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Innovative Approach for Predicting Galvanic Corrosion Effects on Airframe Systems

Alan Rose, Keith Legg
Corrdesa LLC
1590 S. Milwaukee Ave, Suite 205
Libertyville, IL, 60048, USA
arose@corrdesa.com, klegg@corrdesa.com

Christophe Baeté
Elsyca nv
Vaartdijk 3/603
3018 Wijgmaal (Leuven) Belgium
christophe.baete@elsyca.com

ABSTRACT

Naval aircraft typically comprise multiple materials each exhibiting unique electrochemical properties. When exposed to harsh marine environments the difference in material properties can lead to severe galvanic corrosion resulting in safety risks, costly repair and reduced readiness.

Current design tools do not have the capabilities to account for this corrosion degradation. The accepted approach is to minimize galvanic corrosion by introducing sealants, coatings and other barrier materials but these technical solutions degrade and become damaged over time and eventually corrosion attack is inevitable.

In this paper we show how a new physics-based corrosion prediction software tool [1] can be used, in order to assess and mitigate potential galvanic corrosion problems in the design phase. The electrochemical properties of the materials are derived from laboratory testing and are directly used as input in a 3-D computational CAD model of any complex airframe structure or subsystem. The corrosion prediction software tool is very comprehensive and can easily be used by materials & process (M&P) engineers as well as designers, even with restricted knowledge of corrosion and finite element analysis.

An SBIR project funded by the Office of Naval Research (ONR)[2], has already demonstrated that this new modeling approach could identify and quantify the severity of several corrosion issues observed in some aircraft systems. Further, new material combinations and surface finishes are constantly evolving in response to ever more stringent environmental legislation. It is therefore, critical that engineers have a tool that can objectively assess material choice upfront in a timely fashion. In this way, downtime and maintenance cost of the naval air fleet can be significantly reduced, by avoiding galvanic corrosion issues due to coatings degradation and damage.

INTRODUCTION

Corrosion impacts safety, function and appearance of products and annually costs our economies an estimated 6% GDP – resulting in $552Bn in the USA alone [3] (direct **and** indirect costs). It is estimated that 35% of this cost can be avoided by implementing better, upfront analysis techniques and engineering software tools.

The cost of corrosion to the Department of Defense for infrastructure and equipment is estimated to be $22.5 billion each year [4] and specifically, for Navy and Marine Corps aviation this amounts to $2.6 billion, or 26.1 percent of total maintenance costs [5]. Further, corrosion also results in 95,237 non-available days per year for all Navy and Marine Corps flying assets, which equates to an average of 25 days of corrosion-related non-availability per year for each aircraft on active status.

50% of Depot maintenance costs are attributed to corrosion and 80% of these are unscheduled. Safety is indeed impacted by corrosion and galvanic corrosion has been suggested as an initiator for more than 80% of corrosion fatigue issues.

PREDICTING GALVANIC CORROSION

The risk for galvanic corrosion is investigated by using Elsyca's *GalvanicMaster,* a software tool for predicting galvanic corrosion locations and severity on complex assemblies of mixed materials. The software based on Finite Element Methods (FEM) is employed to solve the fundamental electrochemical equations that govern the corrosion phenomena, taking into account the potential distribution in the electrolyte with a given conductivity, the potential drop in the electrolyte, the coating resistance and the polarization behavior of the substrate. The electrolyte is modeled as a thin film with defined thickness (microns to millimeters). The software can take into account different film thicknesses in the same CAD model and automatically calculates the overlap between thin films on different bodies to ensure ion transfer between neighboring bodies with overlapping films. Details on the software have been reported elsewhere [1].

The user-friendly, yet comprehensive software has been developed for design engineers with restricted knowledge on corrosion. It comprises:

- Pre-processor
    - Generic and flexible CAD-import tool (STL-based[†])
    - Automatic high quality surface mesh
    - Automated polarization curve selection
- Solver
    - Robust and fast
    - Supports multi-body configurations and external current sources
- Post-processing
    - Fully automated and configurable reporting
    - Powerful visualization tool available throughout the organization

The software tool was used to study the corrosion issues on the wheel attachment bolts and wing lug bushings of a military aircraft.

CASE STUDY 1: CORROSION PREVENTION OF AL WHEEL OF AIRCRAFT VESSEL

Originally the wheel was forged Al alloy, anodized, primed and painted. Held on by high strength fasteners and steel washers, the Cd plated and anodized finishing was easily damaged during the many wheel/tire change-outs, exposing the bare aluminum to bare steel.

