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# **Galvanic corrosion evaluation of 6061 aluminum coupled to CVD coated stainless steel**

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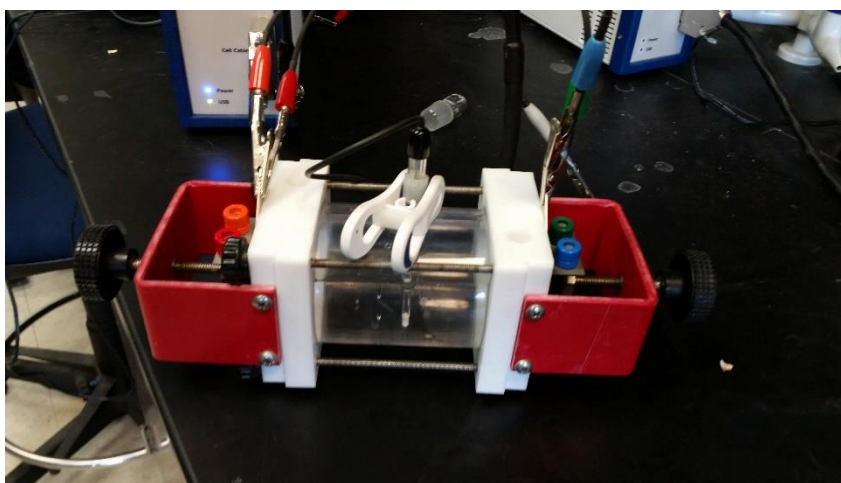
## Evaluation of galvanic corrosion of aluminum coupled to CVD coated stainless steel.

All experiments were carried out in normal strength artificial seawater at ambient conditions (open to air, room temperature about 22°C). Potential was measured with a saturated calomel reference electrode (SCE). The cathode and anode in the galvanic couple where of equal areas.

Materials used: Al 6061, 304 stainless steel (SS) –bare and with CVD coatings (Dursan and SL1000). Three replicas of each coating were tested.

Experiments conducted: galvanic corrosion assessment with Al-coated SS couples, Al-bare SS couple and as a control: Al exposed to sea water for 1 week (no galvanic connection to anything).

**Figure 1** presents electrochemical cell employed for carrying out galvanic corrosion experiments. The surface area of each specimen was 2.75cm<sup>2</sup> and the distance between the specimens was 14cm.



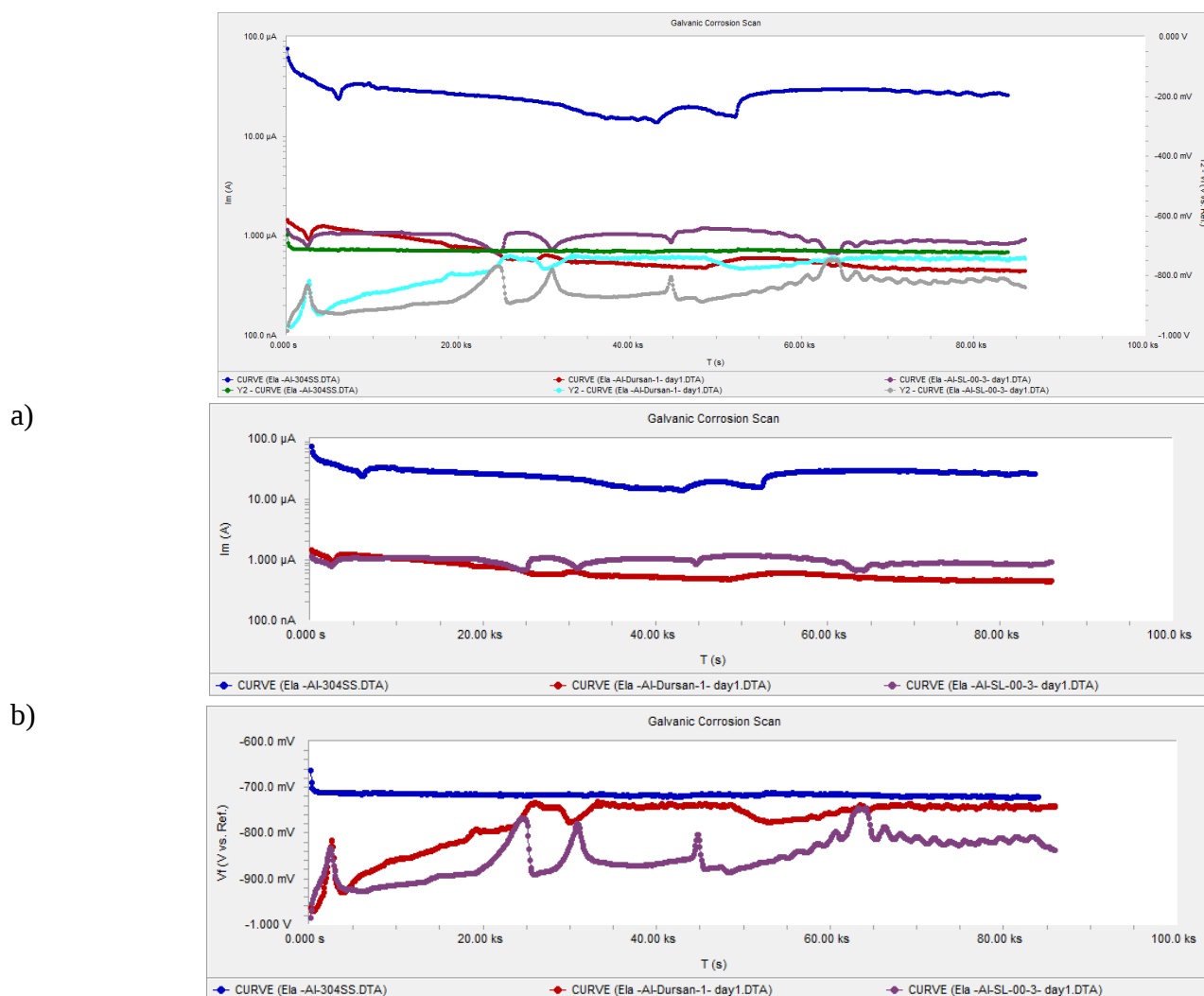
**Figure 1.** Photograph showing the experimental setup for conducting galvanic corrosion experiments using a standard flat cell arrangement with the cathodic member of the couple and one end and the anodic member at the other end and a separation distance of 14 cm between the two. An artificial seawater (conforming to ASTM D1141) electrolyte was used for the experiments.

