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Research Article

Effect of Partial Cladding Pattern of Aluminum 7075 T651 on Corrosion and Mechanical Properties

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The corrosion resistance of aluminum 7075 T651 in full clad (Alclad), partial clad, and bare (unclad) forms was compared after 300 hours of corrosion exposure in an acidic salt spray cabinet test at 36°C. After corrosion exposure, severe to moderate exfoliation corrosion was observed on the unprotected medium sized test panel, light general corrosion was observed on the partially clad panel, and patches of corrosion not penetrating the clad layer were observed on the fully clad panel. After corrosion tests, the tensile strength of partially clad, fully clad, and unprotected panels decreased by 3.4%, 4.0%, and 5.3%, respectively.

1. Introduction

One of the primary drivers for materials selection in the aerospace industry is to maximize the economic efficiency of aircraft [1]. Commercial aircraft of the past utilized the high specific strength of the high strength aluminum alloys of the 2000 and 7000 series almost exclusively for the construction of structural components [2]. These materials were selected in an effort to minimize aircraft weight resulting in maximized aircraft payloads and reduce fuel consumption. High strength aluminum alloys are susceptible to localized corrosion such as pitting, exfoliation, and stress corrosion cracking. Presently, corrosion resistance of materials is also of great concern because of the cost of corrosion inspections and the high cost of unscheduled maintenance and aircraft downtime associated with replacing corroded aircraft components [3]. Corrosion as well as the ability to construct larger structural components that are more easily joined has resulted in a shift in preferred construction materials from high strength aluminum alloys to composites for new aircraft [1]. In spite of this, aluminum alloys will remain an important structural material for aircraft components, especially in compression where composites are less suitable. This shift in materials selection has caused the need for aluminum alloy innovation to maximize specific strength while maintaining acceptable corrosion resistance for aluminum to remain a competitive material choice [2]. The susceptibility of high strength aluminum alloys to corrosion requires them to be protected from corrosive environment using an anodic coating for components with complex geometries or by using Alclad products with an aerospace coating system on sheet and plate components. Alclad products are produced by the metallurgical bonding of a high strength aluminum alloy core sandwiched between two layers of a more electronegative aluminum alloy. The outer aluminum cladding layers corrode preferentially when exposed to a corrosive environment and prevent corrosion to the core by cathodic protection. The Alclad layers can comprise up to 4% of the total sheet or plate thickness [4] and are assumed to carry no load, reducing the overall material specific strength by increasing the weight without contributing to the strength.

Petroyiannis et al. have suggested in previous works that a continuous cladding layer may be excessive and that the application of a partial cladding pattern may provide equivalent corrosion protection for aluminum 2024 T3 alloys [5, 6]. They have found that a partial cladding layer covering only 7% of the core aluminum substrate provides equivalent corrosion protection to the mechanical properties of Al 2024 T3 when compared to Alclad products after a 300-hour immersion exposure in a neutral 3.5% NaCl solution. However, they have also concluded that this accelerated corrosion test is likely too mild to accurately represent the corrosion environment experienced by in service aircraft [6].

In this work, an appropriate partial cladding geometry for Al 7075 T651 is estimated by exposing an aluminum panel with a single clad spot to an acidic salt fog accelerated corrosion environment. The area of the panel protected from corrosion by the clad spot is then estimated and used to determine dimensions for a two-dimensional array of clad spots applied to a medium scale test panel. For comparison, medium scale test panels in both the as-received Alclad state and having the entire cladding layer removed have also been produced. These three test panels were exposed to the acidic salt fog accelerated corrosion environment and the resulting corrosion was compared through visually rating and by producing characteristic cross sections. Tensile specimens were then machined from the three corroded panels as well as tensile specimens having undergone the same machining processes as the three panels unexposed to the corrosion environment. All of the tensile specimens were then tested and compared.

