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MULTIFREQUENCY EDDY CURRENT INSPECTION OF CORROSION IN CLAD ALUMINUM RIVETED LAP JOINTS AND ITS EFFECT ON FATIGUE LIFE

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ABSTRACT. Aging aircraft are prone to corrosion damage and fatigue cracks in riveted lap joints of fuselage skin panels. This can cause catastrophic failure if not detected and repaired. Hence detection of corrosion damage and monitoring its effect on structural integrity are essential. This paper presents multifrequency eddy current (EC) inspection of corrosion damage and machined material loss defect in clad Al 2024-T3 riveted lap joints and its effect on fatigue life. Results of eddy current inspection, corrosion product removal and fatigue testing are presented.

Keywords: Multifrequency Eddy Current Inspection, Riveted Lap Joints, Accelerated Corrosion Testing, Aluminum 2024-T3, Fatigue Life
PACS: 81.70.Ex, 81.40.Nq

INTRODUCTION

Aircraft which are in operation beyond their original design life (20-25 years) are known as 'Aging Aircraft'. These aging aircraft are susceptible to corrosion damage and fatigue cracks, which result in catastrophic failures if not detected and repaired. The inspection and maintenance of aging aircraft is receiving much attention in recent years, due to their increasing numbers in the aviation industry [1]. The safety of aging aircraft is very important, especially after the Aloha Airlines in-flight accident, where a part of the fuselage was blown off during flight at a height of 7315 m. The investigation report of National Transportation Safety Board revealed the cause for the accident as the failure of the operator maintenance program to detect corrosion damage, resulting in multiple site failure of the fuselage structure [2]. Therefore the focus on aging aircraft inspection and maintenance has increased to ensure safety and integrity of the aircraft to achieve longer operational periods. Corrosion damage and fatigue cracks occurring between the sheets of riveted lap joints in aircraft structure go unnoticed. Conventional detection techniques, like visual inspection, dye penetrant, single frequency eddy current, cannot be used as the defects are hidden below the surface and the structure causes noise signals. Detection of such hidden defects requires nondestructive evaluation techniques, which can penetrate the layers of fuselage structure and detect damages without being affected by noise signals.

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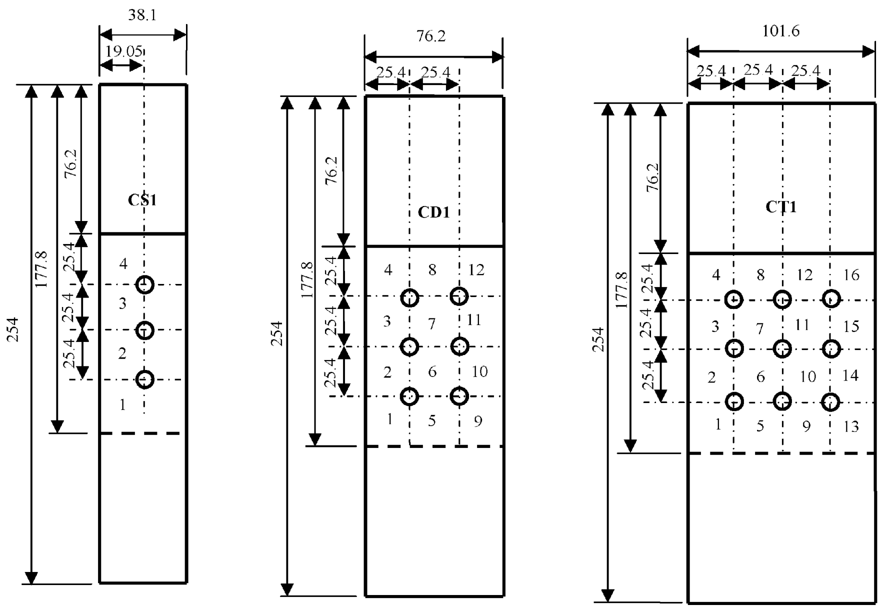


(a) (b) (c)

FIGURE 1. Geometry, dimensions of riveted lap joint specimens and division into zones for EC inspection; (a) Single column riveted lap joint (b) Double column riveted lap joint (c) Triple column riveted lap joint.

