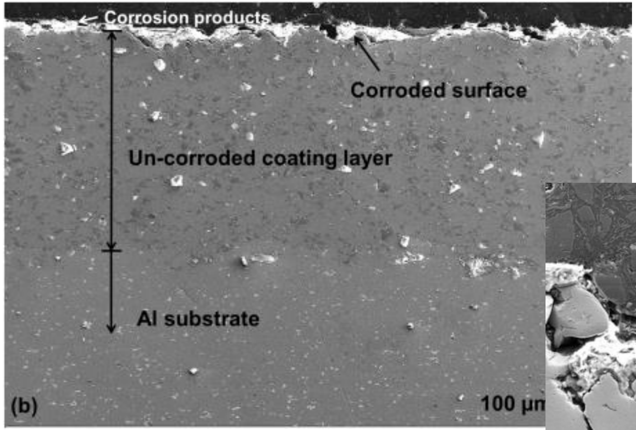
No passivation = no strong oxide film

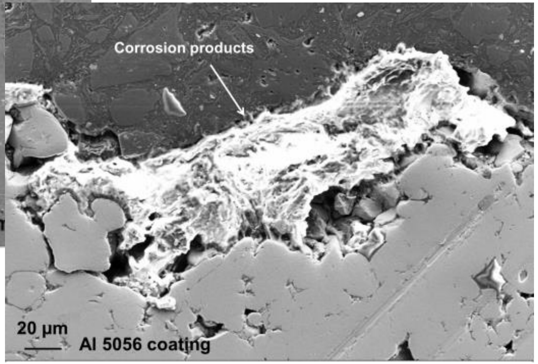
More rouhgness/waviness = more reactivity