2. Experimental

2.1. Corrosion Environment. The corrosion environment selected for all of the experiments presented in this work was a 300-hour continuous acidic salt fog cabinet test in accordance with ASTM G85 Annex A1 [7]. The tests were conducted in a 120-liter benchtop Ascott S120ip salt spray chamber maintained at 36°C. The solution used to produce the acidic salt fog was composed of deionized water prepared with a Purite DC9 deionizing cylinder. The pH was then adjusted to a value between 3.1 and 3.3 by the addition of 99.7+% ACS reagent grade acetic acid purchased from Alfa Aesar. A solution salt concentration of 4–6 weight percent sodium chloride was produced by the addition of "Corro-Salt" purchased from Ascott. "Corro-Salt" meets the strict salt purity requirements detailed in ASTM B117 [8], namely, total impurities less than 0.3%, total halide (excluding chloride) composition of less than 0.1%, and a copper content of less than 0.3 ppm. The fog fallout rate was set between 1.0 and 2.0 mL per hour per 80 cm^2 horizontal area.

2.2. Single Central Clad Spot Panel. Initially a single clad spot test panel was produced from 6.35 mm thick Alclad Al 7075 T651 plate having a total area exposed to the corrosion environment of $10 \times 10\,cm^2$ with a square $1\,cm^2$ clad spot located in the panel center. The panel surface geometry was produced by mechanically milling approximately 0.19 mm over the panel surface removing the Alclad layer except at the clad spot. The cut edges and back surface of the test panel were protected from the corrosion environment with corrosion resistant polyvinyl chloride tape with the seams sealed with super glue gel. After corrosion exposure, the panel was cleaned in accordance with ASTM G1 [9]. The panel was cleaned with water and stiff brush to remove deposited salt and some of the bulk corrosion products. This was followed by a four-minute immersion in nitric acid at room temperature to remove the remainder of the corrosion products. The exfoliation damage to the panel was characterized by applying a 2.5×2.5 mm grid to the surface and estimating the percentage of the panel surface affected by corrosion in each grid section. This data was then used to produce a surface plot showing the distribution of corrosion damage relative to the protective clad spot. To characterize the penetration of the corrosion damage, the machining method for determining pit depth described in ASTM G46 [10] was adapted to better describe exfoliation penetration. Approximately 0.02 mm and 0.17 mm were milled from the corroded panel surface and surface plots were produced characterizing the extent of exfoliation corrosion penetrating to these depths. The surface plots of the initial single clad spot test panel were used to estimate the area of the test panel effectively protected by the clad spot and used to determine appropriate dimensions for a partial cladding pattern to be applied to a medium scale test panel.

2.3. Medium Scale Test Panels. A series of medium scale test panels were produced again from 6.35 mm thick Alclad Al 7075 T651 plate to investigate if a partial cladding pattern provides equivalent corrosion resistance when compared to Alclad in the selected corrosion environment. The medium scale test panels had a surface exposed to the corrosion environment of approximately 30×25 cm. The back surface and cut edges of the panels were protected for the corrosion environment using the same method described above for the initial single clad spot panel. Three medium scale test panels were produced to compare the relative corrosion resistance of fully clad aluminum plate, aluminum plate with a partial cladding pattern, and aluminum plate with no cladding. The fully clad test panel remains in the as-received Alclad form. The partially clad test panel was produced by mechanically milling the Alclad layer over the majority of the panel surface producing 1×1 cm clad spots. The clad spots were arranged in a two-dimensional array spaced 2 cm apart. During the machining process of the partially clad test panel, it was desired that only the Alclad layer be removed by milling approximately 0.19 mm from the panel surface to produce the clad spots. Due to difficulties in the machining process, such as the panel not being perfectly flat and issues with affixing the aluminum panel to the CNC milling machine, an average thickness of 0.69 mm was removed from the panel thickness to produce the clad spots. This resulted in the clad spots being comprised of both the cladding layer and a significant thickness of the high strength aluminum 7075 core. The presence of the layer of Al 7075 within the clad spots is not expected to significantly affect the corrosion behavior of the partially clad panel but may influence the mechanical testing results. The test panel with no cladding was produced by removing the entire Alclad layer through mechanical milling.