Multifrequency eddy current inspection is well suited for inspection of multilayered aircraft structures. In this method, more than one input signal, each corresponding to a different frequency is supplied to a single eddy current probe/transducer for scanning and their outputs are obtained and analyzed separately. Since the depth of penetration of eddy currents depends on the frequency of input signal, inspection can be performed at various depths of the structure in a single scan. The dual frequency mixing technique of multifrequency eddy current inspection is useful in eliminating the noise signals during inspection of aircraft structures. In the past, noise signals due to varying interlayer gap [3], fastener heads [4], separation due to sealant layer between layers of lap joint [5], edge-effect from a butt joint [5] and lift-off due to bulge in the paint [6] were eliminated by dual frequency mixing technique of multifrequency eddy current inspection.

This paper presents the results of multifrequency eddy current inspection of corrosion damage induced in riveted lap joint specimens using accelerated corrosion testing and its effect on the fatigue life of the specimens. Details of the calibration process, output of eddy current inspection in the form of amplitude of impedance plane signal and impedance plane plots are presented. The results of corrosion product removal and fatigue testing are also presented.

EXPERIMENTAL SPECIMEN FABRICATION

Test specimens were fabricated from clad Al 2024-T3 alloy sheet of dimensions 177.8 mm x 101.6 mm, 177.8 mm x 76.2 mm and 177.8 mm x 38.1 mm with the length in the rolling direction for triple, double and single column riveted lap joints, respectively. Figure 1 shows the specimen geometry and dimensions for the single, double and triple column, 3-row riveted lap joint specimens respectively. Holes of 6.35 mm were drilled and countersunk machining was done on CNC vertical machining center. Al 2117-T4 alloy flat rivet with a 100 degree countersunk included angle and a diameter of 4.06 mm at the shank with a length of 7.94 mm were fit into each of these holes and compressed between two hard steel plates at a static load of 44.5 kN, on Instron Universal Testing Machine, to obtain a bucktail of 8.64 mm diameter and 0.86 mm thickness.

EXPERIMENTAL SETUP AND PROCEDURE

Accelerated Corrosion Testing and Corrosion Product Removal

The accelerated corrosion test was conducted in a Q-Fog accelerated corrosion chamber using ASTM G85 A5 (Prohesion) test [7]. In this test the specimens are exposed to salt fog at 25°C for 1 hour, followed by drying at 35 °C for 1 hour, using a salt solution of 0.05% NaCl and 0.35% $(NH_4)_2SO_4$. These two steps are repeated in a cycle continuously. One each of the single column, double column, and triple column riveted lap joint specimens were removed from the corrosion chamber after exposure period of 4 weeks (672 hours), 8 weeks (1344 hours), 12 weeks (2016 hours), 16 weeks (2688 hours) and 20 weeks (3360 hours), and subjected to further tests. The riveted lap joint specimens were masked at both ends to a length of 44.4 mm, before placing in the corrosion chamber, to prevent corrosion of areas that would later be gripped during fatigue tests. The bucktail side of the riveted lap joint specimens was also masked to prevent corrosion in this region, as it is within an aircraft structure and will not be exposed to the outer atmosphere. Hence the layers of the riveted lap joint which were exposed to accelerated corrosion are (i) top surface of the top layer, which will henceforth be referred to as Top of Top (TOT) layer, (ii) the bottom surface of the top layer which will henceforth be referred to as Bottom of Top (BOT) layer and (iii) the top surface of the bottom layer which will henceforth be referred to as Top of Bottom (TOB) layer.

The accelerated corrosion test resulted in products of corrosion adhering to the top surface of the specimen causing unevenness which results in noise signals in EC inspection due to probe lift-off. Also, the corrosion products accumulating between the layers of the lap joint resulted in the formation of interlayer gaps larger than that observed in real-life aircrafts. Hence it was required to remove the corrosion products from the specimens. Ferrer and Kelly [8] found that nitric acid immersion with ultrasound was the most effective method for complete removal of corrosion products from Al 2024-T3 alloy. Hence this technique was used for corrosion product removal in this experiment. The mass of the specimen when removed from the corrosion chamber was measured and used as the initial mass. Then the specimen was immersed in concentrated nitric acid in a glass tray, which was placed in an ultrasonic bath filled with water, for 90 minutes. During this process, mass of the specimen was measured after test intervals of 0-5 minutes, 5-10 minutes, 10-15 minutes, 15-30 minutes, 30-45 minutes, 45-60 minutes and 60-90 minutes. The mass loss for each test interval was calculated by subtracting the mass of the specimen, at the end of that test interval, from the initial mass of the specimen, after removal from the corrosion chamber. The time at which all the corrosion products were removed and the attack on base material started was determined using the ASTM G1 standard procedure [9]. The mass loss at that time was used as representative of the mass lost due to corrosion products for the specimen. The details of the experimental setup, procedure and calculation of mass loss, is presented in a separate paper [10].

