Galvanic Sensor for Monitoring Structural Damage

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ABSTRACT

In recent years there has been an increased research activity on aircraft health monitoring tools. Numerous studies have been carried out as a response to the demand for a better damage detection in inaccessible areas. In most of these studies, the hidden corrosion events are significantly related to the nature and magnitude of corrosive environment present in the localized hidden areas.

Because of the difficulty in accessing hidden zones and the limitations of NDE currently used, primarily corrosion damages go undetected in the hidden areas during routine maintenance inspection. For old aircraft, the accumulation with time of even weak/least corrosive environments can produce serious structural damage, as demonstrated by enormous weight loss of material in some parts. In many critical aircraft parts the undetected corroded surfaces may lead to structural concerns acting as promoters and/or initiation sites of stress corrosion cracking and corrosion fatigue phenomena.

In an earlier effort, galvanic probes were designed and employed to measure galvanic current using electrochemical technique to monitor the corrosivity of an environment on a continuing basis in inaccessible areas. Among them, the ICS (Intelligent Corrosivity Sensor) has been the most successful application: this probe is a galvanic device that uses the condensed moisture and the environment's pollutants as an electrolyte, generating a cell current that relates to the corrosivity of the condensed film.

In the present work, a preliminary study has been done on modified ICS, to develop a probe for specifically measuring the corrosion structural part as in lap joints; i.e., probes were installed on the internal side of sandwich specimens made of Al 7075-T6 alloy. Preliminary results show that the sensor output from such tests can be used in the evaluation of hidden surface corrosion and serve as a meaningful tool to provide quite an accurate warning for subsequent inspection.

1.0 INTRODUCTION

In recent years there has been an increasing research activity on aircraft health monitoring tools. A lot of studies in this area have been made as a response to the demand for better corrosion detection in inaccessible areas. Hidden corrosion damages are significantly related to the nature and magnitude of corrosive environment present in various locations of an aircraft. Primarily, such areas go undetected during routine maintenance inspections. It is because of the difficulty in accessing such zones and the limitations of NDE currently used. In many critical aircraft parts, the undetected corroded surfaces lead to structural concerns acting as promoters and/or initiation sites for stress corrosion cracking and corrosion fatigue [1]. The Aloha Airline Boeing 737 accident, when a part of the front top fuselage was blown away during flight, has been a well documented case of multi-site fatigue damage in the fastener hole areas due to corrosion effects; it was because environment can easily penetrate and condense in almost any location and crevices, adding pitting and crevice corrosion to mechanical stress concentration sites. On old aircraft, the accumulation with time of even weak/least corrosive environments can lead to serious structural damages, as demonstrated by enormous weight loss of material in some parts [2].

2.0 BACKGROUND

Currently the assessment of corrosivity of an environment is the cumulative result of outdoor, long-term exposure tests and accelerated laboratory tests. Although these tests have been somewhat successful, the prediction (extrapolation) of the real life of an aircraft part is typically inaccurate. This is because of the occurrence of rapid weather changes that modify the environment continuously and affect the localized chemistry in crevices or tight geometries.

In the last years probes based on well-known techniques have been developed, to monitor the corrosivity of an environment on a continuous basis and also in inaccessible areas [3]. Amongst them, the Intelligent Corrosivity Sensor (ICS) has been the most successful development [4]. This probe is comprised of a series of interdigitated strips of two alternating different materials (gold and cadmium), deposited on a non-conducting polymer with a little gap that serves as an insulator between the two metallic strips. At relative humidity values greater than 50% the condensed moisture and the environment's pollutants create a thin liquid film on the strips, which serves as an electrolyte. Upon short circuit of bimetallic strips through an external electronic device such as a zero-resistance-ammeter a galvanic potential is developed between the two metals and corrosion of the anodic element occurs. The magnitude of this galvanic cell current gives a measure of the corrosivity of the condensed film. Corrosivity measurements above certain values can serve as a warning signal during maintenance operations, promoting inspection on aircraft areas exposed to the same ICS environment. A number of experiments have been done in the past by putting these sensors under coatings and inside hidden structural areas and composites in order to study the effects of environment on the degradation mechanisms of these materials. In the present work, a preliminary study has been done on modified ICS, to develop a probe for specifically measuring corrosion of the actual metal than the environmental corrosivity. Sandwich specimens were designed to simulate lap joints and experiments were performed to monitor corrosion of the internal side of the sandwiched plate.