In addition to galvanic couple experiments, anodic potentiodynamic polarization and EIS experiments were also performed on bare 304SS and on Dursan coated SS and SL1000 coated SS specimens.

### 1. Galvanic corrosion experiments

In these series of experiments, Al samples were galvanically coupled to CVD coated SS samples and galvanic current and potential were recorded during the exposure (1 week). Uncoated SS coupled to Al was also evaluated as a control case. In some cases, photos of the Al surfaces were taken. The quality of the photos is not the best, because of the reflective nature of the highly polished Al surface. In addition, galvanic current and potentials were recorded for Al specimens coupled to bare SS sample.

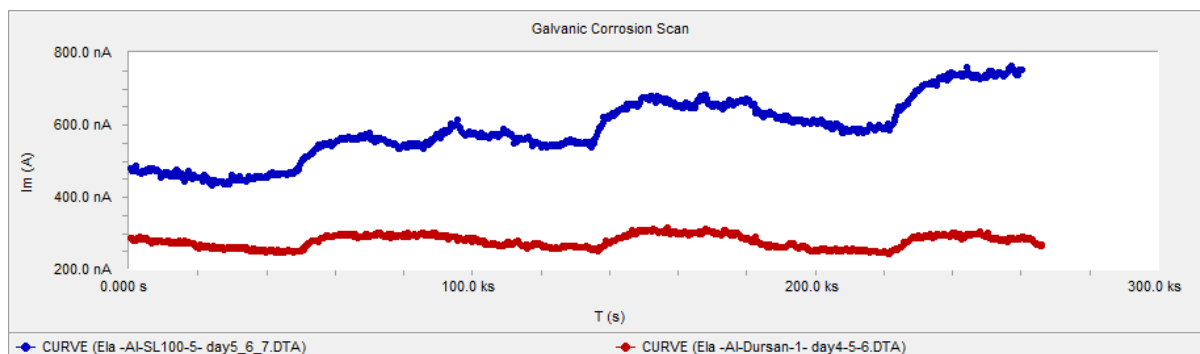
Representative results from the galvanic experiment are shown below in **Figure 2**. **Figure 2** presents a comparison of galvanic scans recorded during the first day of immersion for Al samples coupled with bare stainless steel and steel coated with Dursan and SL-1000. The presence of coatings substantially reduced the galvanic current (the decrease was about two orders of magnitude) and initially it appeared that there was no significant difference between performances of both coatings.



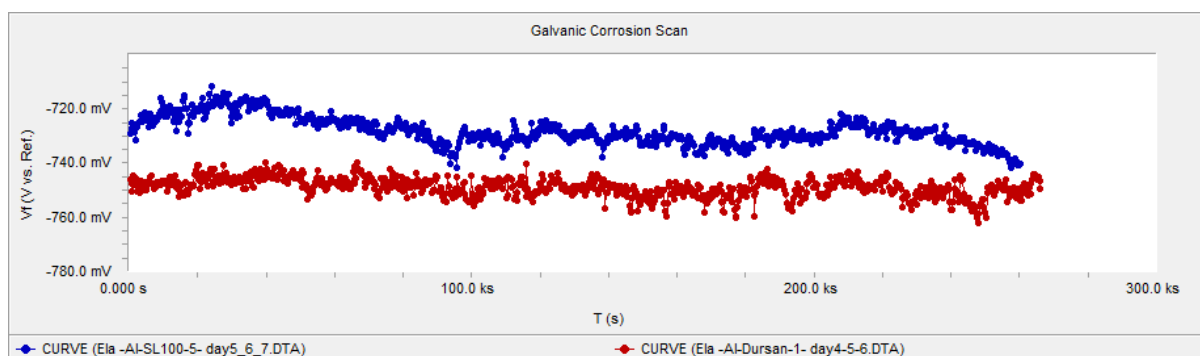
**Figure 2.** Top graph shows galvanic corrosion scans (current and potential) for Al coupled to bare SS, (blue-current, green -potential), Dursan-1 coated SS (red-current, light blue - potential), SL-1000-3 coated SS (purple-current, grey -potential), during first day of immersion in artificial sea water under ambient lab conditions. Bottom two graphs show: a) galvanic current as a function of immersion time (note log scale for current), and b) galvanic potential (vs. SCE) as a function of immersion time, the blue curves a) and B) graph are for the Al coupled to bare stainless steel.