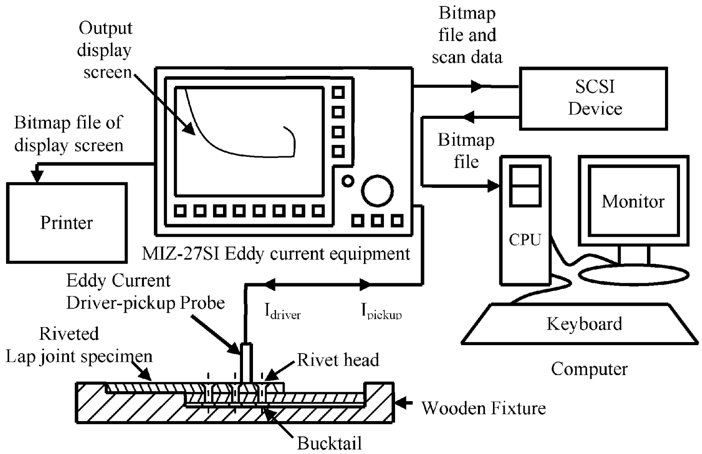


FIGURE 2. Experimental setup for multifrequency eddy current inspection of riveted lap joint specimen.

Eddy Current Inspection and Fatigue Testing

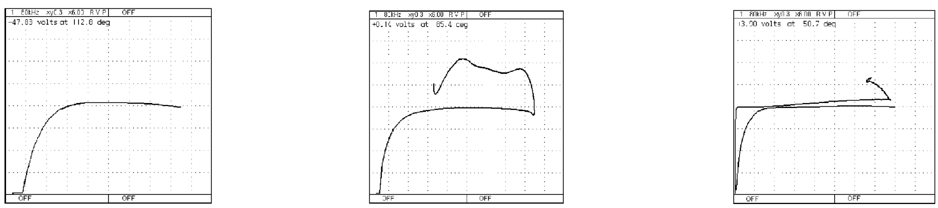
Zetec MIZ-27SI eddy current equipment along with Staveley Instruments driver-pickup type corrosion probes of diameter 15.75 mm and 7.87 mm was used for inspection of the riveted lap joint specimens. The 15.75 mm diameter probe had a frequency range of 100 Hz to 20 kHz, while the 7.87 mm diameter probe had a frequency range of 700 Hz to 80 KHz. A wax sleeve was used around the 7.87 mm diameter probe to avoid wobbling during scanning. Hence the final diameter of this probe with the sleeve was 15.24 mm. After removal of corrosion products, the specimens were manually scanned using EC inspection to detect defects in the TOT, BOT and TOB layers. Fig. 2 shows the experimental setup for multifrequency eddy current inspection. MIZ-27SI EC device was connected to a SCSI device and a printer. Impedance plane plot and digital values of amplitude and phase angle of the signal were obtained as output from eddy current inspection. Specimens were divided into zones, as shown in Fig. 1 and each zone was scanned individually to facilitate location of defects. The rivet heads and edges were avoided during scanning, as they cause very large signals which mask the signals from defects. Before scanning, the probe was balanced on two sheets without any damage of thickness 1.6 mm each, stacked one over the other. A cellophane tape of 0.0254 mm thickness was stuck to the top surface of the specimen for smooth movement of the probe. Table 1 shows the probes, scan frequencies and their standard depth of penetration used for inspection of TOT, BOT and TOB layers. Dual frequency mixing technique was used for inspection of TOB layer using 2.4 KHz and 4.8 KHz frequencies, to eliminate the effect of interlayer gap.

TABLE 1. Eddy current probe, scan frequencies and their standard depth of penetration for inspection of different layers of the riveted lap joint specimens.