Item	Material	Finish	Note
wheel	2014-T61 Al	Anodized, primed, painted	Model as bare Al at affected surface
washer	4130 steel	AMS-QQ-P-416, Type II, Class 2	Model as Cd and as bare steel

Table 1 Material specifications of the components

Galvanic corrosion of the Al beneath and around the bolts caused frequent wheel condemnations. Depot engineering proposed to simply insert Al instead of Cd plated steel washers to act as sacrificial components that can easily be replaced during maintenance and hence keep the expensive, forged wheel free of corrosion. Different thickness and diameter Al washers could then be assessed in the model to optimize the best solution and demonstrate the degree of protection to be expected. Figure 1 shows an example of the wheel with the location of galvanic corrosion and the corresponding CAD model.

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[1] STL is a file format native to the stereolithography CAD software created by 3D Systems[8]. STL files are widely used for rapid prototyping and computer-aided manufacturing[9].

Figure 1 Forged Al wheel with corresponding computational model – arrow shows corroded area

The following assumptions were made in inputting the data to the corrosion prediction software:

- Seawater exposure
- Thickness of the seawater film: 500 microns (also recomputed for different film thicknesses)
- Small gaps between all elements in the model, permitting fluid penetration
- 100% wetting time
- Cd finish has been lost, only bare steel remains.
- Al wheel is anodized and coated (insulator) except small area around and beneath the washer, where anodize is lost.

The polarization behavior of the different materials has been tested in synthetic seawater (ASTM D1141) by linear sweep voltammetry (LSV). A scan rate of 2.0 mV/s starting from cathodic towards anodic potentials.

The CAD model detail around the fastener is shown in Figure 2. In the current design the steel washer is trapped between the nut and the pad in the aluminum wheel counter bore. In the proposed modification an Al washer, the same diameter as the steel washer is interposed between the steel washer and the Al wheel.

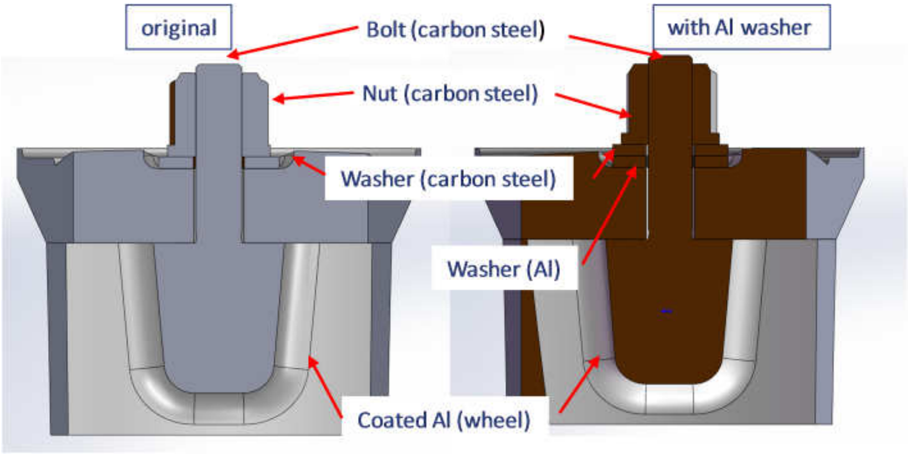

Figure 2 Cross section of the forged Al wheel with details on the washers set-up

The first point to notice is that the calculated corrosion "hot spot" for the current system (top items in Figure 3) matches the actual observed corrosion pattern. This is no surprise since the only area that the aluminum could corrode is in the circular pad, until the anodize in the hole ID or wheel face is damaged. The bolt and washer show no galvanic corrosion because they are more cathodic; of course they do undergo general corrosion, as Figure 1 clearly shows. The initial corrosion rate in the pad is calculated to be about 8,000 µm per year, which of course does not reflect the corrosion rate over the course of a year, because the build-up of corrosion products is not yet included in the model. However, the corrosion rate for the steel plus aluminum washer combination is predicted to be about 2,750 µm per year, about a factor of three lower. This shows that the washer combination should indeed operate in the expected manner to reduce the corrosion rate of the Al wheel.

