Standardized Test Method for Corrosion Pit-to-Fatigue Crack Transition in AA7075-T651 Aluminum Alloy

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Abstract

Corrosion damage (pit) is a stress raiser that can have deleterious effects on the fatigue life of airframe structural components. A better understanding and method for modeling the corrosion pit to fatigue crack transition would advance the fidelity of aircraft structural integrity estimates and fleet management decisions. Here, the focus is on developing a standardized fatigue test method for investigating the transition of a corrosion pit to fatigue crack in aluminum alloy AA 7075-T651 specimens. The standardized test method requires the development and validation of several sub-protocols (1) a pitting protocol to create a corrosion pit, less than 200 μm diameter at the intersection of the central hole bore and planar surface of sheet and (2) a spot welding protocol for attaching the direct current potential drop (dcPD) probes on either side of the corrosion pit for fatigue crack growth measurement. A dcPD fatigue test method coupled with a unique 10-4-6 marker sequence is used to measure the fatigue crack growth. The crack shape evolution and crack growth life are predicted using AFGROW.

Introduction

Corrosion damage has a strong deleterious effect on the fatigue life of airframe structural components. Corrosion damage in the form of pits often occurs near rivet holes in the presence of environments such as humid air and salt water. Fatigue cracks often nucleate and grow from corrosion pits as they act as stress concentrations. A standardized specimen and testing protocol to evaluate the relative influence of the environment, corrosion inhibitors and loading spectrum on the corrosion pit to fatigue crack transition is lacking. The transition of a fatigue crack from a corrosion pit is a complex process. Local macro- and micro-topography of a corrosion pit influence the transition from a corrosion pit to fully formed (continuous crack front from the plate surface to hole bore) fatigue crack. It is often assumed in aircraft damage tolerance analysis that the majority of fatigue life of a component is consumed before the crack is 1.27 mm in length. Therefore, understanding the transition from a corrosion pit on the order of 200 μm to a mechanically small crack is paramount.

The present investigation deals with the development of a standardized test method to determine the corrosion pit to fatigue crack transition in AA7075-T651 specimens with a central hole. The development and validation of several intermediate procedures leading up to the standardization are discussed.

Experimental Procedure

Legacy aluminum alloy and heat treat (AA7075-T651), Al–Zn–Mg–Cu alloy 7075 (Al - 5.7 Zn - 2.53 Mg -1.66 Cu - 0.263 Fe - 0.06 Si - 0.026 Mn - 0.19 Cr - 0.02Ti; wt.%) in the peak aged T651 temper (24 hours at 120 °C) obtained from the Defense Advanced Research Projects Agency

(DARPA) Structural Integrity Prognosis System (SIPS) program [1] is used in this study. Mechanical properties of this alloy are: tensile yield strength (σ_{ys}) was 508 MPa and plane strain fracture toughness (K_{IC}) in the longitudinal–transverse (L–T) orientation was 33 MPa√m. Figure 1 shows the specimen design and dimensions as well as the corrosion pit dimensions. For each specimen the flaw to nucleate the fatigue crack was a small controlled corrosion pit (less than 200 µm diameter) inserted at the edge of the bore hole. Copper wires (0.127 mm diameter) which are used as potential probes are spot welded on each side of the corrosion pit by means of an in-house spot-welding setup. The sample was then loaded into a computer-controlled servo-hydraulic test frame and tested with a direct current potential drop (dcPD) system to monitor crack growth [2, 3]. The dcPD method coupled with load induced marker bands are used to measure the fatigue crack growth. A fatigue crack was propagated from the pit until the crack reached approximately 1.5 mm in length, and then the test was terminated and the sample pulled to failure by static overload. The procedures involved in generating the corrosion pit followed by the spot-welding of probe wires are given below:

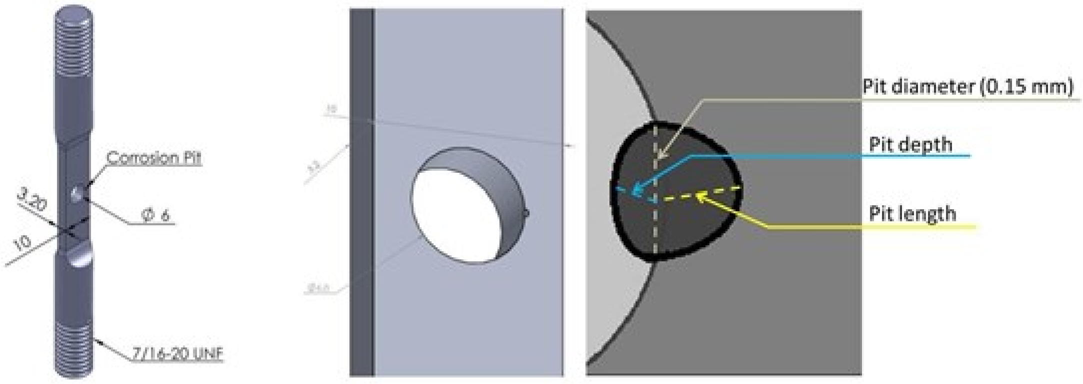

Fig. 1. Specimen geometry and corrosion pit with dimensions (in mm)

Pitting Protocol. The specimen is held at an angle on a stand such that both surfaces (flat surface and curved surface of hole bore) of the hole edge are clearly visible. The portion of specimen near the center hole is cleaned with isopropanol to remove any dirt. A 0.2 mm diameter hole is made by using a drill bit in an acid-resistant tape (0.107 mm thick) with dimensions of (9 mm × 2 mm). This tape with hole is carefully placed on the hole edge by means of tweezers such that both metal surfaces are visible through the tape's hole. Care must be taken to ensure that the tape's hole is clear of tape debris or glue. The specimen (except at the tape's hole) is masked with a stop-off lacquer and dried for one hour. Corrosion pitting of the specimen takes place in a pitting solution (0.1 M $AlCl_3$ + 0.86 M NaCl with HCl added to make the pH 2) with a two-electrode corrosion setup. A very low constant current of 0.2 mA is passed for a prescribed time (1.5 min), obtained per Faraday's law calculations [4].

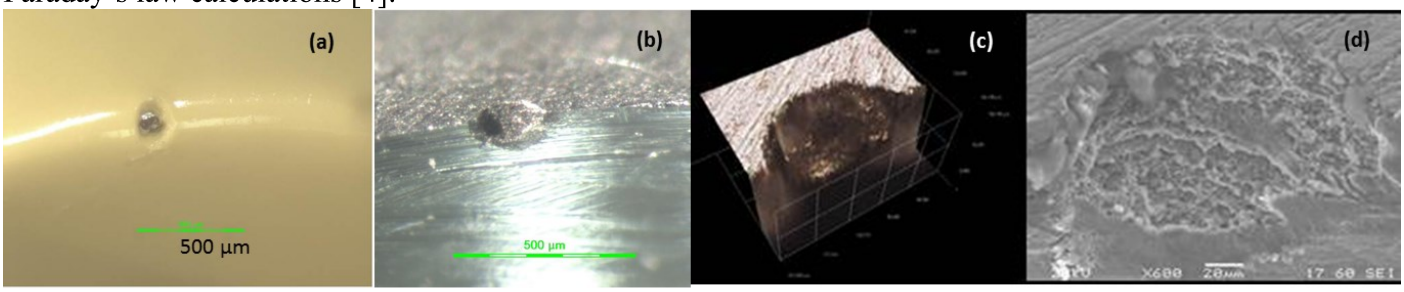

Fig. 2. Example of tape placement at the specimen hole edge, corrosion pit (optical, HIROX and SEM images) on AA7075 T651 specimen.

Since the tape's hole is very small, the pitting solution needs to be circulated using a peristaltic pump and directed toward the hole in the specimen. The specimen is removed from the solution, cleaned with water and placed under an optical microscope to observe the corrosion pit. A dark region in the tape's hole indicates the formation of a pit. The tape and coating are removed and the specimen is cleaned with water and then ultrasonically cleaned in isopropanol for 15 min. Figure 2(a) shows the optical image of tape's hole through which the alloy surface is clearly visible. Figure 2(b), (c), and (d) show the optical, HIROX digital microscope and scanning electron microscope (SEM) images of the corrosion pit on the specimen. The complete corrosion pitting protocol is published in [5]. The micro-topography of the corrosion pit is examined by the SEM and the pit dimensions are measured using the HIROX digital microscope.