3.0 EXPERIMENTAL

3.1 Instrumentation

In this study ICS was modified by cutting away the Cd deposited strip (Figure 1) and connecting the gold terminal directly to aluminum plate of the sandwich by means of conductive paint. The aluminum was thus short circuited to the gold cathodic strips (element) through an electronic module that served as zero-resistance ammeter, data logger and controller. The sensor-unit connections were sealed with bee's wax, to avoid humidity attack and ensure the re-use of the ICS system. Data are stored in the module memory, and then downloaded through RF transmission at 916 MHz (wireless communication) to a PC station. The details of the ICS and its function are described elsewhere [4].

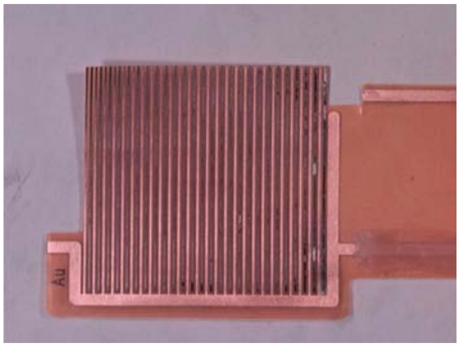

Figure 1: Modified ICS.

3.2 Data Analysis and Interpretation

The principles involved in the use of this probe are those of galvanic corrosion; the driving force is the difference in electrode potentials. When gold and aluminum are galvanically coupled, the former being noble metal acts as the cathode, while the active aluminum becomes the anode. When applied to reactions in which the cathodic reduction is under diffusion control, for each dissimilar metals couple the corrosion current (I_{corr}) is proportional to the measured galvanic current (I_g). This current is a function of the environment, because the constant proportionality factor depends upon three important environmental variables: temperature, relative humidity and the electrolyte composition. The galvanic current is then analytically transformed into cumulative damage by integrating it over time and then re-plotting it again with time.

3.3 Procedures

The experimental program to explore the applicability of the ICS probe as a direct corrosion sensor was pursued in two ways. These were identified as (i) different accelerated exposure conditions and (ii) different sandwich coupon assemblies, thus, generating two sets of data. Generally, measurements have been performed connecting an Al7075-T6 bare metal plate to the second gold strip of the ICS with a conductive paint. A scrim cloth was placed between aluminum and the cathodic gold strips, to avoid direct contact of gold strips of the sensor element with the aluminum plate (see Figure 2). The scrim cloth serves to make an electrolytic contact when gets wet in the presence of moisture or salt fog. Sandwich coupons of untreated (bare) metal plates of Al7075-T6 were joined by an adhesive tape during the first set of measurements; the coupons were placed in continuous high humidity (T=37 °C, near 100% RH) environment (Table 1). Three sensors and three different aluminum sheets have been used for three durations of the exposure times.

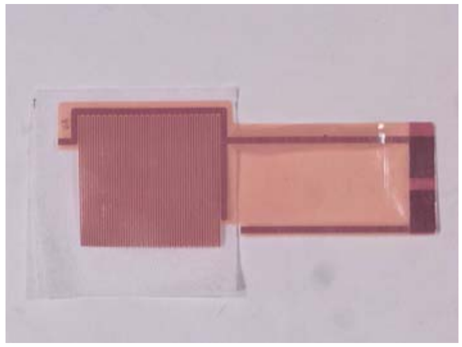

Figure 2: Use of scrim cloth.

Table 1: Materials and Methods.