However, after examining more closely galvanic corrosion parameters of Al-coated steel systems (**Figure 3**) we observe that galvanic current recorded in the presence of SL-1000 is about two times

higher than that recorded in the presence of Dursan. In all of the galvanic experiments the specimens' areas were the same ( $2.75\text{cm}^2$ ) and the distance in the electrolyte between the two coupled metals was the same (14 cm) so it is acceptable to compare currents not current densities. The difference in galvanic potential for the two couples was about 20mV.



a)

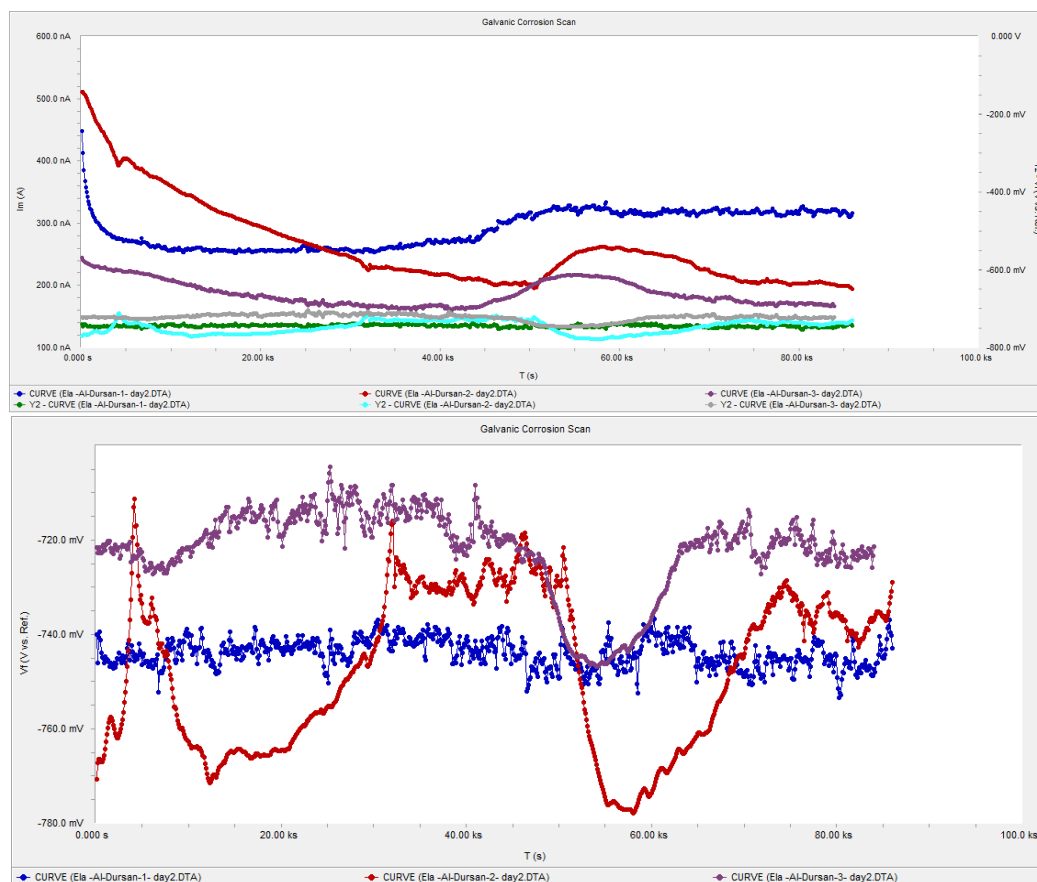


b)

