Galvanic Corrosion and Composites. “Galvanic corrosion is an electrochemical process in which one metal corrodes preferentially when it is in contact with a different type of metal and both metals are in an electrolyte [1].” Thus, corrosion of this type is always a concern when two different materials are to be in mutual contact. In the aerospace industry for instance, galvanic corrosion could occur when aircraft parts made from carbon fiber/epoxy composites (CF) are attached to metal parts of the airframe, particularly since carbon and aluminum are on opposite ends of the galvanic series [2,3]. Thus, when carbon is in direct contact with an Al alloy, the alloy will tend to corrode at a faster rate than it would if it were not coupled to the carbon. This raises serious concerns for aircraft performance and reliability (and for any application involving CF composites in contact with aluminum). Note that an electrolyte, such as humidity or salt water, is required for the galvanic process to occur. In fact, there are five requisite conditions that must be satisfied for composite-to-metal galvanic corrosion [3]: 1) an actively corroding metal, 2) an electrically conductive composite usually carbon fiber, 3) an electrical connection between the composite and the corroding metal, 4) salt water (electrolyte) and 5) oxygen. However, if any of these requirements are absent, galvanic corrosion will not occur. Instead, the components will corrode at rates that they naturally corrode when immersed in an electrolyte.

Figure 1 shows idealized conditions in which galvanic corrosion can occur between carbon composites and aluminum. In Figure 1(a), a typical galvanic corrosion experiment is shown in which the Al and CF are coupled through an ammeter. In Figure 1(b) a typical situation encountered in aircraft is shown in which Al and CF are in direct contact. Therefore, in aircraft applications, one common way to prevent galvanic corrosion from occurring between carbon composite and Al alloy components is to encase the carbon fiber composite component in a few plies of glass-fiber composite. The glass fiber layers provide a barrier between the metal and carbon fiber part, reducing or completely preventing a galvanic current from occurring [3,4]. Other sealants and plating methods are also used to prevent galvanic corrosion between carbon composites and the Al alloys in aircraft [3,4].

The effects of galvanic corrosion between carbon composites and Al alloys and steels have been studied extensively [2-5]. The research has shown conclusively that if the area of the anode \( (A_a) \) (aluminum) is large compared to the area of the cathode \( (A_c) \) (carbon fibers), then galvanic corrosion will be small. This is known as the effect of the area ratio, \( A_c/A_a \). The dissolution rate \( (r_d^a) \) of the anode is given by [2]:
COMPOSITE GALVANIC CORROSION

AIR

SALT SOLUTION

REACTION AT ALUMINUM SURFACE:
\[ \text{Al} + 3\text{Cl}^- \rightarrow \text{AlCl}_3^+ + 3\text{e}^- \]

REACTION AT COMPOSITE SURFACE:
\[ 4\text{e}^- + \text{O}_2 + 4\text{Na}^+ + 2\text{H}_2\text{O} \rightarrow 4\text{NaOH} \]
Figure 1. Conditions required for galvanic corrosion. (a) A typical galvanic corrosion experiment and (b) a typical configuration in which Al and CF are in direct contact, causing galvanic corrosion to occur [3].

\[ r_{d} = K(1 + A_c/A_a) \]  

where \( K \) is a constant. Even when the anode (the metal part) is coupled to the cathode (the carbon fibers), little corrosion will occur to the metal part, provided the area \( A_a \) is much larger than \( A_c \). Both cases in Figure 1 result in a large driving force for Al corrosion. However, in carbon fiber composites, the fibers are embedded in a polymer matrix, which effectively reduces the galvanic current [2]. Specifically, “the presence of the NH, \( \text{SO}_2 \) and \( \text{OH} \) groups of the epoxy resin may contribute to a variation of the free corrosion potential. The low electronic conductivity of the polymeric matrix hinders oxygen discharge, and thus, higher over-potentials are required to obtain the same current, as in the case of a graphite electrode” [2]. Thus, the epoxy matrix acts as a barrier between Al and the carbon fibers and reduces the galvanic current between the two materials. However, the matrix does not completely prevent galvanic corrosion, because some carbon fibers are exposed at the part surface [2]. These issues must be addressed in the design of new composite-and-metal products, such as overhead conductors.