Taped Sandwich Coupons	Riveted Sandwich Coupons
Al 7075-T6 bare (untreated) plates, 2.5''x2.5''x0.063''	Al 7075-T6 bare untreated plates, 2.5x2.5''x0.063''
Scrim cloth, 1.5''x1.5''	Scrim cloth, 1.5''x1.5''
NaCl 3.5% aqueous solution	High strength aluminum rivets (∅= '')
Conductive paint	Trivalent chromium pretreatment;
Bee's wax	Alodyne 1200 (Cr^{+6} treatment or CCC)
Exposure: R.H. 100%, T=37.0° C	Conductive paint
	Epoxy primer (MIL-P-23377 type I, class C)
	Polyurethane topcoat (MIL-C-85285C, type I)
	Sealing compound (AMS-S-8802, class B1/2)
	Bee's wax
	Salt spray chamber: meeting requirements of ASTM-B-117 method

In the second set of measurements, three sets of two or six of AL7075-T6 metal plates were pretreated as follows: as cleaned (degreased and deoxidized), chromium (III) and chromium (VI) pretreated as conversion coatings. Before two likewise plates were sandwiched, the anode of the ICS was connected to the interior surface of the plate as described before. After connecting the sensors, coupons were pneumatically riveted with high strength aluminum rivets. This simulated typical aircraft fabrication or maintenance operation. All sandwich test coupons were sealed only along the external edges and not around the fasteners4 (Figure 3). Then the assembly was coated with epoxy primer and polyurethane topcoat meeting the requirements of MIL specifications (Figure 4). Finally, coupons were placed in the horizontal position inside a salt fog cabinet (Figure 5) meeting the requirements of ASTM B 117-02 standard (Table 1).

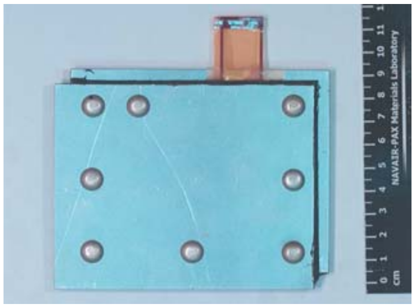

Figure 3: Sandwich test coupons sealing.

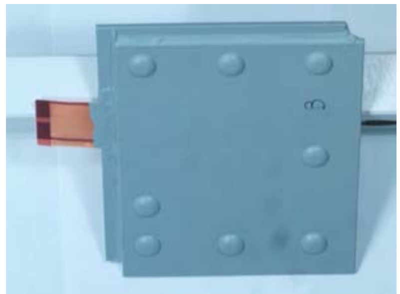

Figure 4: Sandwich test coupons.

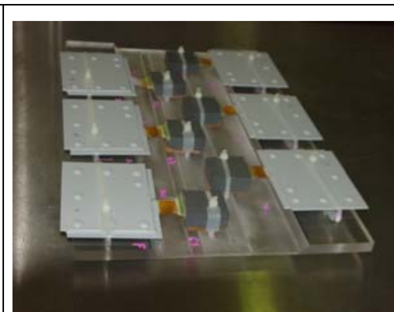

Figure 5: Salt fog cabinet rack.

4.0 RESULTS AND DISCUSSION

Basically, from the first set of measurements it was observed that monitoring the sensor output versus time produces transient (oxidation) curves that are parabolic in nature, and without any sudden output signal variations (Figure 6). Parabolic curves are typically fitted to equation (1):

$$Y^2 = K_{p.}X + C \textit{ equation} \quad (1)$$

where Y is the sensor output and X the time of exposure. The parabolic constant K_p here seems to correlate with the nature of environment, while C perhaps represents exposure time, alloy type, corroded surface area and/or thickness/area of the gold sensor (cathodic area). Predictably, the parabolic curve seems to indicate that the corrosion reaction is controlled by the diffusion of reactants through the corrosion product layers/thickness (system resistance).