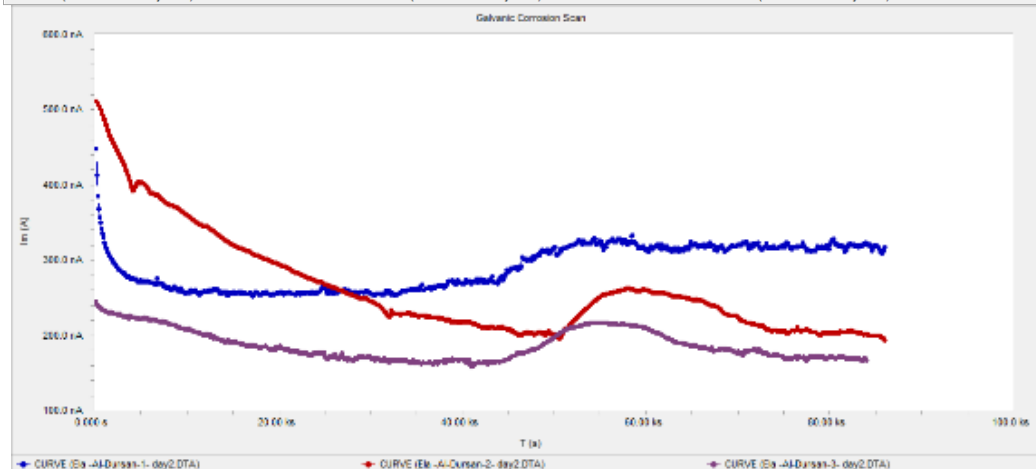
**Figure 3.** Galvanic corrosion scan of Al coupled to Dursan 1 coated SS (red) and SL-1000-5 coated SS (blue). The scans were recorded for 3 days of immersion in artificial seawater under ambient lab conditions: a) galvanic current as a function of immersion time, b) galvanic potential as a function of immersion time.

We also investigated reproducibility in protective performance of both coatings. In **Figures 4** and **5** the galvanic corrosion scans parameters (current and potential) recorded during one day of immersion for 3 replicas are presented. The galvanic current scans obtained for 3 replicas of Dursan coatings (referred to as Dursan-1, Dursan-2, or Dursan-3 (**Figure 4**)) show uniform performance – the difference in current between replicas is less than 100nA. However, potential scans show an interesting feature: potential recorded for Dursan-2 fluctuates periodically at amplitude of about 60 mV (see **Figure 4a**). This potential fluctuation behavior may be consistent with metastable localized corrosion events. The performance of replicas of SL-1000 coatings (**Figure 5**) also show some variation in the electrochemical behavior of the coatings.

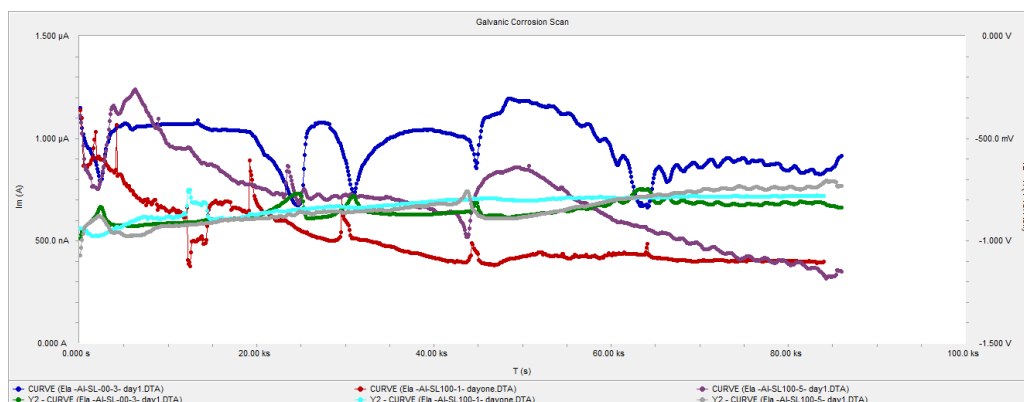
a)



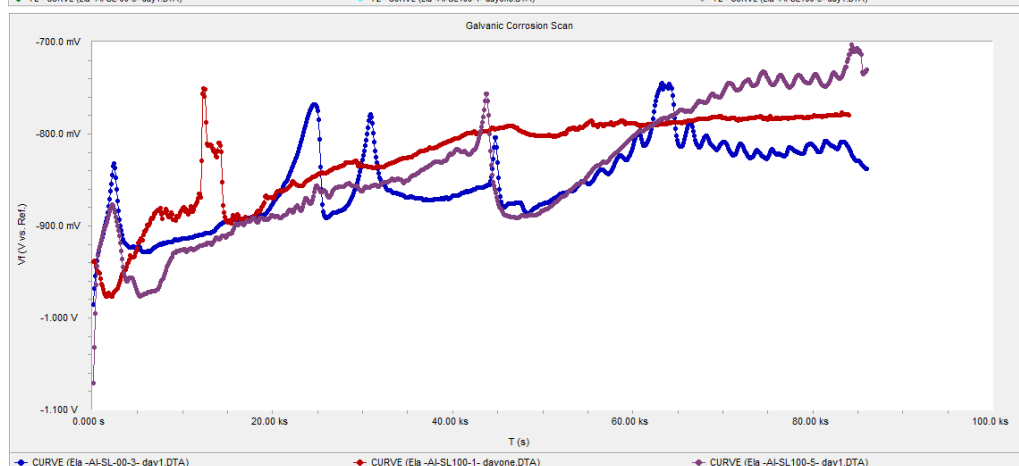
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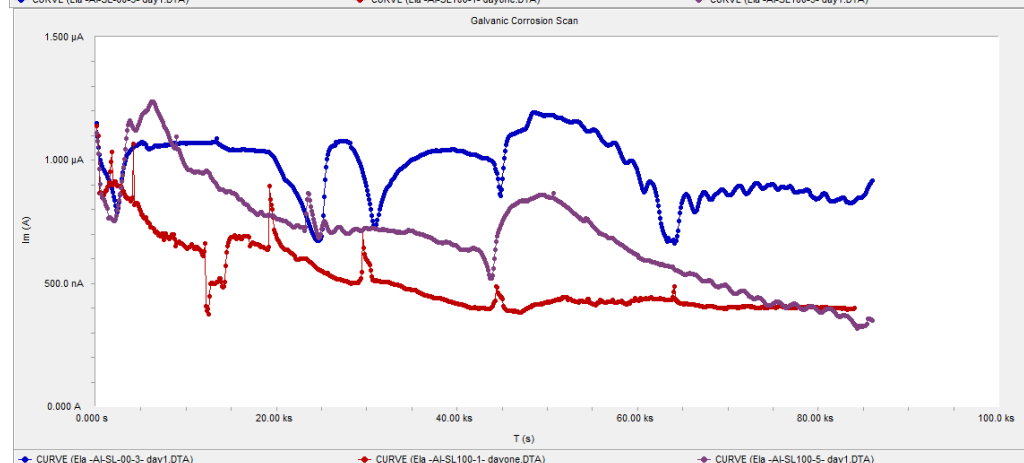
**Figure 4.** The top graph shows galvanic corrosion scans for three replicas of Al coupled to stainless steel coated with Dursan (Dursan-1, or Dursan-2, or Dursan-3). The bottom two graphs show : a) galvanic potential (vs. SCE), and b) galvanic current. The scans were recorded during second day of immersion in artificial seawater under ambient lab conditions.