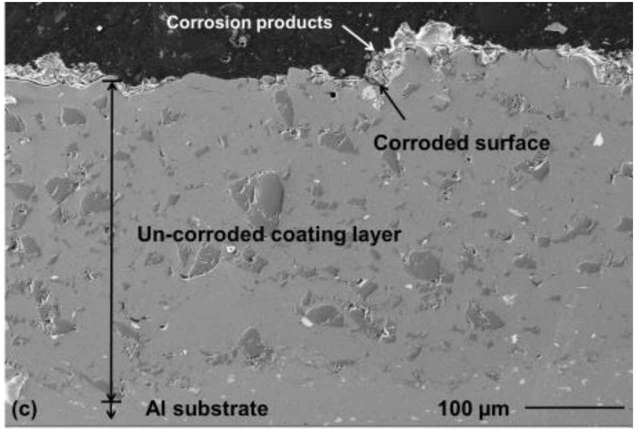
No effect of SiC in coating

COATING CORROSION







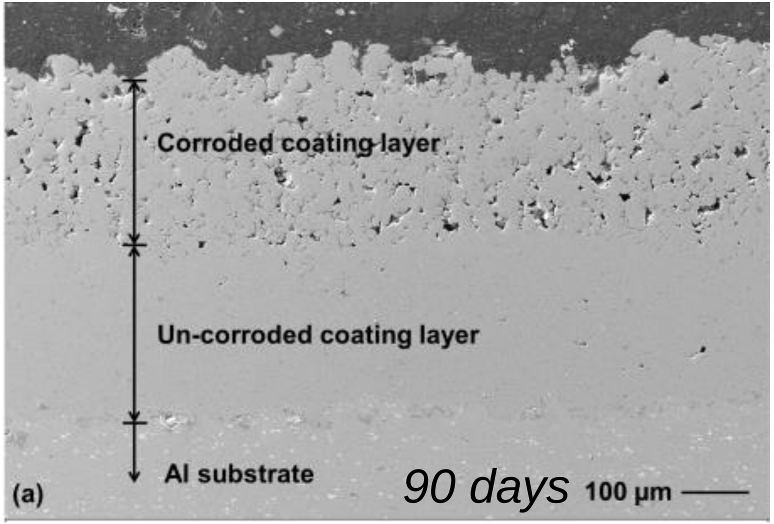


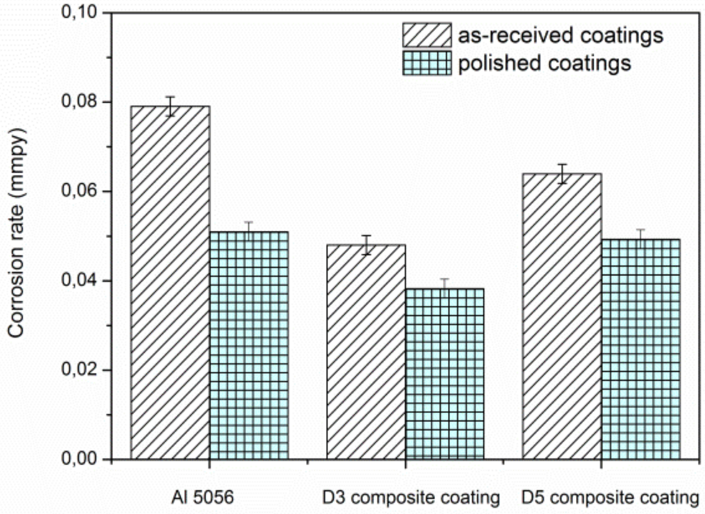
After 90 days in solution: propagation of corrosion