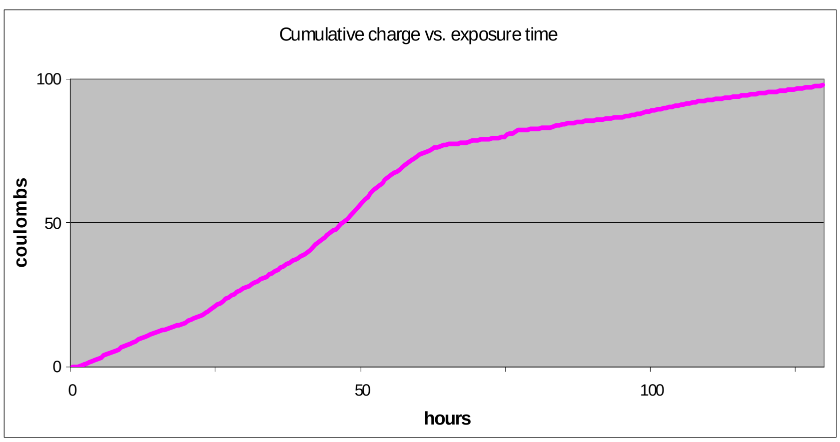

Figure 6: Cumulative charge vs. exposure time.

During the first 100-hour exposure period in near 100% RH, sandwich coupons were used to compare sensor output data with real material mass (weight) loss of the metal plate serving as anodic. A strong correlation was found as shown in Figure 7, which suggests the utility of the modified ICS technology in corrosion detecting and monitoring.

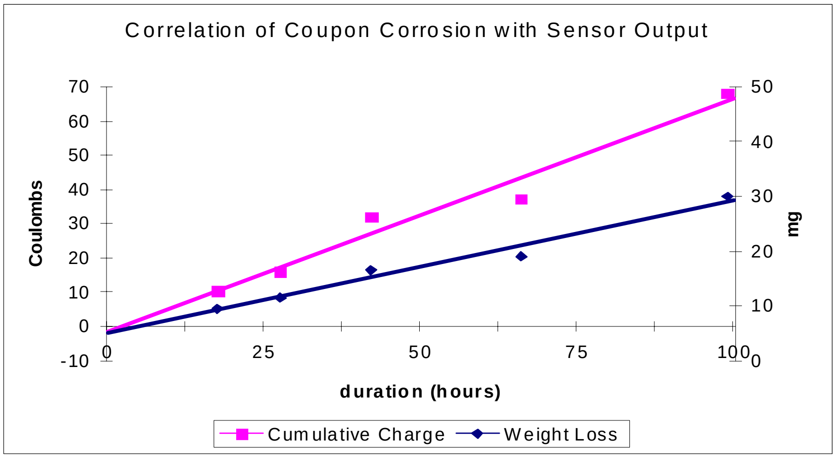

Figure 7: Correlation of coupon corrosion with sensor output.

The mass loss correlation with the sensor output was done through use of Faraday's law. Here the corrosion current produced by the material loss was converted in to charge or coulombs and then calculated by means of equation (2):

Coulombs = (Mass Loss (g) x 96500 x n (electron transfer)) / Atomic weight of aluminium equation (2)

The values obtained from above calculations were related to the sensor output data, to determine the constant factor I_g/I_{corr} through the Cs/Cc ratio (Table 2).

Table 2: Correlation of sensor output with the actual mass loss (corrosion) of the anodic Al plate during 100% RH exposure tests.

	Sensor output		**Anodic plate metal loss**		
Duration (hours)	Cs Measured cumulative charge (Coulombs)	Ws Calculated material weight loss (mg)	Wr Measured material weight loss (mg)	Cc Calculated cumulative charge (Coulombs)	Cs/Cc
17	10.3 ± 1.6	0.9 ± 0.1	9.5 ± 1.1	102 ± 12	0.10
27	16.0 ± 2.4	1.7 ± 0.2	11.5 ± 0.4	123 ± 4	0.13
42	32.0 ± 5.1	3.4 ± 0.5	16.6 ± 2.6	178 ± 28	0.18
66	37.2 ± 3.6	4.0 ± 0.4	19.0 ± 0.9	204 ± 10	0.18
98	68.0 ± 4.7	7.3 ± 0.5	30.0 ± 2.9	322 ± 31	0.21

It should be noted that after an initial conditioning of nearly 50 hours, the correlation factor becomes better and almost constant, i.e., ~0.2. Thus, indicating that a data collected over a long period of time would show a good reproducibility between sandwich coupons and different sensors.