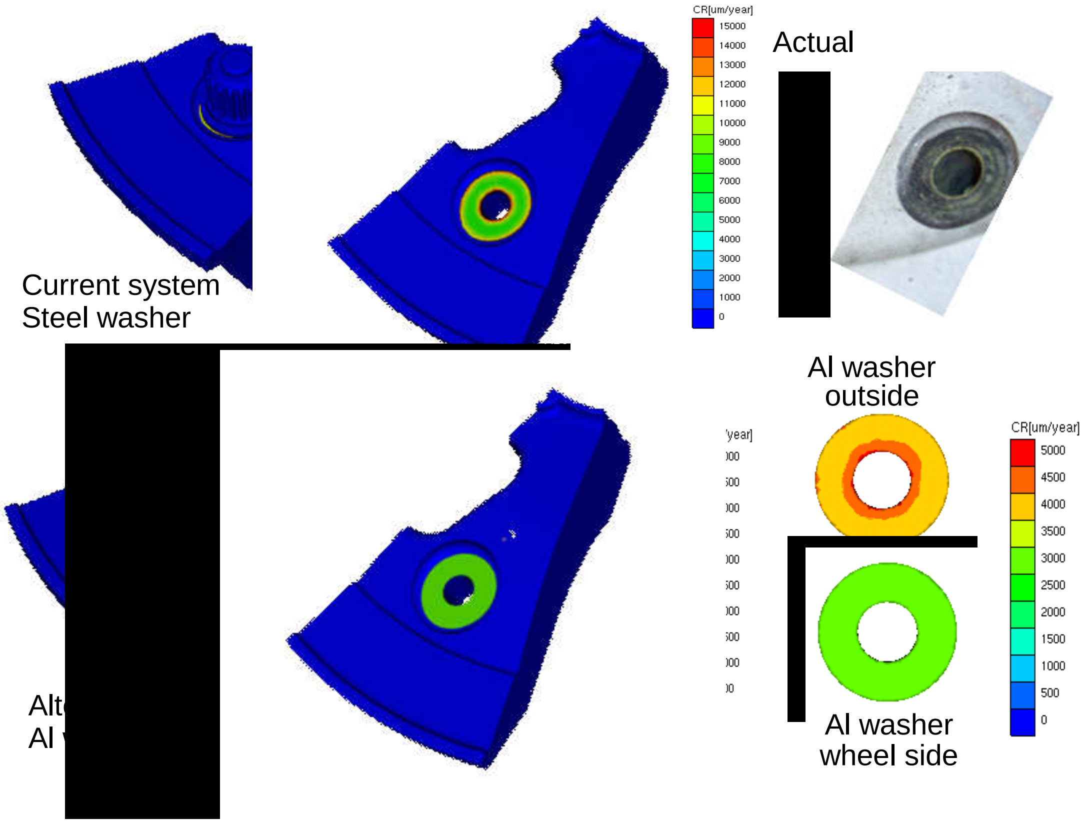

Figure 3 Simulated corrosion rates of assemblies –original set-up (above) compared with improved set-up with Al washer (below)

What happens to the washer is shown on the bottom right-hand side of Figure 3. The outside of the Al washer, which is adjacent to the steel washer, shows the highest corrosion on the inside of the face, where it sees galvanic currents from the steel stud as well as from the steel washer. The area adjacent to the aluminum wheel, of course shows very little corrosion, although it does show some, presumably because of penetration of galvanic currents from the stud on the inside and the steel washer on the outside.

CASE STUDY 2: CORROSION PREDICTION OF WING-FUSELAGE ATTACHED BULKHEADS

Bushed aluminum wing lugs are commonly found in aircraft. A typical lug attachment consists of a bushing through which a connecting lug pin passes. Figure 4 illustrates the set-up.

