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A Literature Review of Corrosion Sensing Methods

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Defence R&D Canada – Atlantic

Technical Memorandum
DRDC Atlantic TM 2009-082
September 2009

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Abstract

Corrosion monitoring, detection and remediation are of particular importance for military vehicles and infrastructure due to the long operational life-cycle of these assets. In this regard, corrosion is a problem that is growing not only because of the increasing number of military assets, but also due to the increasing number that are aging and nearing the end of their operational life-cycle. Even for newer equipment, corrosion can be a significant problem because of the harsh operational environments often encountered. Hence, as military systems age, corrosion becomes one of the largest cost inflators in the life-cycle costs of military systems. Therefore, cost effective life-cycle management of military assets requires a systematic health monitoring approach to prevent and control corrosion. In this respect, nondestructive evaluation (NDE) and nondestructive inspection (NDI) play important roles in this effort, particularly by monitoring, detecting and reporting the early signs of corrosion before the damage becomes significant. This report presents a literature review of corrosion monitoring technologies and applications with a particular emphasis on aerospace materials and structures.

Résumé

Les activités de surveillance et de détection de la corrosion et les mesures correctives connexes sont d'une importance cruciale au bon fonctionnement des véhicules et infrastructures militaires, car ces biens ont une longue durée de vie utile. La corrosion constitue à cet égard un problème de plus en plus important en raison du nombre croissant non seulement de biens militaires, mais aussi de biens qui vieillissent et atteignent la fin de leur durée de vie utile. La corrosion peut aussi représenter un grave problème pour l'équipement plus récent, dans les conditions rigoureuses qui caractérisent souvent les milieux opérationnels. C'est pourquoi la corrosion devient, avec le vieillissement graduel des systèmes militaires, un des plus importants facteurs de gonflement des coûts de leur cycle de vie. Par conséquent, la gestion rentable des coûts du cycle de vie de biens militaires exige l'adoption d'une approche systématique de surveillance de l'état qui permet de prévenir la corrosion et de lutter contre celle-ci. L'évaluation non destructive (EVND) et l'exécution d'essais non destructifs (END) jouent à cet égard des rôles de premier plan, particulièrement au chapitre de la capacité de surveiller, de détecter et de signaler les premiers signes de corrosion avant que les dommages ne deviennent importants. Le présent rapport contient une revue de la littérature sur les techniques de surveillance de la corrosion et de leurs applications, particulièrement dans le domaine des structures et matériaux utilisés en aérospatiale.

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Executive summary

A Literature Review of Corrosion Sensing Methods

Rinaldi, G.; DRDC Atlantic TM 2009-082; Defence R&D Canada – Atlantic; September 2009.

Introduction or background

Corrosion prevention and detection is of particular importance to the Canadian Forces due to the practice of extending the service-life of military aircraft and vehicles beyond their normal life-expectancy. In this regard, unfortunately, the financial liability associated with corrosion can be significant. Therefore, a cost effective, service-life management of military equipment requires an efficient health monitoring approach to prevent, detect and control corrosion. This work provides an overview of some of the latest research in aerospace corrosion and the related sensor technologies and sensing methodologies.

Results

It can be seen that from the number of corrosion sensing methods presented herein that this is an important area of research. The technologies presented in this work all have their associated advantages and disadvantages with respect to cost, practicality, sensitivity, size and safety.

Significance

It has particular significance for aging Canadian Forces aircraft and for aircraft and equipment deployed in coastal locations where humidity and salinity are of particular consequence to aerospace aluminum alloys.

Future plans

It is the aim to develop a MEMS or micro-scale corrosion sensor prototype based on one of the technologies presented herein. To this end, a feasibility study will be undertaken for determining the most suitable technologies for chloride ion and humidity sensing, which are known to be sources of corrosion initiation, in Canadian Forces equipment operating in maritime environments.

Sommaire

A Literature Review of Corrosion Sensing Methods

Rinaldi, G.; DRDC Atlantic TM 2009-082; R & D pour la défense Canada – Atlantique; Septembre 2009.