The experimental approach is highlighted in Figure 1 indicating schematic cross sections of the three medium sized

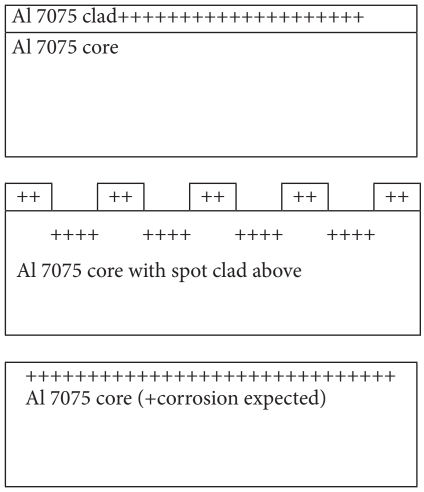

Figure 1: Schematic cross sections of the three medium sized test panels indicating the location (+) of corrosion products expected after corrosion testing. All test panels have visual exposed areas of 30 × 25 cm to salt spray. Alclad means full clad, while spot clad (partial clad) and unclad were machined to remove part or all of the clad layer.

test panels with a plus symbol (+) to indicate the expected development of corrosion products starting at the surface. All test panels have visual exposed surface areas of 30 × 25 cm to salt spray corresponding to Figure 1. Alclad means full clad, while spot clad (partial clad) and unclad were machined to remove part or all of the clad layer.

After exposure to the corrosion environment, the medium scale test panels were cleaned in the same method as the initial single clad spot test panel described above. The corrosion damage resulting from exposure to the acidic salt fog environment on the medium scale panels was qualitatively compared through visual observations and through cutting representative cross sections from each of the test panels. The cross sections were cut from various locations on the medium scale test panels with and Isomet 11-1180 low speed saw and then mounted and polished in SamplKwick fast dry acrylic. The cross sections were viewed at 100x magnification with a Nikon Eclipse 50i optical microscope and images were captured with an Infinity 1 microscopy camera.

Rectangular tensile specimens were cut from each of the corroded medium scale test panels in accordance with ASTM B557 [11]. For comparison, tensile specimens were prepared from uncorroded Al 7075 T651 that has undergone the same milling processes as the medium scale test panels, two tensile specimens for each of the panel surface geometries. All of the tensile samples were tested in accordance with ASTM B557 with an Instron 5585H load frame using wedge type grips. The crosshead speed of all the tensile tests was 5 mm/minute and the strain during the elastic section of the tests was measured using an Instron 2630-106 clip on extensometer with a gauge length of 25 mm.

Materials characterization by scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) was

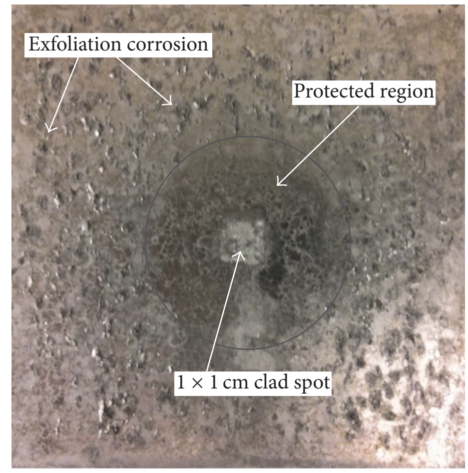

Figure 2: Optical microscopy of a cleaned central clad spot panel, 1 square cm clad spot.

performed using a JEOL-JSM-6000 operating at 15 kV in order to verify the Alclad 7075 cladding, core, and corrosion product elemental analysis (i.e., red corrosion product containing 7.71 mass% Cu). The SEM-EDS results verified the alloying elements of the Alclad layers (cladding, core) as specified by the North American supplier of Alclad in their Al 7075 technical specification, expected reactions, and corrosion products. The Al-alloy clad layer reacts to form Al_2O_3 with Al dissolution; and Al-alloy core reacts to form Al-Cu corrosion product via the elemental Cu level increase from 1.50 to 7.71 mass% to be discussed further in the results and discussion sections. The Al_2O_3 was confirmed by X-ray diffraction using a Rigaku Ultima IV operating with Cu K-alpha radiation at 40 kV and 44 mA. Image analysis was also employed using a PAX system in order to estimate the percentage of surface area that corroded.

