

## Autolab Application Note COR09

# Electrochemical impedance spectroscopy of three coated aluminum samples

### Keywords

Corrosion, aluminum, aluminum oxide, coating, electrochemical impedance spectroscopy, fit and simulations.

### Introduction

Electrochemical impedance spectroscopy (EIS) is a powerful technique used to investigate the linear response of a system perturbed by an alternating potential (potentiostatic EIS) or current (galvanostatic EIS). For an introduction on this technique, the reader is kindly invited to read the application notes EIS01 – EIS06.

EIS has been widely applied in corrosion science and technology, to obtain information on the polarization resistance and time constants of the corrosion processes [1-4]. Besides, experimental data are fitted with equivalent circuits, which give a deep understanding of the corrosion processes. Examples of such circuits are shown in the application note COR04.

One of the most successful protections against corrosion is the application of coating layers on metal surfaces. The coating industry relies on various techniques to test the quality of their coatings. Among all, EIS is one of the most interesting techniques, since it is relatively fast and non-destructive.

In this application note, EIS is applied on three coated aluminium samples, before and after the stepwise dissolution measurement (SDM). This technique has been reviewed in the application note COR08.

### Experimental Setup

Three sheets of coated aluminum have been tested. All of them have a thin coating of aluminum oxide,  $\text{Al}_2\text{O}_3$ . Two of them present one further coating layer. The exact composition of the coatings was not made available. Therefore, further in the text, we will refer to them as “pink” and “gold” coatings. Each sheet was punched to obtain disks of 1.5 cm diameter, to fit the sample holder of the Autolab 1 L corrosion cell, shown in Figure 1. One side of each sample was polished with sandpaper, to remove the coating layers and to assure good electrical contact with the sample holder. All measurement were carried out in artificial seawater,

obtained by dissolving 33 g of NaCl in one liter of Millipore water. A stainless steel counter electrode and an Ag/AgCl 3M KCl reference electrode completed the three-electrode setup. In this note, all potentials are quoted with respect to this reference electrode. The electrodes were connected to an Autolab PGSTAT204, equipped with a FRA32M impedance module, shown in Figure 1.



Figure 1 - The 1 L corrosion cell and the PGSTAT204 with the FRA32M module

### The procedure

The EIS measurements have been carried out before and after the SDM. A 10 mV (rms) amplitude signal has been superimposed to the OCP, with a frequency range from 100 kHz to 10 Hz, with a logarithmic frequency step and 10 frequencies per decade. The data before and after the SDM have been compared and fitted with suitable equivalent circuits.

### The equivalent circuits

In order to determine the proper equivalent circuit, a deep understanding of the system is necessary. Here, a description on different coating types and their relative equivalent circuits is given [5].

In the ideal case, the non-conductive coating adheres perfectly to the metal substrate, with no surface imperfections and a flawless metal-coating interface. This situation results in a so-called blocking electrode, described by an equivalent circuit with the uncompensated resistance  $R_{\Omega}$  in series with the capacitance of the coating layer  $C_L$ , like in Figure 2.

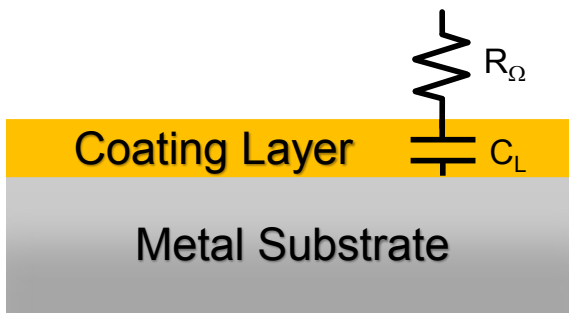


Figure 2 – Ideal, flawless non-conductive coating on a metal substrate and corresponding  $R_{\Omega}C_L$  equivalent circuit

However, in real life, a coating with imperfections is the actual situation. Such flaws can be a non-perfect coverage of the substrate, as shown in Figure 3, where the coated area, represented by the above-mentioned  $R_{\Omega}C_L$  circuit, is exposed together with a non-coated surface, modelled by a double layer capacitance  $C_{dl}$  in parallel with a faradaic impedance  $Z_f$ . The resulting equivalent circuit is shown also in Figure 3.