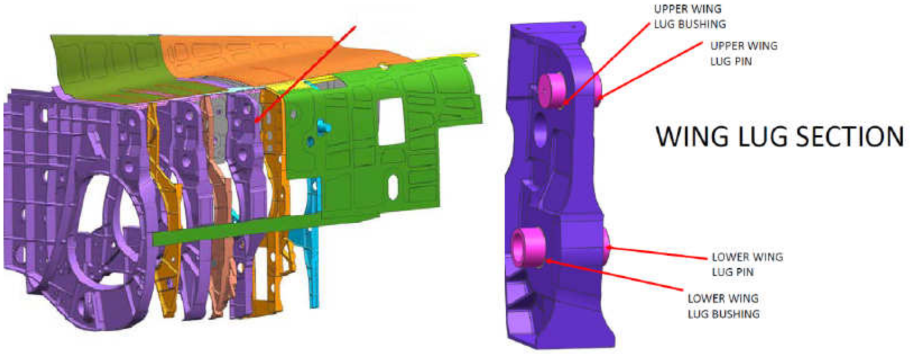

Figure 4 Position of the bulkhead wing lug with bushing and pin

A schematic of the fuselage bushing is given in Figure 5. In principle the bushing is Cd plated, the lug Alodined and the pin is passivated and may or may not be Cd plated depending on the subsystem. The bushing face and the lug area adjacent to it are usually sealed with a chromated sealant and the lug and bushing faces chromate primed and painted. In practice however, due to movement between wing and lug, the paint system will always degrade and develop some porosity which allows some water permeation. Galvanic currents between bushing and lug will eventually corrode the Al. In all cases the aluminum periphery around the bushings shows corrosion attack in practice. The galvanic effect can be caused by the bushing plus pin or by the pin alone in case that the bushing is epoxy coated (Bluecoat).

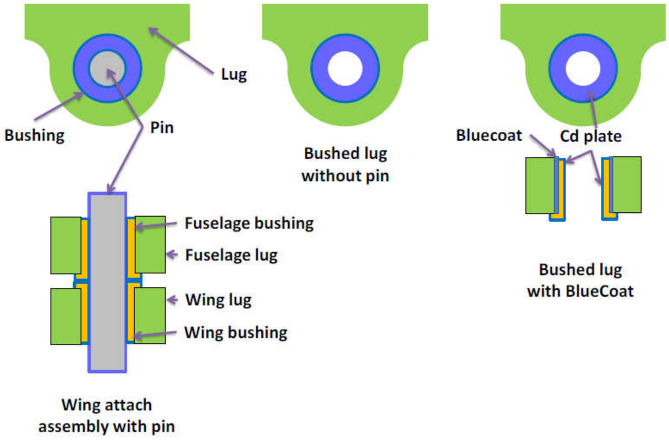

Figure 5 Schematic of wing lug/bushing system

Item	Material	Finish	Note
lug	7050 Al	Anodized, Alodine touch-up	Model as bare
bushing	Cu-Be	Heat treated to HRC 34-36, Cd plated	Model as bare, then epoxy coated
pin	PH13-8Mo	Cd plated or bare	Model as bare

Table 2 Material specifications of the bushed wing lug

In order to find the corrosion hotspots the sealant and paint system are ignored. Corrosion begins in any case where the coating breaks down. Figure 6 shows the CAD model for the simulations containing the bushing and pin in the wing lug.