Spot-welding Protocol. The specimen with a corrosion pit is now ready for spot-welding of potential probes for the dcPD crack growth monitoring. Polytetrafluoroethylene (PTFE) insulated pure copper wires (0.127 mm diameter) are used as potential probes. The copper wires are spot-welded on each side of the corrosion pit equidistant from the pit centerline. The spot welding process is accomplished by an in-house designed and manufactured spot-welding apparatus [6]. The wire positioning pulleys allow for the precise spacing between the probe wires on each side of the corrosion pit.

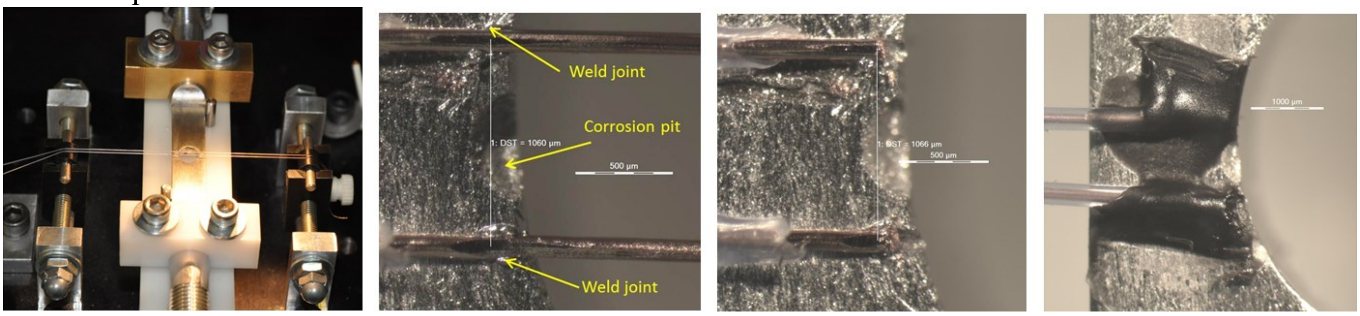

Fig. 3. Examples of wire spacing, weld joints and electrically insulated weld joints on an AA7075-T651 specimen.

An optimum energy level was determined from earlier trials such that a single stable weld joint can be made on each of the probe wires. It is very important to carefully place the wires such that the PTFE insulation of the un-stripped copper wire is as close as possible to the corrosion pit. After welding, the two copper wires are carefully cut with a razor blade at the weld joints. The bare portion of the copper wire away from the weld joint is coated with a Performix® liquid insulation tape so that the potential probes are free from any electrical contact with the alloy specimen except at the spot weld regions. Figure 3 shows the example of wire placement, weld joints, and electrically insulated weld joints. The complete spot welding procedure is published in [6].

Fatigue Test

The principle of dcPD method of monitoring crack length is that the electrical resistance of a cracked body changes with crack length. On application of constant current to a specimen, the change in electrical resistance results in a change of potential drop between the two measuring points (potential probes) across the crack. A closed-form analytical model was used to relate the measured potential to the crack length as a function of crack shape, probe position and probe spacing relative to the growing crack.