a)



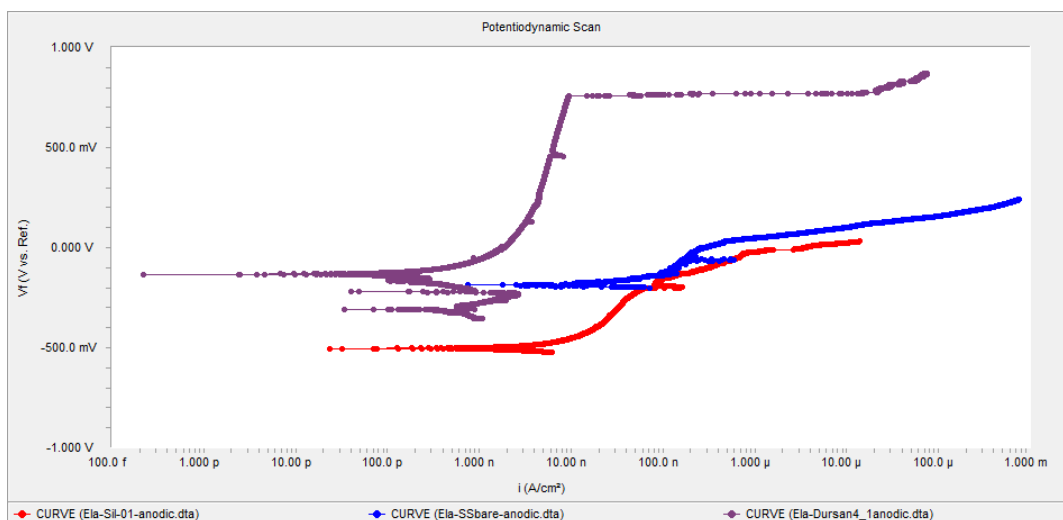
b)



**Figure 5.** Galvanic corrosion scans for three replicas of Al coupled to stainless steel coated with SL-1000 (SL-1000-1, SL-1000-2, SL-1000-3): (a) galvanic potential (vs. SCE) and (b) galvanic current. The scans were recorded during second day of immersion in artificial seawater under ambient lab conditions.

## Protectiveness of the coatings

In order to investigate protective properties of CVD coatings we carried out anodic potentiodynamic polarization experiments in which a specimen is polarized (by applying linearly increasing potentials) until a breakdown of a surface film occurs or another anodic reaction takes over (like oxygen evolution). The value of the recorded passive current density and the potential (vs. an SCE reference electrode) at which the passive film breaks down serves as measure of protection. **Figure 6** shows the potentiodynamic anodic polarization curves for bare steel (blue curve) and steel coated with Dursan-4 (purple curve) and steel coated with SL-1000- 1 (red curve) in artificial sea water (scan rate was 0.2mV/s) under ambient lab conditions.