3. Results

3.1. Single Central Clad Spot Panel. After exposure to the acidic salt fog corrosion environment and cleaning, it can be seen in Figure 2 that there are two regions of interest on the central clad spot panel. A roughly circular region adjacent to the clad spot has been protected from the corrosion environment due to the clad spot acting as a sacrificial anode. The remainder of the panel shows corrosion that could be described as moderate exfoliation [12] or as poorly defined pitting with a large degree of horizontal propagation and delamination [9].

The optical image analysis system application of a grid on the corroded surface was used for an estimation of the percentage of the area of each grid section showing signs of corrosion on the three panels (central clad spot, 0.02 mm and 0.17 mm milled). From these surface plots, the area of the central clad spot test panel effectively protected by the clad spot was estimated as a 3 × 3 cm square. This dimension was used to produce the medium sized test panel with a clad spot pattern. It was estimated that a two-dimensional array of

1 cm^2 clad spots spaced 2 cm apart is sufficient to protect the panel surface from corrosion after a 300-hour exposure in the acidic salt fog environment.

3.2. Medium Scale Test Panels

3.2.1. Initial Visual Observations of the Medium Scale Test Panels. Upon visual inspection of the Alclad medium scale test panel, shallow irregularly shaped corrosion patches are fairly evenly distributed over the panel surface. Smaller, pit-like corrosion is also evident in the cladding layer. It appears that pitting has initiated in the cladding layer and progressed until reaching the aluminum core where the pits widened laterally, combining to form larger corrosion spots. From these observations it appears that the Alclad layer has successfully protected the high strength aluminum core by corroding preferentially in the acidic salt spray environment.

After corrosion exposure, exfoliation corrosion was observed over the entire surface of the panel with the cladding removed. Using the exfoliation corrosion rating system described in ASTM G34, the observed corrosion could be described between pitting and moderate exfoliation. Distinct pit-blisters were observed but with more lifting of the aluminum along the pit edges than is described in the standard. The blistering and lifting of slivers of uncorroded aluminum at the pit edges more closely resembled moderate exfoliation but there is less layering than described in the standard. Overall the observed corrosion can best be described as pit-blisters that have exposed grain boundaries allowing intergranular corrosion in the form of exfoliation to occur in tandem. Where multiple pit-blisters interacted to lift continuous sheets of uncorroded aluminum, the corrosion began to resemble moderate exfoliation. An unexpected observation is the "red colored" corrosion products presumably due to copper since the elemental Cu level increase from 1.50 to 7.71 mass% as measured by energy dispersive spectroscopy over the majority of the panel surface.

The corrosion observed over the partially clad medium scale test panel after acidic salt spray exposure was not uniform. Five distinct regions of corrosion behavior were observed: (1) The surface of the clad spots experienced general corrosion, where the Alclad layer was depleted as a sacrificial anode, protecting the overall panel surface. (2) The majority of the panel surface was successfully protected by the partial cladding pattern. This is evident where the surface retained the shiny appearance and milling marks from the machining process. (3) General corrosion with red color resembled what was observed on the unprotected test panel. (4) Light general corrosion located between the red colored region and the shiny noncorroded region. (5) Finally, there are small patches of corrosion distributed throughout the noncorroded region of the panel. These patches are generally located adjacent and below the clad spots. These patches of corrosion can possibly be explained by the acidic salt solution stagnating in the raised edges of the clad spots or within milling marks and leading to crevice corrosion.