-20% of coating for Al5056

- Limited to surface with addition of SiC

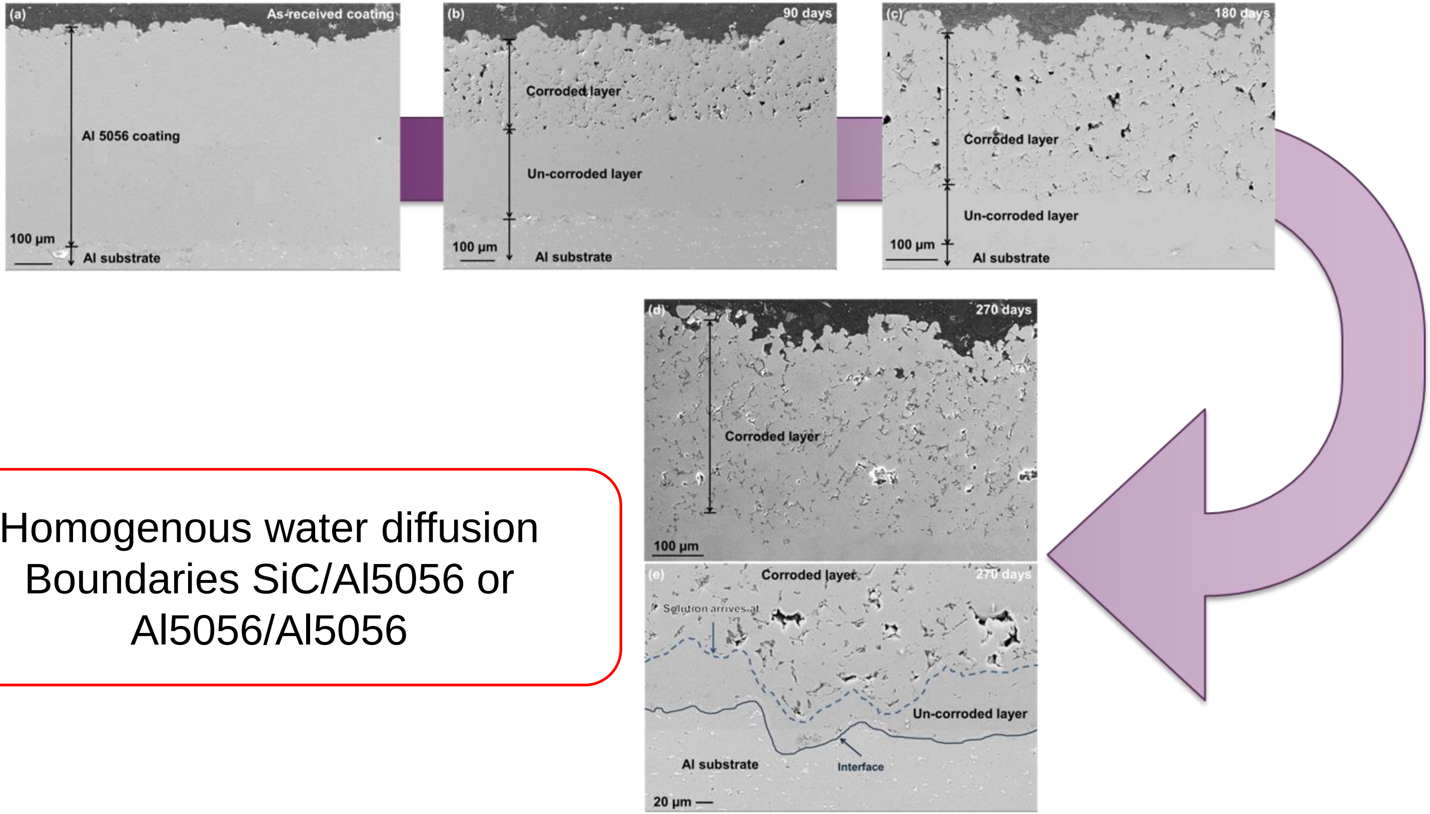
COATING CORROSION





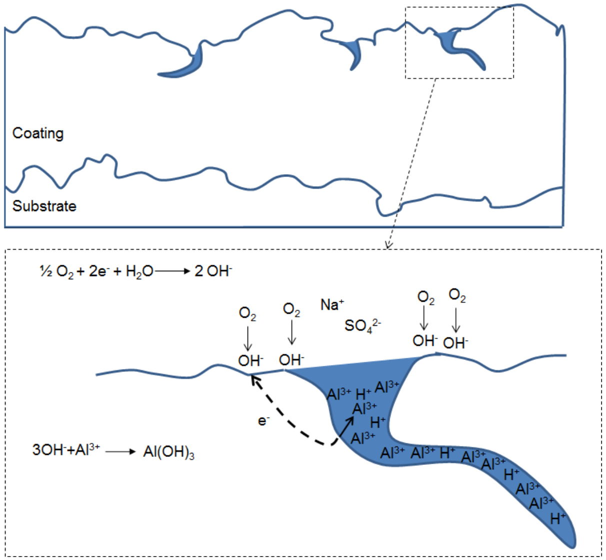
Corrosion reduction by surface roughness/waviness