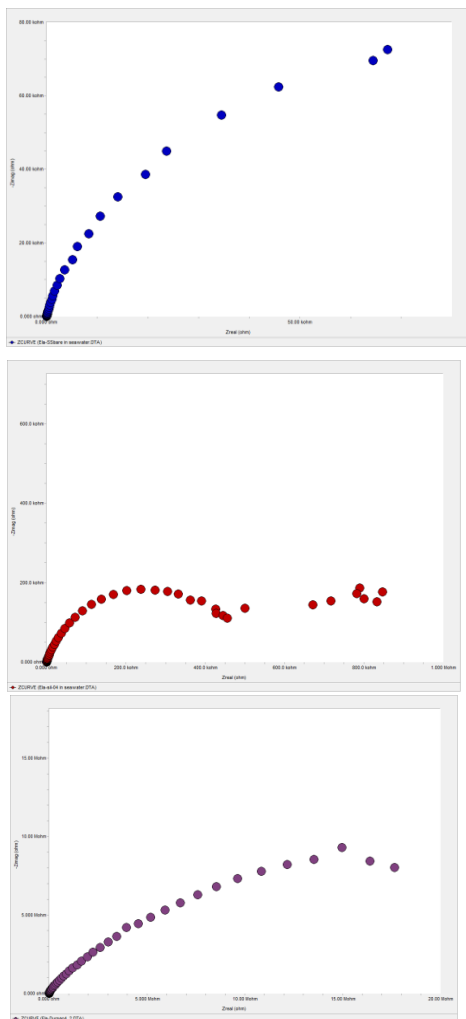
**Figure 6.** Anodic potentiodynamic polarization curves for bare steel (blue plot) and steel coated with Dursan-4 (purple plot) and SL-1000- 1 (red plot) in artificial sea water under ambient lab conditions. Scan rate was 0.2mV/s.

The anodic polarization results show that the Dursan-4 coating provided the best protection; passive current density was very low (about 10nA/cm<sup>2</sup>) and the breakdown of the film was observed at 0.8V<sub>SCE</sub>. Also, the open circuit potential was slightly more positive than that recorded for bare steel, -0.15V and -0.2V, respectively. On the other hand, SL-1000-1 coating does not seem to be able to provide a substantial level of protection to steel. In the presence of this coating the open circuit potential is shifted in the more negative direction by about 0.3V and the passive current density is somewhat lower than that for bare steel but the breakdown of the film occurs at slightly lower potential than that on bare steel. The results suggest that the SL-1000-1 coating may not be very dense and likely contains small pinholes which enable the electrolyte to penetrate it and make connection with the substrate; making the system less noble upon immersion.

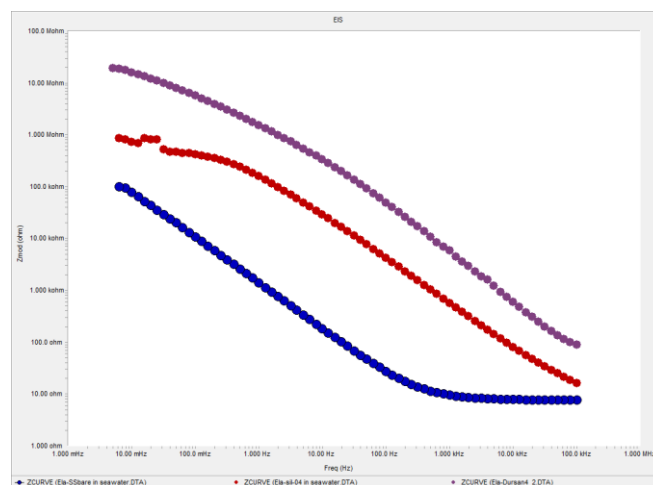
This observation that the SL-1000-1 coating is less protective than the Dursan 4 coating was corroborated by the results of the EIS experiments. **Figure 7** shows a) Nyquist and b) modulus of impedance recorded for bare steel and two CVD coatings. It is apparent that the coatings provide

protection to bare steel and that SL-1000-1 is less protective than Dursan-4. It also shows that SL-1000-1 suffers from some kind of localized attack ('noisy' data at low frequency range). The less satisfactory performance of SL-1000-1 can be due to variations in deposition parameters that led to less reproducible behavior (recall **Figure 5** with comparison of 3 SL-1000 replicas where varied performance was observed).

a)



b)

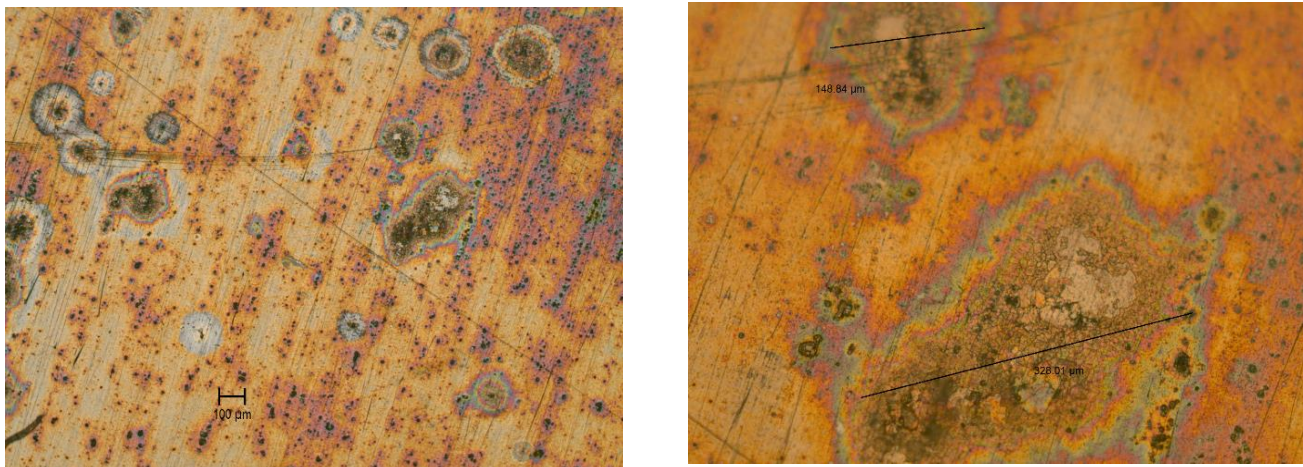


**Figure 7.** Results of EIS experiment recorded bare steel (blue), SL-1000-1 (red) and Dursan-4 (purple) coated steel in artificial seawater under ambient lab conditions. The final frequency was 5mHz, the spectra were recorded at open circuit potential (vs. SCE).