Layers in the riveted lap joint specimen	Eddy current probe	Scan frequency	Standard depth of penetration
TOT	7.87 mm	80 kHz	0.41 mm
BOT	7.87 mm	40 kHz	0.58 mm
TOB	15.75 mm	2.4 kHz	2.36 mm
		4.8 kHz	1.69 mm

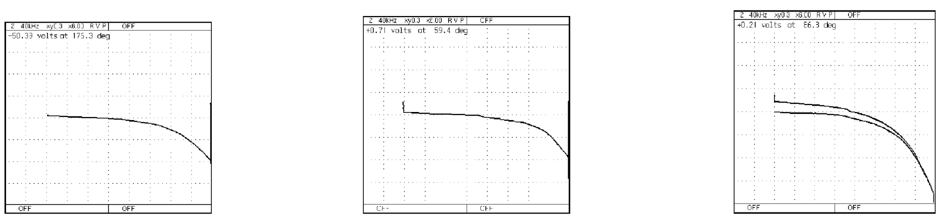
The calibration specimens were fabricated from sheets of thickness 1.6 mm, same as the sheets in riveted lap joint specimens. Three such specimens were fabricated with circular pocket depths of 10%, 20% and 30% of sheet thickness, each, i.e. 0.16 mm, 0.32 mm and 0.48 mm respectively. For each depth, pockets of three different diameters; 6.98 mm, 12.7 mm and 25.4 mm were fabricated on a single sheet. The manufacturing tolerance for the depth of these pockets was ±0.05 mm. These calibration samples were scanned by placing them on or below a sound sheet of clad Al 2024-T3 sheet of thickness 1.6 mm, to simulate damage in TOT, BOT and TOB layer respectively. For dual frequency mixing nonconductive shims of thickness 0.81 mm were placed in between two sound plates and the gain of 4.8 KHz channel was increased from 20 dB to 21.2 dB, to make the response of the two scan frequencies equal for the interlayer gap. Details of the procedure for dual frequency mixing were presented by Thompson [3] and Hagemaier and Nguyen [5].

The fatigue tests were conducted on the riveted lap joint specimens, after EC inspection, on MTS 880 Material Testing System at a frequency of 10 Hz and maximum stress of 150 MPa under tension-tension loading with a stress ratio (R) of 0.1.



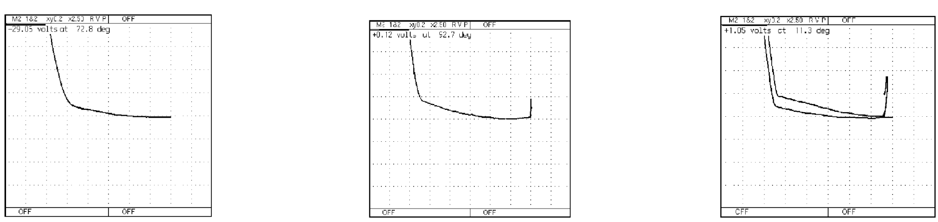
(i) No damage in TOT layer (ii) Machined circular pocket defect (iii) Corrosion damage

(a) Inspection of TOT layer



(i) No damage in TOT layer (ii) Machined circular pocket defect (iii) Corrosion damage

(b) Inspection of BOT layer



(i) No damage in TOT layer (ii) Machined circular pocket defect (iii) Corrosion damage

(c) Inspection of TOB layer

FIGURE 3. Impedance plane plot of eddy current inspection of non-riveted reference specimen with no damage, non-riveted lap joint calibration specimen with machined defect of 12.7 mm diameter and 0.48 mm depth, and riveted lap joint specimen with corrosion damage due to accelerated corrosion testing in (a) TOT layer (b) BOT layer and (c) TOB layer.

RESULTS AND DISCUSSION

Pitting and crevice type of corrosion were observed in the specimens, which are also observed in real-life aircraft lap joints [11]. The corrosion products from BOT and TOB layer accumulated between the faying surfaces of lap joint, resulting in ‘pillowing’. Figure 3 shows the EC scan impedance plane plot for no damage, machined pockets in calibration specimens and corrosion damage in TOT, BOT and TOB layers of the riveted lap joint specimens. Hence by observing the impedance plane plot, defects in different layers of lap joint can be detected. From the results of EC inspection of the calibration specimens it was observed that for a given layer in lap joint the amplitude of impedance plane signal depends on both the diameter and depth of the pocket and hence the defect cannot be quantified. Figure 4 shows the amplitude of impedance plane signal for different zones of the double column riveted lap joint specimens for exposure periods in corrosion chamber. In general, an increasing trend in the amplitude of impedance plane signal with increase in exposure period in corrosion chamber for the different zones in TOT, BOT and TOB layers of double column riveted lap joint specimen can be observed. But the amplitude value for inspection of BOT layer of specimens of exposure periods 4, 8 and 12 weeks showed some overlap and did not follow the trend. Triple column and single column riveted lap joint specimens did not show an increasing trend in the amplitude values with respect to exposure period. The possible reasons for this irregularity could be: (i) The location and extent of damage in the specimens varied due to variation in location in corrosion chamber. (ii) Longer exposure periods resulted in damaged rivet heads causing movement of the upper layer of the lap joint during EC scanning. (iii) The presence of larger interlayer gaps than what was considered during the calibration process of dual frequency mixing.