Variable amplitude fatigue test on an AA7075-T651 specimen (shown in Figure 1) in lab air is described in this paper. Dimensions of corrosion pit are pit length (c): 0.220 mm and pit depth (a): 0.180 mm. The probe spacing on either side of the corrosion pit is 1.063 mm. The sample is loaded into a computer-controlled servo-hydraulic test frame and tested using the dcPD method. A constant current of 10 A is passed through the specimen from a dedicated power supply and amplifier. A unique 10-4-6 marker band loading spectrum [7] is introduced into the loading sequence to determine the evolution of the crack shape by post-test crack dimension measurements. In addition, the marker bands are used to validate the dcPD calculated crack length. The fatigue testing was conducted and test data are stored by means of the Automatic Fatigue Crack Growth Software provided by Fracture Technology Associates (FTA) [8]. In order to establish the initial voltage of the corrosion pit, the specimen is subjected to constant amplitude loading cycles at a very low load such that a crack does not nucleate. The dcPD signal was observed over time to ensure sufficient signal stability. It is well known that the electrical conductivity of aluminum alloys is acutely sensitive to temperature [3, 8]. To ensure sufficient stability of voltage signal both due to specimen heating and mechanical stability due to surroundings, the dcPD signal was observed over time prior to the fatigue test. The stabilization of dcPD signal (voltage) is achieved during constant amplitude cycling at low load. Typically, the stabilization of dcPD voltage can be achieved in one hour. Stabilization of dcPD signal is indicated by the signal fluctuation within ± 0.01 μV which is considered adequate for crack growth detection. After establishing the initial voltage for the corrosion pit, the specimen is tested at a maximum applied remote stress of 120.7 MPa, stress ratio (R) = 0.65, and a frequency of 5Hz with the marker band loading spectrum. At the beginning of the test, the dcPD voltage shows transient readings prior to the crack growth. The transience of dcPD voltage can be attributed to the sudden increase in remote applied load (P_{max}) on the specimen. The voltage corresponding to the corrosion pit can be obtained by averaging the voltage signal prior to the crack growth. The crack nucleation is identified when the dcPD voltage signal crosses a threshold value. The threshold value for the current specimen dimensions and potential probe spacing is given by a normalized voltage ratio (V/V_o) of 1.002, where V_o and V are the initial and instantaneous dcPD voltages respectively. The voltage signal clearly rises after crossing the threshold value indicating crack growth. A steep rise in the dcPD voltage is indicative of the crack becoming a fully formed (continuous crack front from the plate surface to hole bore) fatigue crack. The test was terminated when the crack in the specimen width direction reached approximately 1.5 mm in length and the sample was pulled to failure by static overload.

Results and Discussion

The fatigue tested sample was analyzed for marker band locations using the SEM and corresponding crack growth pattern was plotted. Post-test analysis of the fractured surface using an SEM reveals the crack shape evolution with time from the known defect (corrosion pit) to the final crack length of 1.5 mm. Since the crack originates at the corrosion pit which is at a corner of center hole of the specimen, the crack propagates in two directions along the hole surface ‘a’ and outer surface ‘c’.

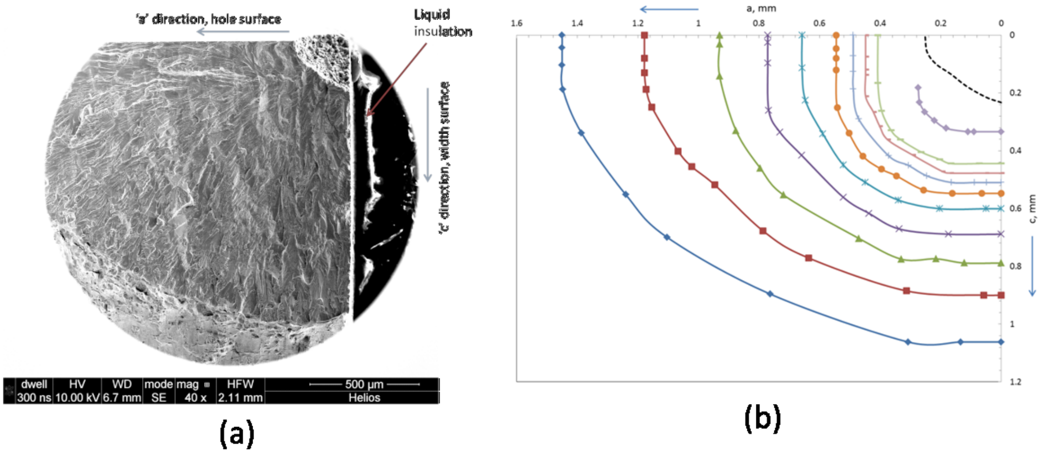

Fig. 4. SEM image of the fractured surface and marker band profiles of crack shape evolution.

Figure 4 (a) shows the SEM image of the fractured surface showing the corrosion pit and final crack length and (b) shows the marker band profiles during crack propagation. The specimen reached the final crack length of 1.5 mm after 61,924 cycles. Each “10-4-6” marker band loading constitutes 8,170 cycles. A total of 7 complete “10-4-6” marker band loading programs and one 10 marker were programmed during the fatigue test before the final crack length was reached. The post-test fractography by SEM revealed the crack propagation by means of marker band profiles which are shown in Figure 4 (b). The experimental crack dimensions (a, c) are obtained from the plot of Fig. 4(b) as periphery cracks (crack profiles that connect to the both ends) and corresponding fatigue cycles are obtained from the programmed loading cycles. The innermost profile (dashed curve in Figure 4(b)) refers to the outline of corrosion pit.