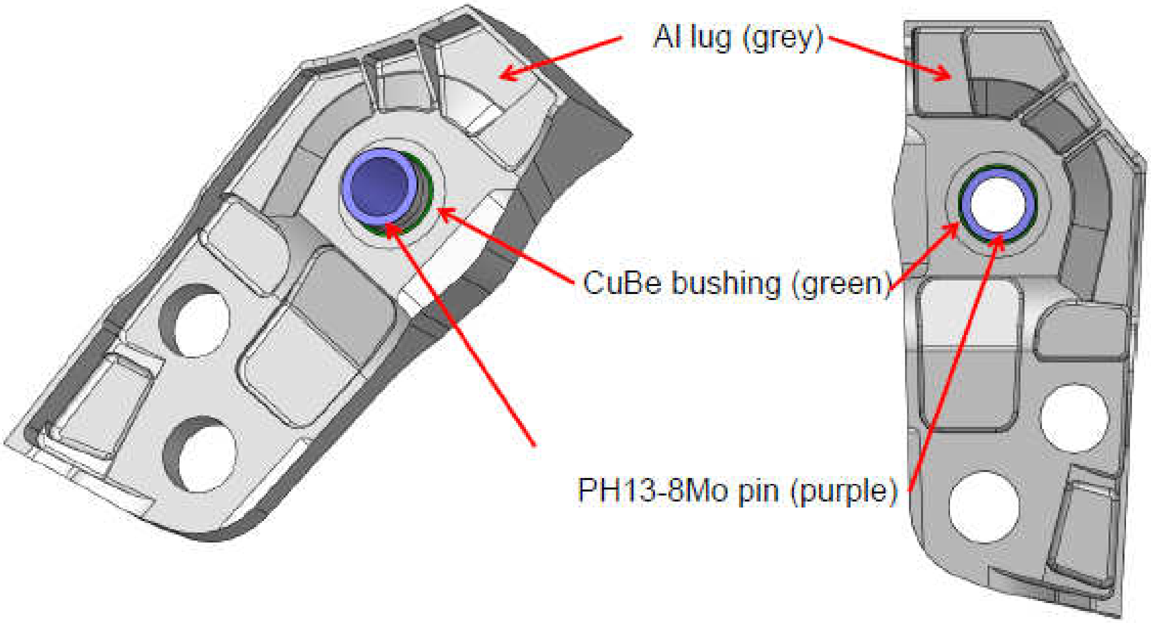

Figure 6 Computational CAD model for the corrosion simulations

It is assumed that only the surfaces under friction will lose their protective layer. In Figure 7 the main part of the aluminum bulkhead is anodized (grey) while the rectangular area (red) around the bushing is bare aluminum. The yellow zone between the bushing (green) and bare aluminum can be selected as being bare aluminum or being coated by epoxy.

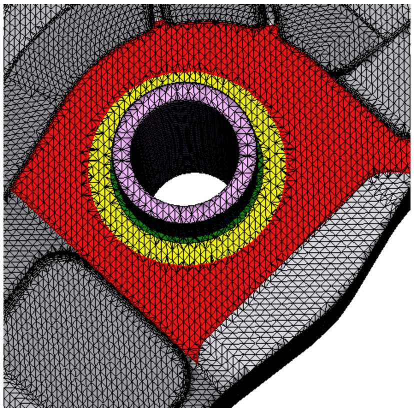

Figure 7 Detail of damaged aluminum zone

The polarization behaviour of the different materials has been tested in synthetic seawater (ASTM D1141) by linear sweep voltammetry (LSV). A scan rate of 2.0 mV/s starting from cathodic towards anodic potentials. Different exposure conditions were employed in this case (compared to Case 1). A film thickness of 100 microns and *10% wetting time* are assumed. Figure 8 shows the simulation results for the lug. The aluminum periphery around the bushing corrodes at 150 µm/y due to the Cu-Be bushing ring. As can be seen in the right picture the Cu-Be bushing has negative (cathodic) current densities marked in blue while the aluminum periphery has positive (anodic) current densities marked in red and yellow.

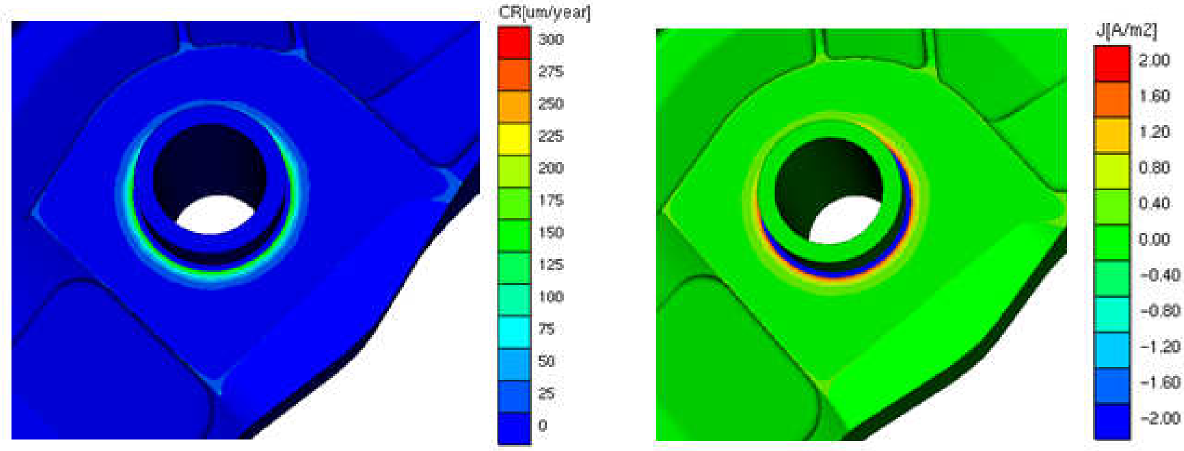

Figure 8 Corrosion rate (left) and current densities of the wing lug assembly

During maintenance the galvanic corrosion effect can be reduced by using epoxy coated bushings as shown in Figure 5 (upper right). The epoxy coating insulates the Cu-Be bushing and the galvanic corrosion risk is determined by the PH13-8Mo pin only. The simulation results in Figure 9 show that the corrosion rate can be decreased from 150 to 90 µm/y by this approach.