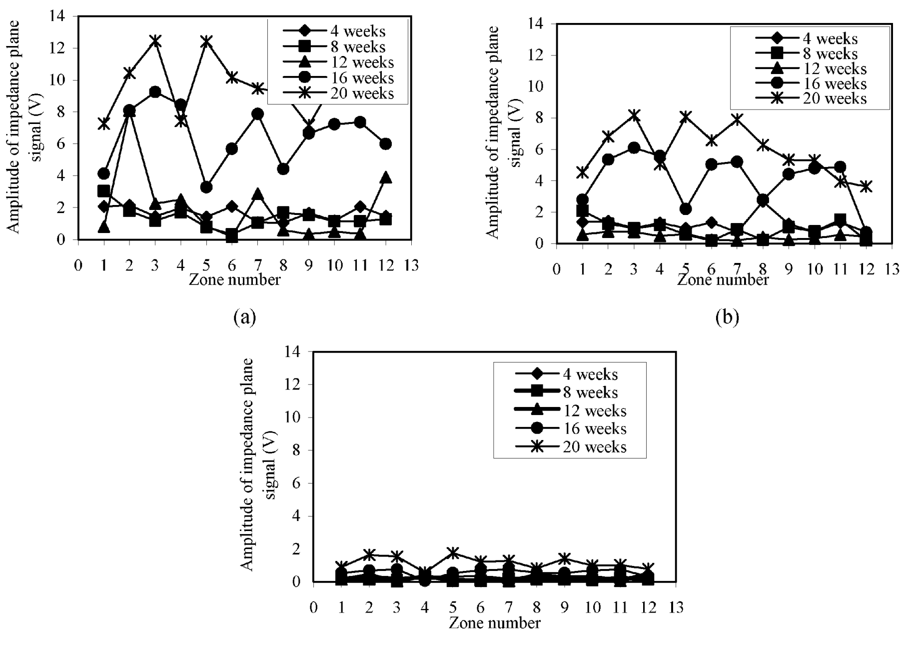


FIGURE 4. Amplitude of impedance plane signal for different zones of (a) TOT (b) BOT and (c) TOB layers of double column riveted lap joint specimens for 4 weeks, 8 weeks, 12weeks, 16 weeks and 20 weeks of exposure period in corrosion chamber.

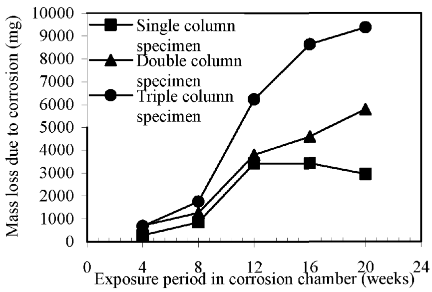


FIGURE 5. Mass loss due to corrosion in single column, double column and triple column riveted lap joint specimens vs. exposure period in corrosion chamber.

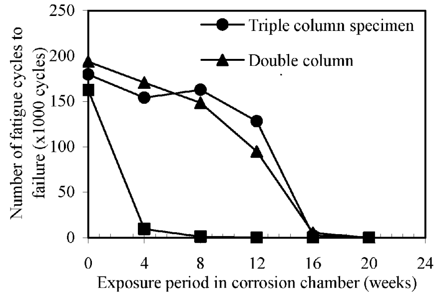


FIGURE 6. Fatigue life of single column, double column and triple column riveted lap joint specimens vs. exposure period in corrosion chamber.