Salt fog exposed sandwich coupons had poor surviving time, because salt moisture could quite easily penetrate the bee's wax used as seal between the plates and ICS unit. This destroyed the electronic module, which recorded the data. Although these limitations required further experimentations by means of new sealing systems, nevertheless it proved as a useful tool in making a comparative evaluation of various surface treatments and their corrosion resistant properties. In particular it was able to discriminate between the protective behavior of Chromium (III) and Chromium (VI) pretreatments.

During recent years considerable evidence has been developed to indicate that both Cr(VI) and Cr(III) oxide layer coming from hexavalent chromate conversion coating (CCC) and Trivalent chromium conversion coating, respectively inhibit the cathodic reaction (oxygen reduction) on Al alloys and forms a protective film that inhibits localized corrosion [5,6,7]. In addition, CCC has an active corrosion inhibition, due to the presence of Cr(VI) that provides self-healing properties for dynamic repair of defects; the high chromate's mobility and solubility inside the moisture producing corrosion seems to explain this particular behavior [8,9,10]. In short exposure period tests, although both pretreatments work well producing low I_g values, the comparison of the ICS cumulative charges allows to confirm that the most cathodic-anodic protection given by CCC permits less aluminum corrosion than the Cr (III) pretreatment (Figure 8). Based on the outputs observed during the tests (Figure 9), it is possible to extrapolate different slopes and demonstrate that two different corrosion rate processes operate - an indication that there is an evidence of early corrosion way before the surface degradation becomes appreciable by traditional accelerated tests and visual inspection methods. On the other hand, long-term salt fog exposures allow distinguishing two phases in the cumulative charge versus time behavior.

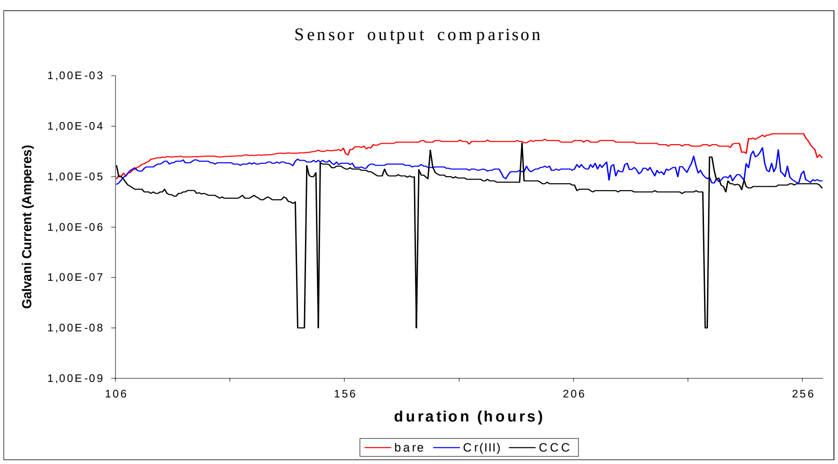

Figure 8: Different conversion coating data during salt fog exposure.