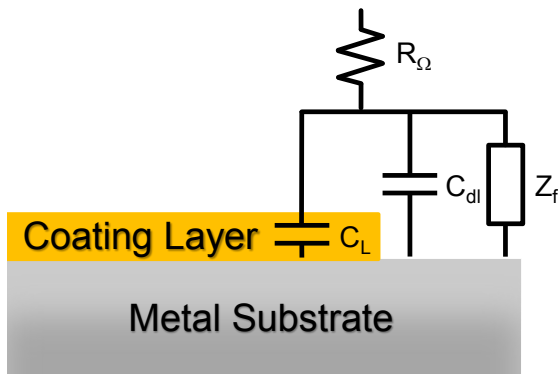


Figure 3 – A metal substrate partially coated, with the respective equivalent circuit

Pores present in the surface are also imperfections of the coating layer. A pore can be considered as a non-coated portion of substrate, like in Figure 3, but with a size so small that the exchange of the electrolyte between the pore and the bulk is hampered. Therefore, the ion concentration inside the pores could differ from the bulk concentration. This results in an electrolyte resistance  $R_L$  different from the bulk electrolyte resistance  $R_{\Omega}$ . In Figure 4, the presence of the pores is shown, together with the respective equivalent circuit.

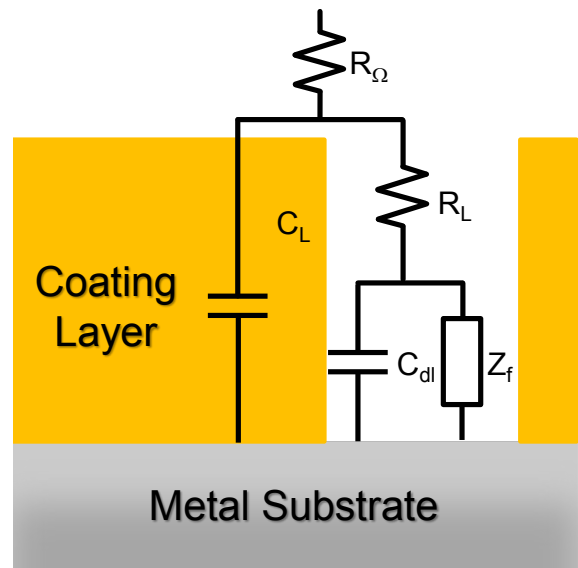


Figure 4 – A porous non-conductive coating layer, with the resulting equivalent circuit

Finally, the presence of an outer layer of coating, placed on top of the first layer, is taken into consideration. This top layer adds a second interface, modelled with a further resistance  $R_{L2}$ , in parallel with a double layer capacitance  $C_{L2}$ . The system and the resulting equivalent circuit are shown in Figure 5.

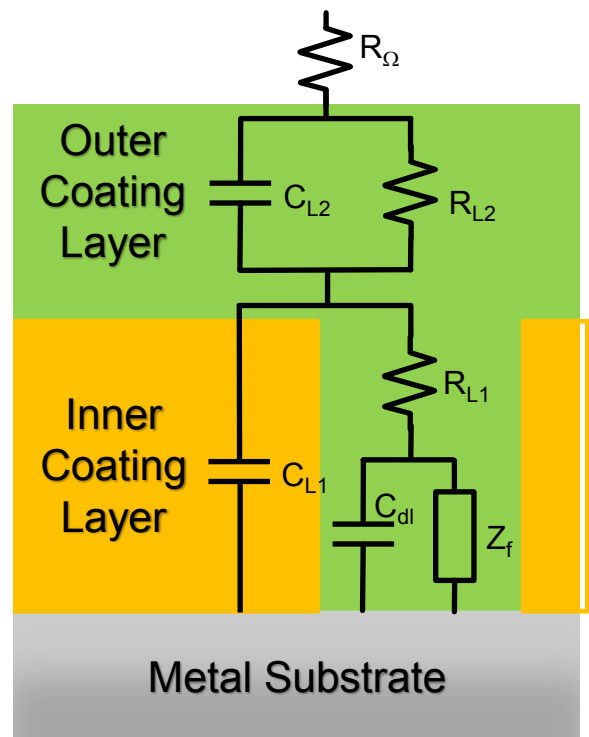


Figure 5 – Two porous non-conductive coating layers, with the equivalent circuit

Regarding the impedance  $Z_f$ , it is important to know the composition of the coating layers and their behavior when exposed to the electrolyte, in order to choose the proper circuit element. Examples of such elements are the constant phase element, and the Warburg diffusion element.