ACCC/TW overhead conductor is comprised of trapezoidal wires (TW) of aluminum wrapped around a hybrid composite rod. The core of the rod is comprised of unidirectional carbon fiber/epoxy composite rod encased in a shell of glass fiber/epoxy, as shown in Figure 2. The glass fiber shell isolates the carbon fiber from the Al wires and prevents galvanic corrosion, just as in composite aerospace structures. Corrosion of the Al wires is limited to normal rates typical of aluminum in humid atmospheres, which is normally negligible because of the self-passivation of Al alloys that occurs naturally [3,4]. Pure Al, (1000 series Al, known also as electrical grade Al), is the most corrosion resistant of the Al alloys, and is the primary type of Al used in most overhead conductors. If electrical grade Al wires were to come into contact with carbon fibers from the core region, galvanic corrosion could occur, although the rate and extent of the galvanic corrosion would depend on the \( A_c/A_a \) ratio, as discussed previously. A few examples are considered below to illustrate the principles involved.
Case 1. Suppose the composite core of the ACCC/TW developed a longitudinal, crack along the length of the span, splitting the core into two semi-cylinders. This would expose two surfaces of carbon/epoxy. However, assuming the glass shell remained intact, there would be no physical connection to the Al, and thus galvanic corrosion would not occur. The corrosion of Al wires would depend on the electrolyte present, such as rain water, acid rain, water vapor, salt water vapor, etc. Thus, the Al would corrode at natural rates in these electrolyte solutions. Even if water were to inundate the conductor, such that the Al and carbon fibers were effectively immersed in water, galvanic corrosion would not occur, provided there was no physical connection bridging the Al wires and the carbon fibers. If, on the other hand, a few carbon fibers were to make contact between the carbon fiber core and the Al wires, then galvanic corrosion would be expected. However, given the small diameters of carbon fibers (typically 7 microns in diameter), and assuming relatively few contact points, the area of the Al wires would be orders of magnitude larger than the surface area of the bridging carbon fibers. Thus, according to the area fraction rule and equation 1, galvanic corrosion would be negligible.

Case 2. A second relevant situation concerns the development of a small crack in the glass/epoxy shell, measuring only 1/16\textsuperscript{th} of an inch in depth and perhaps a few inches in length. This would expose about 150 carbon fibers along lengths of a few inches. If such as crack were to fill with water, with no physical connection between the Al wires and carbon fibers, Al corrosion would proceed at a rate equivalent to the corrosion rate of Al when immersed in rain water. No galvanic corrosion would result from such a crack in the glass shell.

Case 3. A worst-case scenario could be realized if all of the matrix dissolved from the core at midspan - perhaps sublimating from a lighting strike or short circuit - (which has never been observed during testing), leaving only bare fibers. Provided the carbon fibers have no physical connection to the Al wires, the Al corrosion rate will depend only on the ambient environment. If, due to a complete loss of matrix combined with mechanical vibrations, the carbon fibers became co-mingled with the glass fibers, Al-CF contact could occur. In such case, electrons
would flow from the Al to the carbon, and the corrosion rate of Al would then be determined by two factors - the nature of the electrolyte (e.g., water vapor, rain water, or other material), and the surface area of the Al and carbon exposed to the electrolyte. In this case, the carbon fiber surface area could be comparable to (or even exceed) the surface area of the Al wires (depending upon how much of the aluminum strands might still be intact after some significant event), and the Al would undergo galvanic corrosion at a rate much greater than passive corrosion. However, if only a few of the carbon fibers were to make contact with the adjacent surface of the Al wire, then galvanic corrosion would not occur, because the surface area ratio would not favor accelerated corrosion of Al. On the other hand, if all the carbon fibers made contact with the Al, the Al would corrode rapidly, and a situation similar to Figure 1 (b) would be realized. Note that the galvanic corrosion could still be resisted to a significant extent by the natural self-passivation (oxidation) of the Al surface, in effect, creating a “contest” of competing processes, as long as the pH values of the solutions are between 4 and 8 [6]. For highly acidic alkaline solutions, corrosion will occur.

A 3.5% salt water solution is typically used as an electrolyte since it is known to accelerate galvanic corrosion. Salt water is also present in marine environments and is a major concern to many industries. Al alloys and steels are typically susceptible to salt water corrosion, primarily because of the chloride ion, Cl\(^-\), present in salt water. The chloride ion is small, and can penetrate the natural passivated layer of the Al and start to attack the Al, as shown in Figure 1 (b). Thus, while a 3.5% salt solution has a pH value of 6, the chloride ion is still able to attack the Al surface and cause corrosion, and accelerated corrosion occurs when the Al is coupled to the carbon cathode. Thus, preventative measures must be taken to prevent ferrous and aluminum alloys from undergoing normal and galvanic corrosion. For ACCC/TW overhead conductors, the preventative measure is intrinsic to the design of the product – an inert glass fiber shell surrounds the higher modulus carbon fiber composite core, all embedded in a toughened high-performance epoxy matrix.