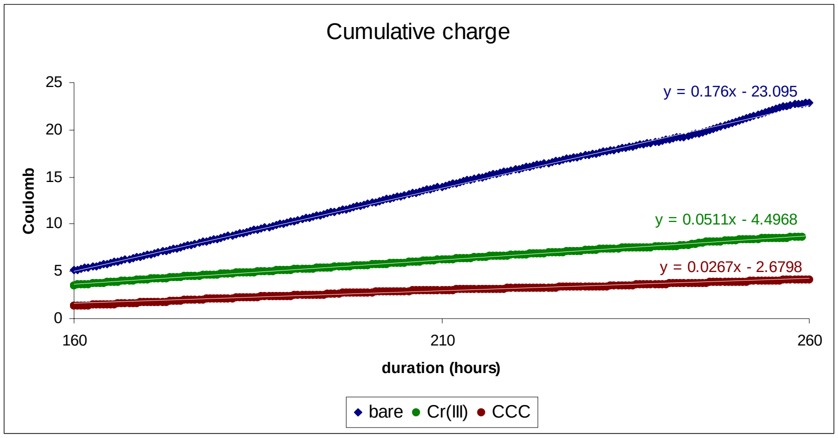

Figure 9: Cumulative charge behavior during salt fog exposure.

As shown from the Cr(III) pretreated coupon data (Figure 10), the first phase shows the protective activity of the pretreatment, a very low but increasing cumulative charge values suggestion that Cr(III) oxide layer perhaps acts as a primary barrier coating against environment, being effective for more than 15 days exposure. The second part of the curve, characterized by a different slope, shows much higher charge values good enough to be easily detected, represents a massive environment attack on substrate suggesting that this pretreatment is no more protective or able to inhibit corrosion. Other specific factors are supposed to affect time at which the protection is over, such as the lack of sealing efficiency (Figure 11) and some penetration moisture pathways forming in the fasteners hole areas (Figure 12). However, the graphs shown above do suggest that ICS technique can be used to monitor pretreatment efficiency, thus providing a meaningful warning signal before visual degradation of riveted parts, like crevice, pitting and mass loss can be observed.

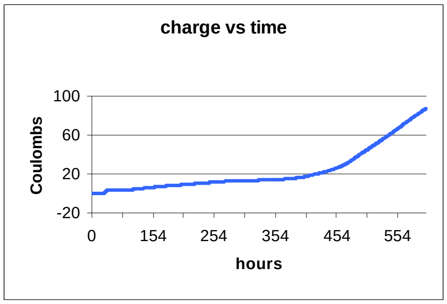

Figure 10: Cr(III) pretreated sandwich test coupon data.

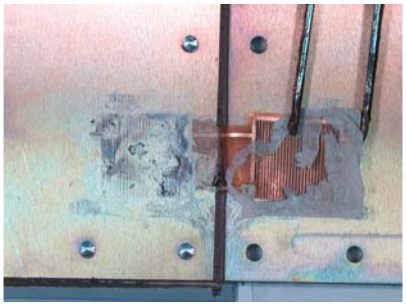

Figure 11: CCC pretreated coupon sandwich test coupon: inside view.

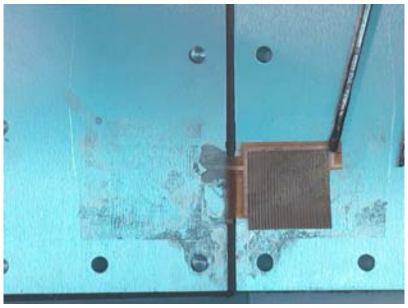

Figure 12: Cr(III) pretreated sandwich test coupon: inside view.

5.0 CONCLUSIONS AND POTENTIAL PAYOFFS

The ICS technology as used developed in this study can work very successfully as a direct corrosion probe for metal substrates. Preliminary data show that sensor output can be used as a meaningful tool in the evaluation of hidden surfaces corrosion, providing a quite accurate warning for subsequent inspection.

In near 100% RH, the bee's wax allows units to survive and to be re-used. The following factors that would further improve and/or extend this kind of corrosion monitoring should be considered in future works:

- Better sensor element design with more consistent gold film geometry on the sensor should improve confidence and data reproducibility;
- Use of better sensor sealing system on sensor/unit connections and better protection of ICS in high aggressive environments; and
- For aircraft application, both ICS monitoring systems, some working as corrosivity sensors and some working as corrosion sensor, would produce a more comprehensive data for even better prediction of the structural health in wide inaccessible areas.

6.0 REFERENCES

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