### Results and discussion

In all the measurements, the presence of pores has been taken into consideration. For the fitting of the data collected before the SDM, the equivalent circuits mentioned in the previous section has been considered. For the oxide-coated sample, the equivalent circuit in Figure 4 has been chosen and, for the gold-coated and pink-coated samples, the equivalent circuit in Figure 5 has been used. Due to the unknown nature of the coatings, the impedance  $Z_f$  has been chosen according to the best fit obtained.

In the following sections, the Nyquist plots of the three samples are presented, before and after the SDM, respectively. For each Nyquist plot, the blue dots represent experimental data and the black line is the corresponding fit, performed with the equivalent circuit drawn in the top left corner of the plot. Only the choice of the equivalent circuits, in relation with the experimental data and with the above-mentioned models will be discussed. The values of the circuit elements will not be part of the discussion.

#### Aluminum oxide

In Figure 6, the Nyquist plot of the oxide sample before the SDM is shown. The chosen equivalent circuit resembles the one used to model the presence of pores in the coating (Figure 4).

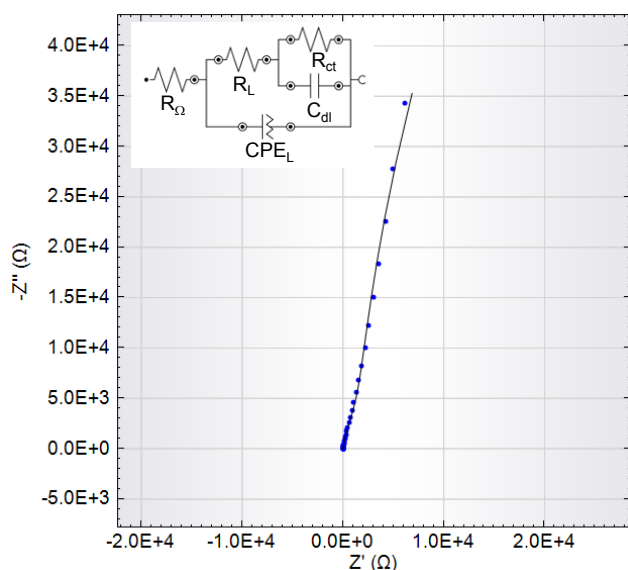


Figure 6 – Nyquist plot of the oxide sample, before the SDM

The double layer capacitance  $C_L$  of the oxide layer has been replaced with a constant phase element ( $CPE_L$ ), to take into account the roughness of the surface. The general impedance  $Z_f$  has been found to be close to a charge transfer resistance  $R_{ct}$ .

After the SDM, i.e., after the corrosion process, the Nyquist plot of the oxide sample (Figure 7) presents a 45° line at low frequencies, which could be addressed to the ion diffusion inside the pores and fit with a Warburg element. The ions could be a product of the corrosion process.

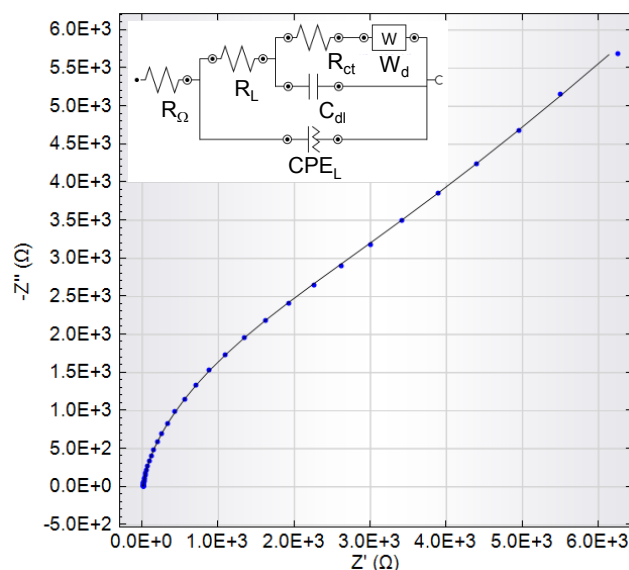


Figure 7 – Nyquist plot of the oxide sample, after the SDM

#### Gold-coated aluminum

In the case of the gold-coated sample, a two-layer coating model has been chosen since the gold coating has been applied above the oxide layer. This results in the Nyquist plot shown in Figure 8. The best fit has been performed with capacitors instead of CPEs, so influenced the roughness of the surfaces looks negligible. The general impedance  $Z_f$  was chosen to be an interface, with the charge transfer resistance  $R_{ct}$  in parallel with the double layer capacitance  $C_{dl}$ .