AFGROW Analysis and Crack Growth Rate Calculations. An analytical relationship between measured electric potential and crack length was developed by Roe and Coffin [9] for a three dimensional ellipsoidal surface disturbance in an infinite plate. The influence of initial defect on near-defect crack monitoring was modeled for a specimen with a specific initial defect (corrosion pit) and potential probe dimensions [10]. Potentials corresponding to the AFGROW predicted crack growth profiles are obtained from the analytical solution. Crack growth rates for the experimental data in both directions are calculated using the incremental polynomial method [2].

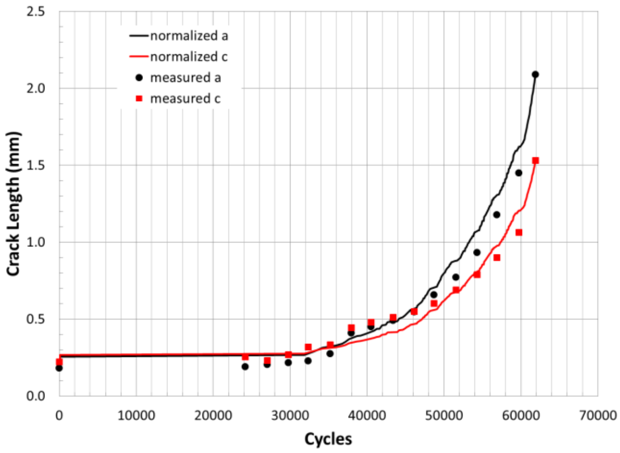

Fig. 5. Comparison of dcPD calculated and experimental crack lengths (a, c)

Figure 5 shows the comparison between the experimental crack length and depth to those of dcPD calculated values. The calculated crack length and depth are normalized with respect to the initial pit dimension and final crack dimensions. The aspect ratio (a/c) of the crack was less than 1.0 at the beginning and exceeds 1.0 after 46,000 cycles. The crack growth based fatigue life is predicted using AFGROW [11].

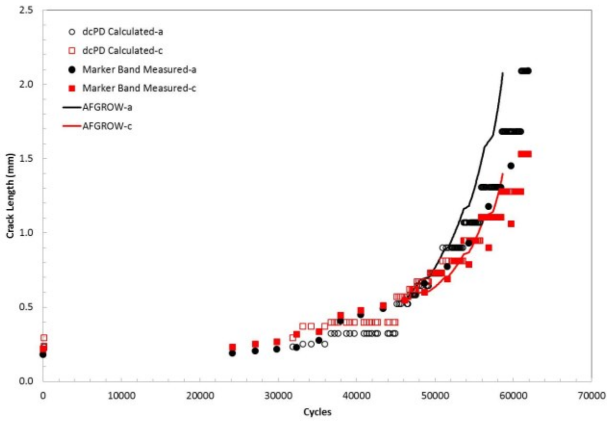

Fig. 6. Comparison of AFGROW predicted crack length and depth (a, c) profiles to that of experimental data

AFGROW is a fracture mechanics and fatigue crack growth analysis software tool that allows crack initiation and growth to predict the life of metallic structures. Corner crack solutions developed by Fawaz and Andersson [12] are used for the crack growth rates. Figure 6 shows the AFGROW predictions done from a periphery crack (orange filled circles in Fig. 4(b)) as functions of cycles. The variation in 'a', 'c' dimensions with that of measured 'a', 'c' can be attributed to the low c-tip K values and crack grows through the thickness ('a' direction) very quickly.

Summary

A laboratory procedure was developed and successfully demonstrated in introducing small corrosion pits (200 μm diameter) at center hole edge of an AA7075-T651 specimen. A single stable weld joint of the potential probes was achieved. The fatigue life of AA7075 aluminum alloy with an induced corrosion pit was determined. AFGROW predicted crack growth profile showed excellent agreement (within 10%) of that of the experimental data.

Acknowledgements

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