3.2.2. Representative Cross Sections of the Medium Scale Test Panels. Many cross sections cut from the medium scale test panels largely confirm the initial visual observations made of the corroded panels. Figure 3 shows one of the large corrosion patches distributed over the Alclad test panel surface. Dense pitting penetrating the Alclad layer until reaching the high strength aluminum core and widening laterally, combining to form larger shallow pits, is evident. Alclad that was representative of the majority of the test panel exhibited a smooth surface and intact cladding layer, indicating that these regions were unaffected by the corrosion environment.

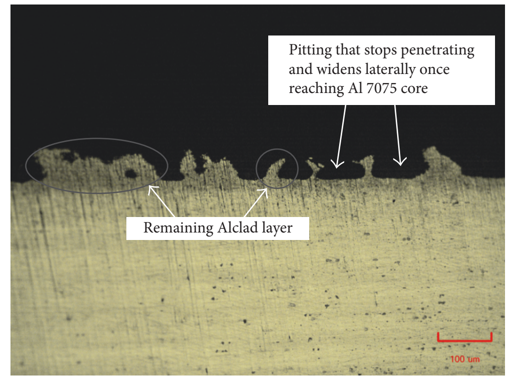

Figure 3: Clad panel and region after corrosion, 100x magnification and 100-micron bar.

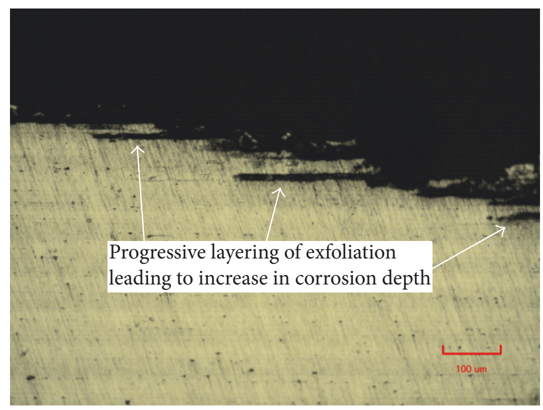

Figure 4: Unclad panel deep exfoliation damage, 100x magnification and 10-micron bar.

Figures 4 and 5 are cross sections representing the corrosion observed on the bare test panel. Figure 4 shows successive layers of exfoliation resulting in increasing corrosion penetration depth after corrosion product expansion. As slivers of uncorroded aluminum are lifted from the substrate, additional grain boundaries are exposed to the corrosion environment and a new layer of exfoliation corrosion is initiated. Figure 5 shows one of the few examples of a well-defined pit in the unclad test panel. The absence of many examples of pitting can be explained by the large number of grain boundaries exposed by the pit. The pit initiates intergranular corrosion that progresses into exfoliation and obliterates evidence of the pit [13, 14].

Table 1: Mechanical properties summary.

Property/material	Mechanical property and change (Δ) due to corrosion					
	No cladding		Spot cladding		Full clad	
	Corrosion	No corrosion	Corrosion	No corrosion	Corrosion	No corrosion
Tensile strength (MPa)	550 Δ-5.3%	581	561 Δ-3.4%	581	551 Δ-4.0%	574
Yield strength (MPa)	520 Δ2.2%	509	528 Δ3.9%	508	520 Δ3.4%	503
Young's modulus (GPa)	66.5 Δ-7.4%	71.8	70.5 Δ1.0%	69.8	69.1 Δ3.6%	66.7
Elongation (%)	13.7 Δ-18.4%	16.2	13.5 Δ-8.7%	14.8	17.3 Δ-4.2%	18.1

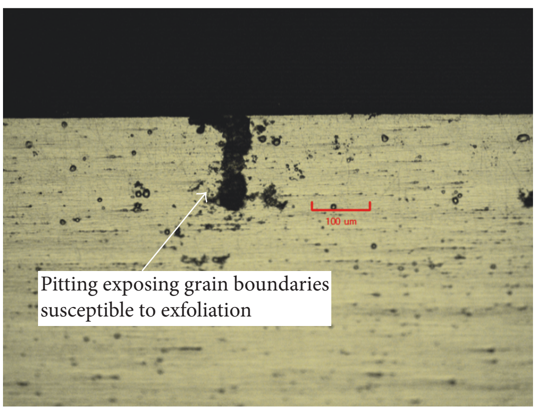

Figure 5: Unclad panel and evidence of pitting, 100x magnification and 100-micron bar.