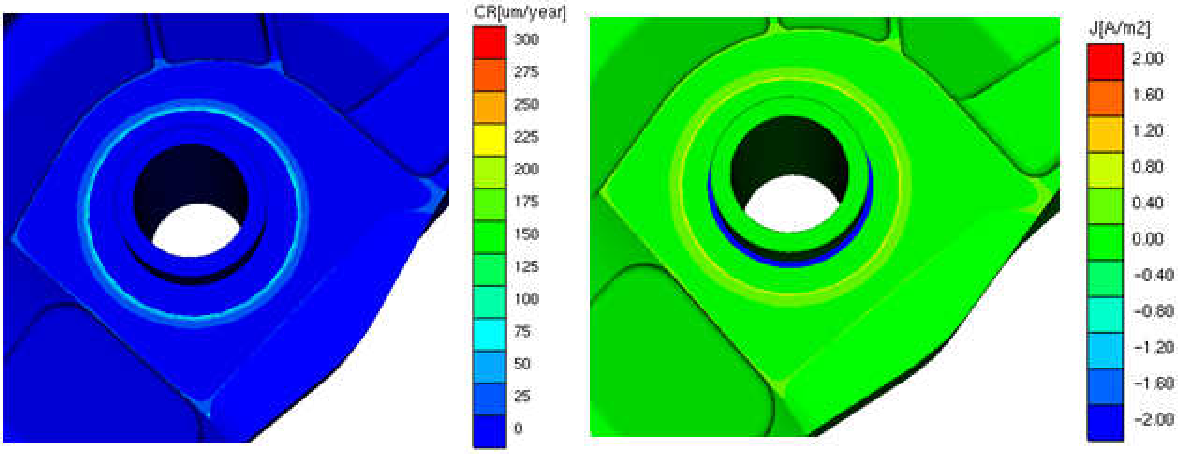

Figure 9 Corrosion rate (left) and current densities of the wing lug assembly with epoxy coated bushing

POLARIZATION DATA

The modeling tool employed in the two previous cases did indeed predict the locations of 'galvanic hotspots' as observed in the field and also provided an indication of relative severity. In *absolute terms*, the previous examples predicted corrosion rates that were unrealistically high, especially in case 1. Reasons for this might include the assumed time of wetting (100% for case 1 and 10% for case 2), film thickness (500 versus 100 microns) and the polarization data. In order to better understand sensitivities, the method of measuring polarization data was studied into more detail.

The corrosion rate of a galvanic couple is determined by the polarization data of both active and noble metal where respectively the anodic and cathodic reactions are taking place. The polarization data can be acquired in different ways. In this article the effect of the type of polarization technique and the scan rate on the galvanic corrosion current was further investigated. Effect of film thickness and time of wetting will be investigated in the near future.

In principle linear sweep voltammetry (LSV) curves taken at two different scan rates were compared with a point-by-point potentiometry (PP) measurement. For the latter a coupon is polarized at a fixed potential during for a set time (typically 600 sec) while the current is measured. After the time is elapsed the potential is increased by 50 mV. For the fast point-by-point method the same coupon is used to apply the different potential steps. At higher over potentials the time was gradually decreased from 600 to 300 seconds. For the slow point-by-point a new coupon is used for each potential step. The potential is maintained during 200 minutes. For the other techniques a new coupon is used for the anodic and the cathodic scan.

As an example, a carbon steel plate with copper U-bend tubes is used. A CAD model of the assembly is given in Figure 10.

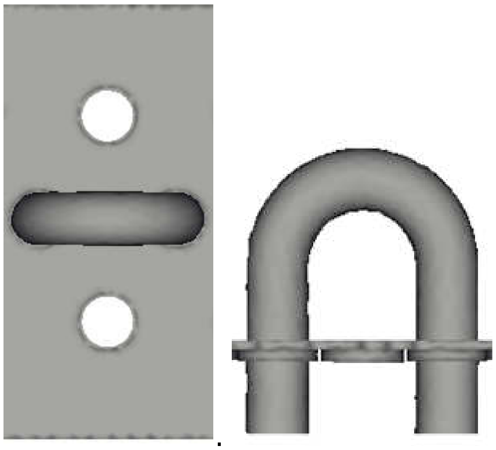

Figure 10 Computational model to study the effect of polarization technique on corrosion rate

The polarization data of the materials were measured in 3% NaCl at room temperature. The coupon surface was first degreased with acetone, then dipped in 10 vol% HCl and well rinsed in running tapwater and distilled water. The coupons were mounted on a rotating disc electrode system. The measurements were performed at 100 rpm. The samples were stabilized at open circuit potential during 1 hour prior to start polarization. Figure 11 shows the polarization data for carbon steel and copper obtained by the different techniques.