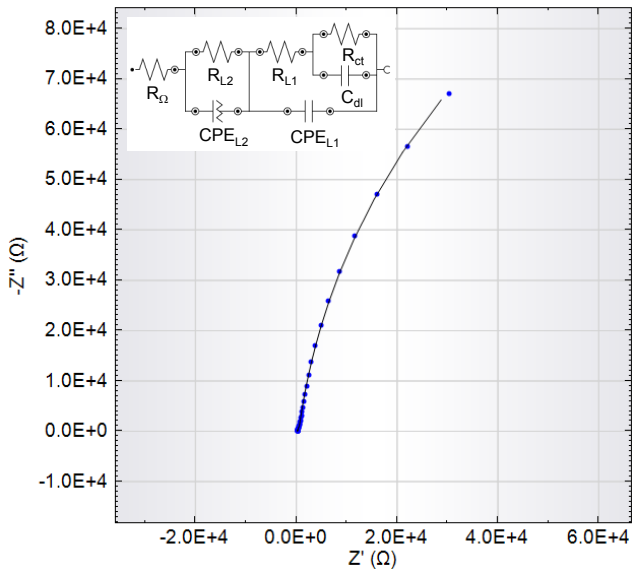


Figure 8 – Nyquist plot of the gold-coated sample, before the SDM

After the corrosion process, the roughness of the surfaces had to be taken into account, as Figure 9 shows. Also in this case, corrosion changed the properties of the coating layers.

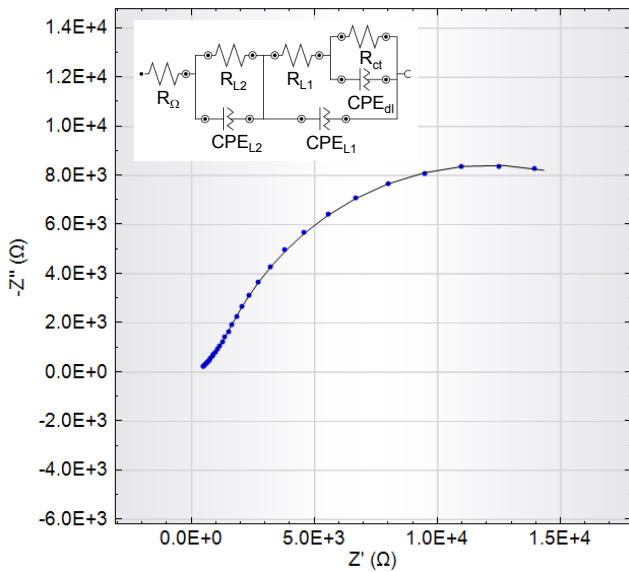


Figure 9 – Nyquist plot of the gold-coated sample, after the SDM

*Pink-coated aluminum*

In the last example, the pink layer has been applied over the oxide layer, like in the case of the gold-coated sample. However, before the SDM, Figure 10 shows how the Nyquist plot has an almost vertical line at low frequencies. The best fit has been obtained neglecting the faradaic impedance  $Z_f$  and adding a CPE in series,  $CPE_{dl}$ , which represents the interface between the metal and oxide surface. This could be an indication of a good-quality coating.