3.3. Mechanical Properties. Table 1 shows the mechanical properties summary of the tensile specimens cut from the corroded medium scale test panels and the tensile specimens that have undergone the same mechanical processes but have not been exposed to the corrosion environment. When comparing the corroded and the uncorroded tensile specimens, there is a decrease in tensile strength in each case. The partially clad test panel exhibits the smallest decrease in tensile strength with a percent decrease of 3.4%. This was followed by the fully clad test panel with a tensile strength percentage decrease of 4.0%. Finally, the cladding removed panel showed a percentage decrease in tensile strength of 5.3%.

In all cases, the yield strength of the tensile specimens increased after corrosion exposure. The spot clad, fully clad, and cladding removed test specimens showed a percent increase in yield strength of 3.9%, 3.4%, and 2.2%, respectively. This trend is interesting, as it is expected that the yield strength would decrease with corrosion exposure.

Young's modulus of the spot clad and fully clad test panels increased after corrosion exposure while there was a decrease for the bare test panel. The percent increase in Young's modulus for the spot clad and fully clad test panels was 1.0% and 3.6%, respectively. The percentage decrease in Young's modulus for the unprotected panel was 7.4%.

In all cases, there was a decrease in percent elongation after corrosion exposure. The percent decrease in percent elongation for the cladding removed, spot clad, and fully clad test specimens was 18.4%, 8.7%, and 4.2%, respectively.

4. Discussion

The single central clad spot panel was used to evaluate the region of corrosion surrounding the surface containing a 1 × 1 cm spot clad. Optical image analysis tools can provide an estimate of corroded surface area and from this approach the spot clad spacing of 2 cm was determined to be sufficient for adequate corrosion protection. For more quantitative analysis additional work would be required and it should therefore be considered by characterization methodologies such as scanning electron microscopy with energy dispersive spectroscopy capable of X-ray mapping chemical elements and also comparison of one spot to perhaps an array of four spots. From the visual observations and representative cross sections of the medium scale test panels, it is apparent that the cladding layer of the Alclad test panel successfully protected the high strength aluminum core from the corrosion environment. Conversely, the absence of the cladding layer was detrimental to the corrosion resistance of the bare test panel. Uniform exfoliation corrosion was observed over the entire panel surface after corrosion exposure. The corrosion to the high strength aluminum core observed on the partially clad test panel remained mild when compared to the bare panel but was somewhat more severe than the Alclad panel.

From the visual observations and representative cross sections of the medium scale test panels, it is apparent that the cladding layer of the Alclad test panel successfully protected the high strength aluminum core from the corrosion environment. Conversely, the absence of the cladding layer was detrimental to the corrosion resistance of the bare test panel. Uniform exfoliation corrosion was observed over the entire panel surface after corrosion exposure. The corrosion to the high strength aluminum core observed on the partially clad test panel remained mild when compared to the bare panel but was somewhat more severe than the Alclad panel.

An unexpected result was the red coloring of corrosion products on the bare test panel. It is believed that the red colored corrosion products are the result of alloyed copper dissolving into the corrosive electrolyte and plating back onto the aluminum alloy substrate.

During the corrosion of aluminum alloys containing copper as a major alloying element, in the presence of chloride ions, copper containing intermetallic particles found in Al 7075 T651 such as $MgCu_2$ or Al_2CuMg can be subjected to dealloying where magnesium and aluminum are selectively dissolved, leaving behind a microporous region consisting primarily of elemental copper. These high surface area regions of copper can then act as a local cathode and cause pitting and trenching to the alloy adjacent to the copper. It is then possible for the copper region to detach from the aluminum alloy, dissolve into the corrosive electrolyte, and electrically be plated back onto the alloy surface [15, 16]. The presence of the plated copper could then cause galvanic corrosion, accelerating the overall corrosion rate of the bare test panel.