**Results of Galvanic Testing:**

Galvanic cells, similar to the one shown in Figure 1(a), were assembled. The galvanic current was measured for a cell in which both the anode (Al) and cathode (CF) exhibited nearly the same area and the cathode (CF) surface area was 17\(\times\) smaller than the anode (Al) area. This experiment was performed to test Equation 1. For a 3.5% salt solution at room temperature, when the Al was not coupled to the carbon composite, the only visible sign of corrosion was observed at the location where the Al entered the water. Here, a small amount of discoloration was observed. The weight of the Al did not change after 3 days of exposure. However, when the Al was coupled to the cathode and the surface areas were comparable, there was significant weight change (~0.3%). A picture of the Al coupled to the cathode of nearly the same surface area is shown in Figure 3. In contrast, when the cathode area was 17\(\times\) smaller than the Al area, the Al weight loss was negligible (<0.1%). This test confirmed that when the CF surface area was smaller than the Al surface area, the galvanic corrosion was negligible.
The same experiment was performed in 4% ammonium nitrate (NH₄NO₃) solution at room temperature. Regardless of the CF/Al ratio used in this experiment, no corrosion of the Al was observed and no weight loss in the coupled or uncoupled Al was detected. This can be attributed to the size of the nitrate ion (NO₃⁻), which is much larger than the chloride ion. The nitrate ion cannot penetrate the passivated layer on the Al, and thus could not react with Al. Thus, we expect that even at 150°F, no galvanic or normal corrosion would occur when Al is in this electrolyte solution.

While the galvanic cell in Figure 1 (a) represents an ideal case, questions remain about how and if galvanic corrosion will occur if the carbon fiber were to become exposed and some fibers actually did touch the Al strands. Thus, additional experiments using small conductor samples were devised and undertaken. Figure 4 shows a cross-section of the ACCC/TW conductor. A notch, representing hypothetical severe damage to the core that exposes carbon fibers to the air and glass fibers are no longer shielding the carbon. A silicon cap is placed at the end of the carbon core to isolate it. In the first case, this notch is not filled with carbon fiber and there is no physical connection between the carbon and Al. In the second case, bare carbon fibers are inserted in the notch to provide a physical connection between the carbon of the core and the Al strands. This somewhat artificial configuration constitutes an extreme case that simulates a hypothetical local damage event in which all matrix material is eliminated (locally). In both cases, the carbon in the notch has only about 4% of the surface area of the inner Al surface area of the conductor.
Figure 4. Cross-section of the ACCC/TW conductor illustrating setup for galvanic corrosion experiments.
Figure 5 shows the experimental configuration for Case 1, in which the Al wires and carbon fiber core are coupled through a voltmeter and the conductor sample is immersed in 3.5% salt water electrolyte. (In Case 2, bare carbon fibers were inserted into a notch in the composite rod.) The voltmeter was used to record the galvanic current for both types of experiments for 4 days. For Case 1, virtually no galvanic current was measured, although the Al exhibited slight discoloration and loss of shine. In Case 2, where several thousand carbon fibers were touching both the exposed carbon in the notch and the Al strands, the galvanic current was on the order of $10^{-6}$ A. This value is comparable to the galvanic current reported for a CF-to-Al area ratio of 1:30 [6]. Inspection of the Al of the conductor revealed a similar discoloration in the Al, and slightly diminished reflectivity, (see Figure 6). No weight loss was detected.
Figure 6. ACCC/TW before and after exposure to 3.5% salt water solution for 4 days.

In these experiments, the measureable galvanic current was negligible, despite the presence of thousands of bare carbon fibers coupling the Al strands to the CF core region. The corrosion experienced by the Al strands in this case was identical to the corrosion that would result from simple immersion in salt water in the absence of galvanic coupling. The experiments are intended to simulate a “worst case scenario” for the ACCC/TW conductor. Thus, extended duration corrosion experiments (for a month or more) were deemed unnecessary. Prolonged exposures under conditions similar to those described in the present report are likely to produce similar changes in the Al finish, but nothing more.

In conclusion, these experiments described here, using Al and CF as electrodes and immersing the conductor assembly provide an accurate picture of what to expect for the ACCC/TW conductor in service conditions, should the Al wires come in contact with CF core material. Galvanic corrosion is likely to cause for concern only if the surface areas of carbon and Al in contact are comparable, a condition that is difficult to imagine. In a realistic scenario, carbon fibers might make contact with Al strands due to core fracture or local loss of matrix material (again, difficult to imagine), galvanic corrosion is expected to be negligible, because of the vastly dissimilar surface areas. The glass fiber shell that encases the carbon fiber core is more than sufficient to protect the Al wires against galvanic corrosion.

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