Figure 5 shows the plot of mass loss due to removal of corrosion products versus exposure period in the corrosion chamber. The mass loss increased with increase in the exposure period in corrosion chamber for the single column, double column and triple column riveted lap joint specimens. The mass loss for single column riveted lap joint specimen is less for 20 week exposure period when compared to 16 week exposure period. The reason for the 20 week exposure period single column riveted lap joint specimen having lesser mass loss is that the two layers of the lap joint came apart due to the pillowing effect and hence some products of corrosion were lost. The results of fatigue test till failure on the corroded riveted lap joint specimen is shown in Fig. 6. The plots clearly show that fatigue life of the single column, double column and triple column riveted lap joint specimens decreases with increase in exposure period in the corrosion chamber. Details of the fatigue test results and failure modes are reported in a separate paper [12].

There was a large increase in the amplitude of impedance plane signal for the double column riveted lap joint specimen exposed for 16 weeks and 20 weeks in the corrosion chamber which corresponded with drastic reduction in the fatigue life. Hence in double column riveted lap joint specimens an increasing trend in amplitude of impedance plane signal, increase in mass loss and decrease in fatigue life with increase in exposure period in corrosion chamber, can be observed. But such a trend was not observed for single and triple column riveted lap joint specimens. Hence further investigation is required to confirm this trend.

CONCLUSIONS

Multifrequency eddy current inspection of corrosion in riveted lap joint specimens induced by accelerated corrosion test and machined material loss defect and the study of its effect on fatigue life of the specimen was conducted successfully. From the results of this research the following conclusions could be made: 1. Accelerated corrosion testing caused pitting and crevice type of corrosion in the clad Al 2024-T3 riveted lap joint specimens. The products of corrosion accumulated in between the layers of the lap joint specimen and caused deflection of the layers, resulting in ‘pillowing’. 2. Multifrequency eddy current inspection successfully detected machined circular pockets in TOT, BOT and TOB layers in calibration specimens. Dual frequency mixing technique eliminated the effect of interlayer gap and detected damages in the TOB layer. 3. Eddy current inspection of machined circular pockets showed that the amplitude of impedance plane signals depends on lateral dimension as well as depth of the pockets and hence the material loss cannot be quantified based on the amplitude value of impedance plane signal. 4. Corrosion damage in riveted lap joint specimens was detected and located within the zones marked on the specimen by observing the nature of impedance plane plot and the amplitude of impedance plane signal values. Presence of noise factors like uneven and unsteady surface, large interlayer gaps, made it difficult to detect corrosion damage. 5. Fatigue life of riveted lap joint specimen decreased and mass loss due to corrosion products increased, with increase in exposure period in corrosion chamber.

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REFERENCES

1. A. Mal, "The Role of NDE in Structural Health Monitoring of Aging Aircraft and Aerospace Structures," in Proceedings of *SPIE Conference: NDE of Aging Aircraft, Airports and Aerospace Hardware*, Newport Beach, California, March 2000.
2. www.corrosion-doctors.org (Last visited on 04/29/2006)
3. J. G. Thompson, *Materials Evaluation*, **51**, 1398-1401 (1993).
4. B. A. Lepine, "Eddy Current Imaging using Multi-frequency Mixing Methods for Aircraft Structural Integrity Verification," in *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 17, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1998, pp. 355-362.
5. D. J. Hagemaier and K. Nguyen, *Materials Evaluation*, **52**, 91-95 (1994).
6. B. van den Bos, S. Sahlen and J. Andersson "Automatic Scanning with Multi-frequency Eddy Current on Multilayered Structures," in *Proceedings of the 15th World Conference on Nondestructive Testing*, Roma, Italy, 2000. Retrieved from www.ndt.net. (Last visited on 09/22/2004)
7. ASTM G85, "Standard Practice for Modified Salt Spray (Fog) Testing", ASTM International, 2002.
8. K. S. Ferrer and R. G. Kelly, *Corrosion*, **57**, 2, 110-117 (2001).
9. ASTM G1-03, "Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens," ASTM International, 2003.
10. A. C. Okafor and C. Nnadili – submitted to the *International Journal of Fatigue*, (2006).
11. J. J. De Luccia, "The Corrosion of Aging Aircraft and its Consequences," in Proceeding of *AIAA/ASME/ASCE/AHS/ASC 32nd Structures, Structural Dynamics and Materials Conference*, Washington D.C., 1991, pp. 1667-1675.
12. A. C. Okafor and C. Nnadili, – submitted to the *Journal of Engineering Failure Analysis*, (2006).