The red corrosion products believed to be copper were also present on the partially clad test panel. The location of the red corrosion products on the top edge of the panel surface where there are not yet any clad spots may suggest that the ability of the clad spots to protect the aluminum substrate from corrosion exposure may be influenced by the downward flow of the corrosive electrolyte as the acidic salt fog is deposited on the surface. If the red coloring is plated copper, as is believed, the area of light general corrosion on the partially clad panel may be explained by galvanic corrosion caused by the copper accelerating the corrosion rate in this area.

From the results of the tensile testing of the medium scale test panels, the tensile strength and percent elongation show the most conclusive results. The results for the yield strength and Young's modulus remain fairly ambiguous, possibly because the aluminum plate selected for the experiment was rather thick (6.35 mm) and it is possible that the corrosion damage on all three test panels was superficial when compared to the plate thickness.

From the tensile strength results, the partially clad test panel had the smallest reduction in tensile strength after corrosion exposure with a percent decrease of 3.4% while the Alclad and bare panels had percent decreases of 4.0% and 5.3%, respectively. This suggests that the partial cladding pattern successfully protected the test panel from the corrosion environment when compared to the Alclad and bare panels. The fact that the tensile strength of the bare test panel was not more severely affected by the corrosion environment may suggest that the selected corrosion environment was too mild for the corrosion damage to significantly affect the tensile strength for 6.35 mm aluminum plate.

The results for the degradation in percent elongation of the test panels in this experiment suggest that the ductility of the aluminum was significantly affected by both the machining processes conducted on the aluminum plate and the corrosion environment exposure. The percent decrease in percent elongation for the bare, spot clad, and fully clad test specimens after corrosion exposure was 18.4%, 8.7%, and 4.2%, respectively. In this instance, the Alclad test panel outperformed the partially clad test panel but the partially clad panel performed much better than the bare panel. The percent elongation of the uncorroded spot clad, bare, and Alclad test panels was 14.8%, 16.2%, and 18.1%, respectively. These values differ significantly and imply that the machining processes subjected to each of the test panels had an effect on ductility. It is possible that the milling of the surface of the bare panel had a work hardening effect that reduced overall panel ductility. For the partially clad test panel, it is believed that the presence of the clad spots comprising not only the soft Alclad layer but also a thickness of the high strength aluminum core reduced overall ductility by reinforcing the sections of the test specimens with clad spots. As a result, the majority of the deformation of the tensile specimens occurred only in locations without the clad spot and the specimens fractured with an overall lower percent elongation.

When correlating mechanical properties results to corrosion test data and microstructure the issue of uncertainties deserves some discussion. Since these mechanical properties results are presented after several times of testing it is important to include the following caveat (i.e., the results fall within the uncertainties of experimentation that includes sample homogeneity, aging, microstructure, machining, anisotropy, residual stress, equipment calibration, grip forces, and work hardening); otherwise conclusions can be misinterpreted, misused, and misleading.

Therefore additional research study inclusive of detailed uncertainties analysis is recommended in order to verify the general trends in results that only approximate spot clad and fully clad mechanical properties. In general, the overall performance of full clad (Alclad) to corrosion should favor the clad versions (full clad = Alclad, partial clad) over unclad because aircraft alloys in service are normally held to a high level of standard in terms of performance, risk, and safety.

5. Conclusions

(1) The spot clad spacing of 2 cm was determined to be sufficient for adequate corrosion protection.

(2) After corrosion tests, the tensile strength of the partially clad, fully clad (Alclad), and unprotected test panels decreased by 3.4%, 4.0%, and 5.3%, respectively.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

The authors involved are the graduate student Evan Rendell who performed the original research and master's thesis under supervision of Dr. Amy Hsiao and Dr. John Shirokoff the latter of whom created the paper from the thesis and performed some additional research and writing to clarify and validate specific results.

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