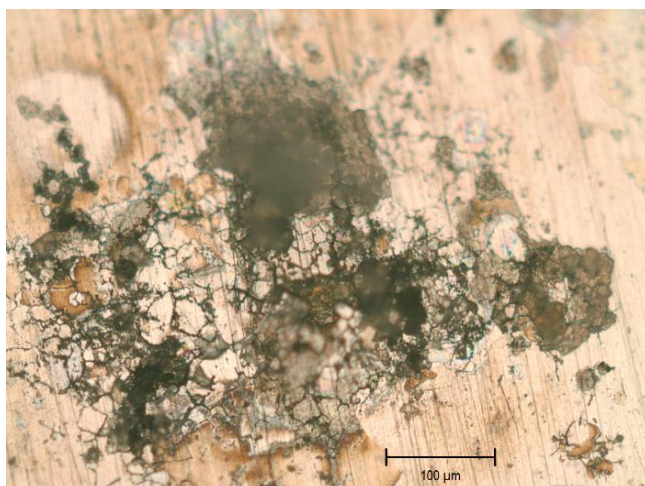
## 2. Preliminary microscopic evaluation of galvanic corrosion of Al when coupled to coated or uncoated stainless steel

Overall, when Al is coupled to coated stainless steel vs. uncoated stainless steel, the resulting galvanic current is significantly lower: indicating protective action of applied coatings in limiting the area of the cathode (the stainless steel) available to drive galvanic corrosion. However, if the appearance of Al surface is considered an indicator of presence or lack of galvanic corrosion performance then the protectiveness of the applied coatings may not be sufficient. When Al is exposed to sea water it spontaneously undergoes pitting corrosion. When Al is galvanically coupled to more noble metal (like stainless steel) it suffers from more severe pitting. This suggests then that presence of these protective coatings on the stainless steel surface can diminish the degree of pitting, but cannot obliterate it entirely. Generally, galvanic corrosion can be suppressed (lowered) by coating the cathode or by coating both the cathode and the anode (never the anode alone!). Coating only the anode will result in increasing the galvanic attack at coating defects.

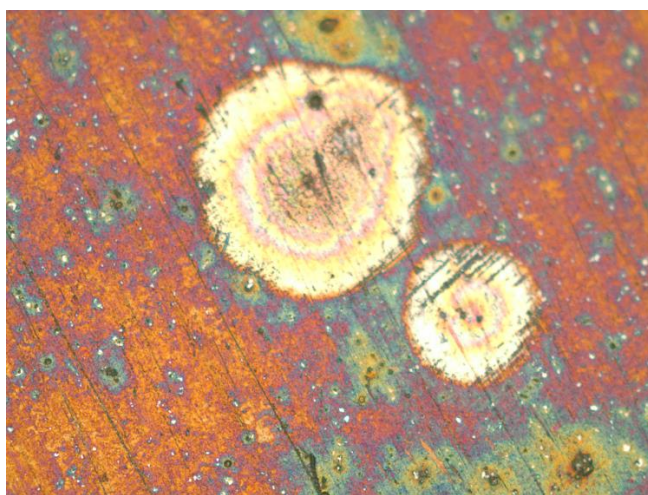
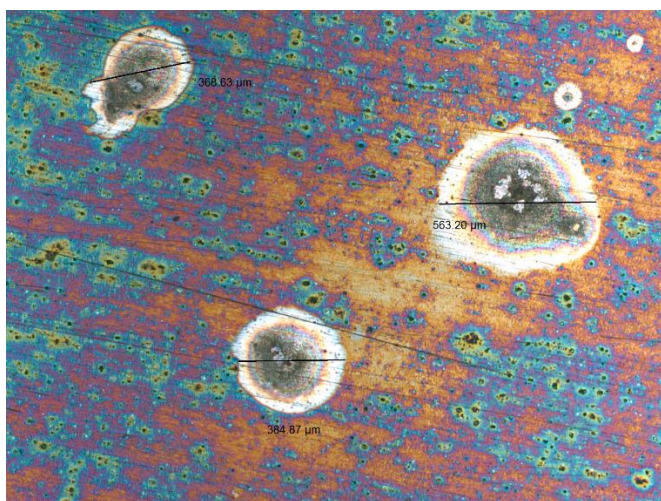
The assessment of coating effectiveness in mitigating galvanic corrosion should be evaluated by examining the Al surface and a preliminary investigation of this was started by Dr. Min Yuan of Silco Tek. To illustrate what was noted during this preliminary optical investigation of the pitting on the Al, **Figures 8, 9, 10 and 11**, show some qualitatively representative images of Al surface after being exposed to sea water with no galvanic connection (Figure 8) and when coupled to uncoated stainless steel (Figure 9) and finally, when coupled to steel coated with CVD coating (Figure 10 and 11).