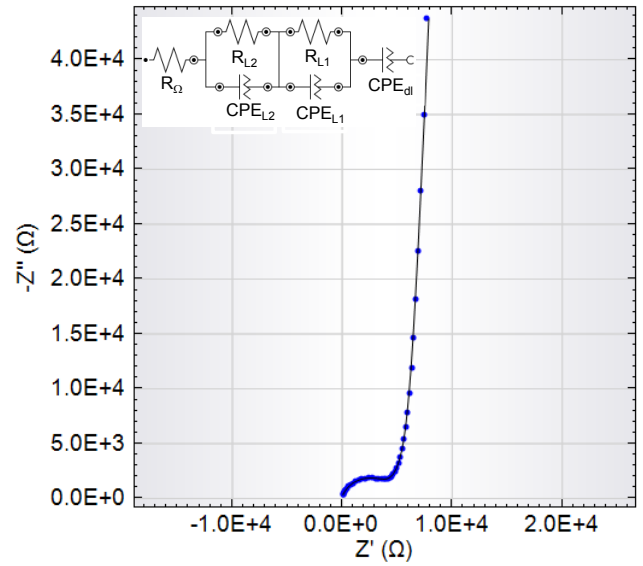


Figure 10 – Nyquist plot of the pink-coated sample, before the SDM

After the SDM, however, the best fit has been obtained with a double layer capacitance  $C_{dl}$  instead of the  $CPE_{dl}$ . This is shown in Figure 11. This could mean that the coating has suffered less the corrosion process induced by the SDM, with respect to the other two samples, and no faradaic process occurs at the aluminum-pore interface.

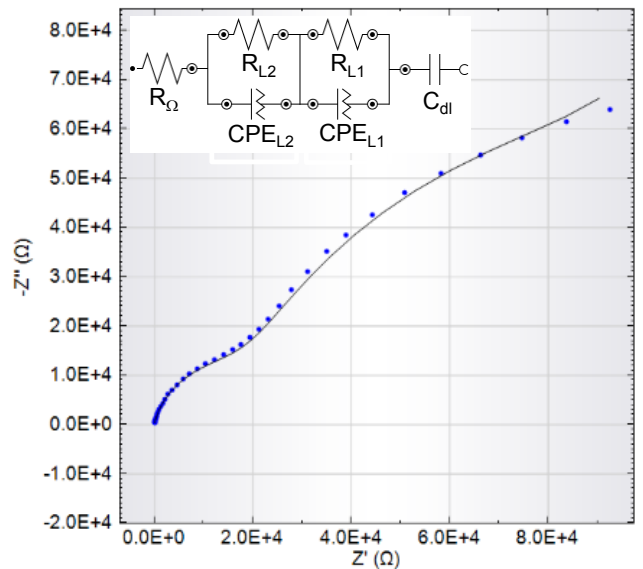


Figure 11 – Nyquist plot of the pink-coated sample, after the SDM

The three Nyquist plots after the SDM in Figure 12 show the comparison between the impedances of pink-coated sample, the oxide and gold-coated sample.

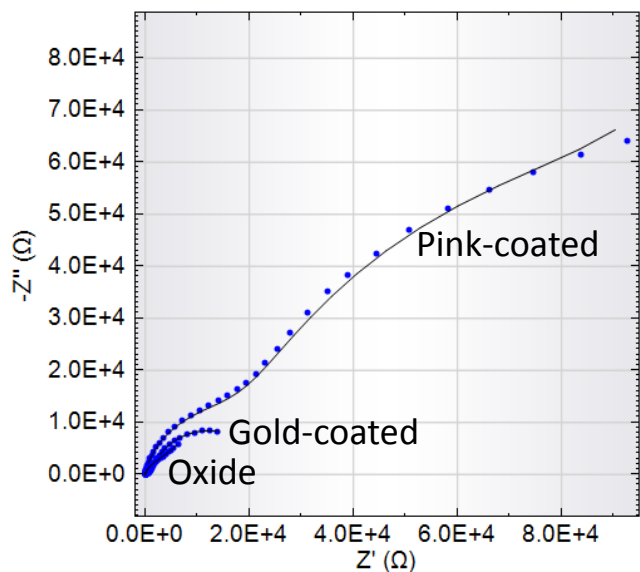


Figure 12 – Nyquist plot of the three samples, after the SDM

The pink coating seems to have the best performances against corrosion, at least during the SDM. Similar conclusions have been drawn on the application note CR08, which reviews the SDM technique.

**Conclusions**

The electrochemical impedance spectroscopy (EIS) is a fast, non-destructive and powerful technique, widely used in corrosion science. Provided a good knowledge of the system under investigation, EIS can give valuable insights on the quality of the coatings against corrosion. In this application note, it is shown how with an Autolab PGSTA204, with the Autolab 1 L corrosion cell and the help of the NOVA software, it is possible to perform EIS on samples of aluminum, coated with different materials.

The flexibility of the NOVA software was of help in writing the procedure to perform EIS measurements before and after the SDM. Data analysis is performed using the provided fitting tool.

**References**

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**Date**

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