COATING CORROSION

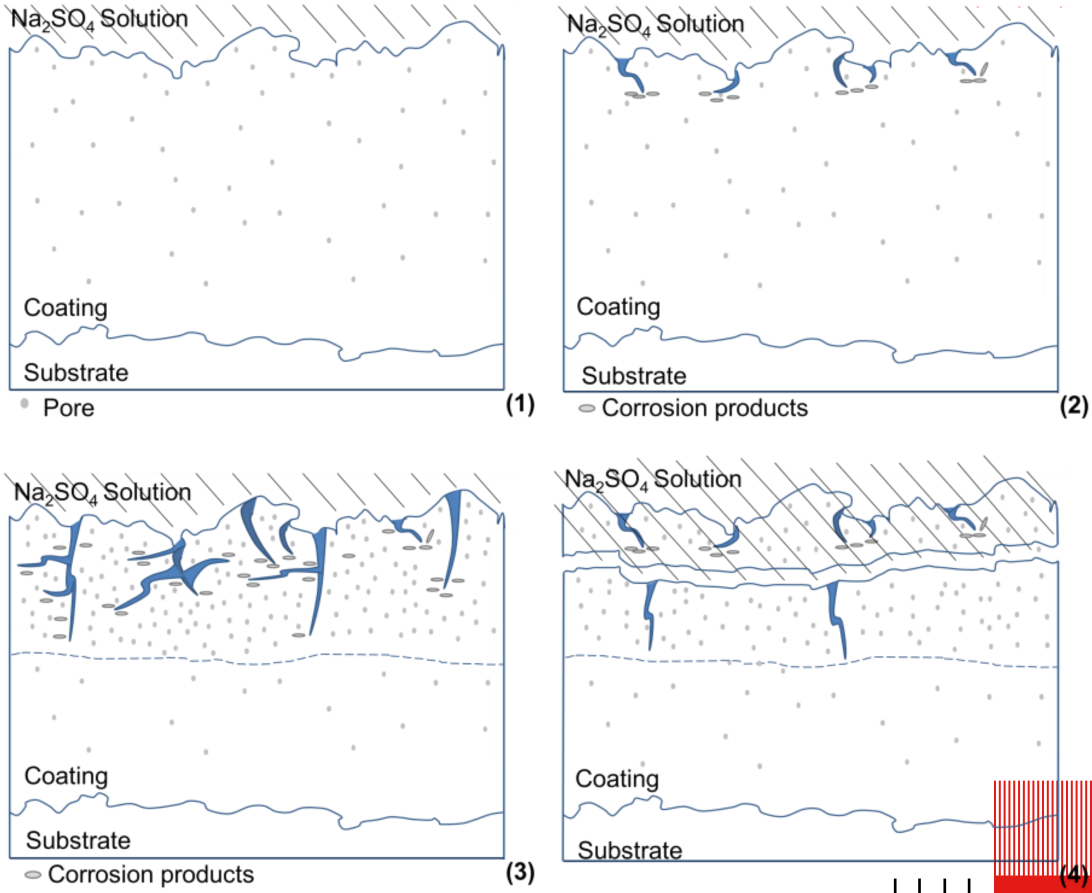


Homogenous water diffusion
Boundaries SiC/Al5056 or
Al5056/Al5056

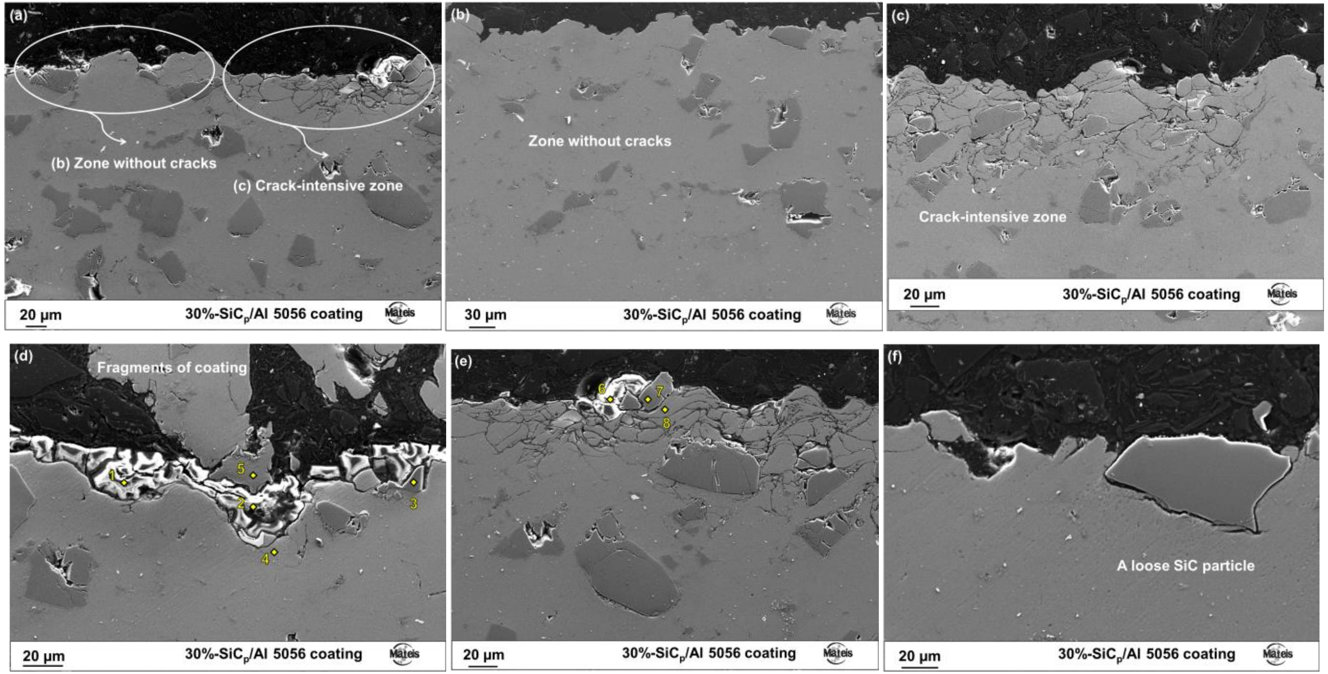
COATING MECHANISMM



After Fontana



COATING MECHANISMM



Corrosion initiation induced by surface roughness/waviness

COATING MECHANISMM