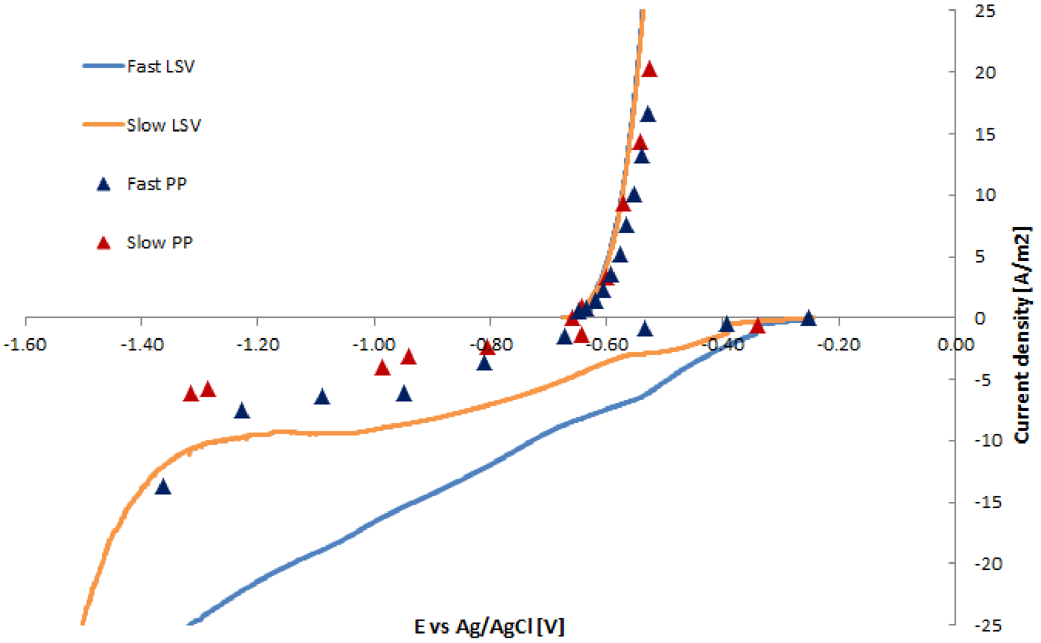

Figure 11 Polarization data for copper and carbon steel measured by different polarization methods

For the carbon steel (anodic branch, i.e. positive current)) there is only a slight difference between the polarization curves measured at different speeds, especially at lower overpotential, where, in this case, galvanic mixed potential is situated. For the copper however (cathodic branch) the polarization data determined from the different measurements differs significantly. The lowest current densities are found for the point-by-point method. The effect of polarization data on the corrosion results was assessed by using the different curves in the simulations of the steel plate with copper U-bends.