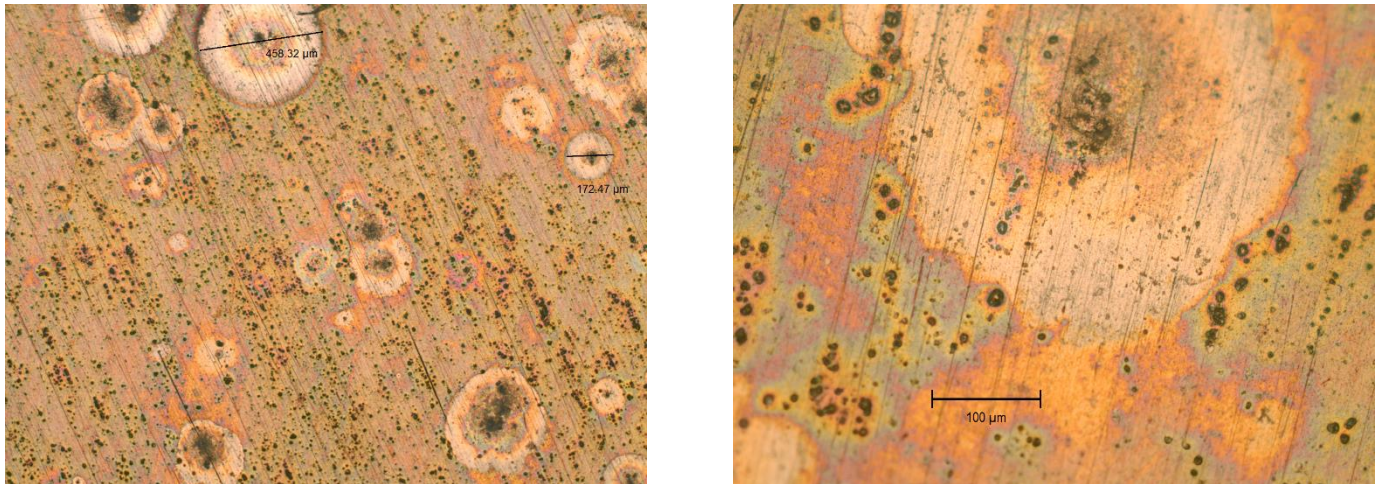
**Figure 8.** SEM images of Al surface after immersion (no galvanic coupling) in artificial seawater under ambient lab conditions for 1 week, left) magnification 5X, right) magnification 20X. Note the pit diameters in the two images.



**Figure 9.** SEM images of Al surface galvanically coupled to bare stainless steel after immersion in artificial seawater under ambient lab conditions for 1 week, left) magnification 5X, right) magnification 20X. Note the pit diameters in the two images.



**Figure 10.** SEM images of Al surface galvanically coupled to SL-1000-5 coated stainless steel after immersion in artificial seawater under ambient lab conditions for 1 week, left) magnification 5X, right) magnification 20X. Note the pit diameters in the two images.



**Figure 11.** SEM images of Al surface galvanically coupled to Dursan coated stainless steel after immersion in artificial seawater under ambient lab conditions for 1 week, left) magnification 5X, right) magnification 20X.

The above images clearly illustrate the presence of localized attack on Al surface. The most severe localized attack, with large and **presumably** deep pits, was observed on Al surface galvanically coupled to bare stainless steel and this is what was expected. The pits on these control galvanic couple were as large as 1220  $\mu\text{m}$  in diameter, and there were also a significant number of smaller pits. Coating stainless steel with SL-1000-5 appears to have helped to reduce the size of the pits (to about 500  $\mu\text{m}$ ) and their density. The presence of the CVD coatings on stainless steel appears to have resulted in lowering the galvanic corrosion effects. Specifically, the number of pits present on the Al surface appeared lower than the number for when it was coupled to bare steel and; more importantly, the sizes of the pits appears to be significantly smaller (450  $\mu\text{m}$  vs. 1200  $\mu\text{m}$ ) (and likely, they were also shallower).

The above observations are preliminary and are based on a cursory microscopic analysis of the specimens and as such are not to be taken quantitatively. An assessment of the effectiveness of CVD coatings needs a more thorough analysis of the localized attack: calculation of pit density, pit size distribution, and pit depths based on a statistically significant analysis of areas on each specimen.

### 3. Conclusions

The effect of galvanic corrosion on Al coupled to stainless steel was diminished by the presence of CVD produced coatings (SL-1000 and Dursan). Both coatings lowered the galvanic current recorded for the Al-coated steel couple and reduced the number and size of pits observed on Al surface. Dursan coating appears to possess better protective properties (evidenced by lower passive current density, higher breakdown potential and higher overall impedance) than SL-1000: however, these properties may vary between the replicas.