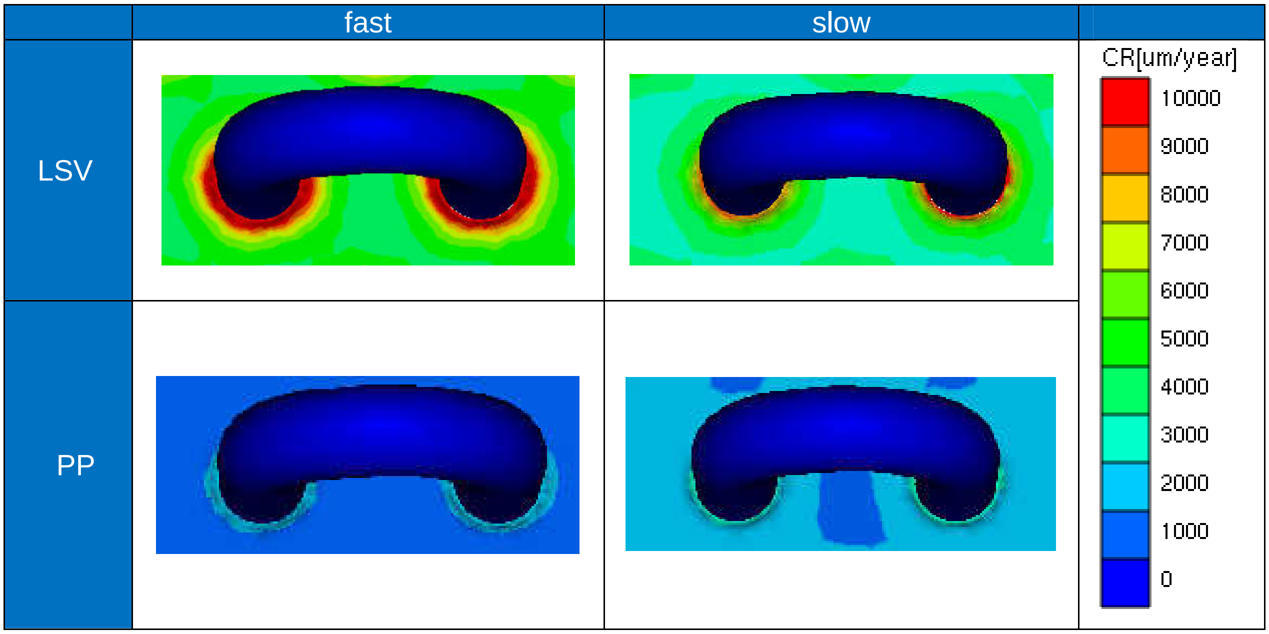

Figure 12 – effect of polarization technique on the corrosion rate

From the simulation results it can be seen that the corrosion rates using the point-by-point data are much lower those obtained when using the linear sweep voltammetry. Table 2 summarizes the scan rate and maximal corrosion rate of carbon steel plate at the interface with the copper U-bend.

Technique	Scanrate [mV/s]	Max CR [µm/y]
Fast linear sweep voltammetry	2.0	14401
Slow linear sweep voltammetry	0.2	7912
Fast Point-by-point potentiometry	0.02	1978
Slow point-by-point potentiometry	0.002	2848

Table 3 – polarization techniques to study effect on corrosion rate

As can be seen in Table 3 the corrosion rate can be a factor 7 higher, depending on the measured polarization curve and it is therefore important that the measured curve represents the real situation as closely as possible. However, the slower the measurement, the more time-consuming and expensive it is to obtain the data. Looking at the total time for each experiment there is little to be gained by using the slow point-by-point potentiometric method. The technique is time consuming and labor intensive (took 84 hours and required several coupons) while the corrosion rate stays in the same range as the fast point-by-point technique. A scan rate of 0.02 mV/s therefore seems to be the optimum choice.

For simulation purposes the point-by-point technique is not so appropriate. The software needs to interpolate the data points of the polarization curve so a slow linear sweep voltammetry at 0.02mV/s scan rate, is more suitable than a point-by-point scan. The sampling rate can be adjusted in order to have sufficient points around the OCP, with fewer points taken further way, outside the region where the system typically operates. Since polarization data need to be monotonic for this simulation technology a data post processing step must be included in order to smooth the data and eliminate the noise to ensure that the curve exhibits monotonic behavior.

CONCLUSION

It is clear that the galvanic corrosion modelling approach is an interesting tool to predict up-front the susceptibility of a multi material assembly to galvanic corrosion. Corrosion risk can be reduced by evaluating alternative designs or material combinations.

Using only geometry and material information, this approach can identify, upfront, the locations of the corrosion "hot spots" and deliver an indicative severity, or corrosion rate magnitude.

Presently, this approach does not yet take into account the build-up of corrosion products which in reality begin to slow the t=0 predicted corrosion rate. Moreover the way that the polarization behavior is measured can strongly influence the result. At higher scan rate the corrosion rate predictions are too high. This was expected, considering the assumptions employed. Other factors affecting the corrosion rate results include the time of ‘wetting’ and the assumed film thickness. The analyses presented in this report have assumed 100% wetting for 100% of the time with constant film thickness. Clearly in real-world corrosion this is not correct, nevertheless these are the conditions of a standard ASTM B117 test, which is the most widely used method for measuring corrosion experimentally. It is possible to carry out a great many computational corrosion analyses and evaluate a great many ways to mitigate the corrosion within the 1,000+ hours duration required for a single B117 test.

LITERATURE

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