Introduction ou contexte

La prévention et la détection de la corrosion revêtent un intérêt particulier pour les Forces canadiennes (FC), du fait qu’elles prolongent la durée de vie utile des aéronefs et des véhicules militaires au-delà de la durée de vie prévue. À cet égard, malheureusement, la responsabilité financière associée à la corrosion peut être considérable. Par conséquent, la gestion économique du cycle de vie de l’équipement militaire exige l’adoption d’une approche de surveillance de leur état permettant de prévenir et de détecter la corrosion ainsi que de lutter contre celle-ci. Le présent travail donne un aperçu global de certaines des plus récentes recherches sur la corrosion dans l’espace ainsi que des technologies et des méthodes de détection connexes.

Résultats

Compte tenu du nombre de méthodes de détection présentées, il apparaît clairement qu’il s’agit d’un important secteur de recherche. Les technologies présentées dans cette étude ont des avantages et des désavantages en ce qui concerne le coût, la valeur concrète, la sensibilité, la taille et la sécurité.

Importance

L’étude est particulièrement importante en ce qui concerne les aéronefs vieillissants des FC ainsi que les aéronefs et les véhicules déployés dans les régions côtières où l’humidité et la salinité ont une incidence particulière sur les alliages d’aluminium dans l’espace.

Perspectives

On prévoit de développer un système micro-électromécanique (SMEM) ou un prototype de détection de la corrosion à micro-échelle selon l’une des technologies présentées dans cette étude. À cet effet, une étude de faisabilité sera effectuée pour déterminer les technologies les plus appropriées pour la détection de l’ion chlorure et de l’humidité, qui sont reconnus comme les causes du déclenchement de la corrosion sur l’équipement des Forces canadiennes opérant dans des environnements maritimes.

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1. Corrosion Sensing and Characterization

1.1 Background and Motivation

Corrosion is possibly the most important factor in the inflation of life-cycle costs of military vehicles and structures. Therefore, effective life-cycle supervision of military assets requires an efficient health monitoring program to (i) prevent and (ii) detect and (iii) control corrosion. In this respect, nondestructive testing (NDT), nondestructive evaluation (NDE) and nondestructive inspection (NDI) can play important roles in this effort, particularly by monitoring, detecting and reporting the early stages of corrosion before the damage becomes significant. In this regard, corrosion monitoring, detection and remediation are important for both civilian and military vehicles and structures. For the case of the military, it is of particular importance due to the long operational life-cycle of military vehicles and structures.

Presented in this literature review is a comparison of corrosion detection methods and how they might be used for aerospace applications. In this regard, several corrosion technologies are presented and 190 journal and conference papers and articles relating to corrosion are summarized in Appendices A1-A13. The Appendices are primarily organized by technology, then by year of publication within that technology, and then by first author alphabetical order within that year.

Suggested examples from each type of corrosion monitoring technology are also included in the technology descriptions below.

The corrosion research topics covered in this literature review include:

1.1.1 Spectroscopic methods

- Most of the work in this area is related to electrochemical impedance spectroscopy (EIS) [1-18]. Electrochemical impedance spectroscopy is a multi-frequency technique with applications in corrosion, battery and fuel cell development, surface coating characterization, and sensor development. This technology has miniaturization and wireless transmission capabilities (A1.3, A1.11) and can also be used for monitoring early corrosion (A1.1, A1.18), pitting corrosion (A1.2) exfoliation corrosion (A1.7, A1.9, A1.13), and corrosion under paint (A1.18).
    - Pros: (i) Impedance measurements can be performed easily and quickly, and can be easily automated. (ii) EIS can be used to determine mass adsorption. (iii) Impedance spectra can characterize sorbent materials.
    - Cons: (i) Only weakly conducting materials should be considered. (ii) Interpretation of impedance measurements can be challenging. (iii) Linearity of impedance regime dependent upon small amplitude excitation.

1.1.2 Terahertz radiation methods

- Terahertz radiation based approaches offer non-contact imaging of a variety of different structures [19-30]. It is capable of detecting hidden corrosion under surfaces (A2.2, A2.6), surface roughness of metals (A2.7), and evaluation of composites (A2.3, A2.8)
  - Pros: (i) Cost effective. (ii) High resolution imaging. (iii) Non-contact.
  - Cons: (i) THz radiation sources need to be cryogenically cooled to achieve high sensitivity.

1.1.3 Fiber optic methods

- The channelling and manipulation of light through an optical fiber and monitoring the variation of the output power or intensity of the light is the basic concept of optical fiber sensor methods [31-50]. With the appropriate coating, optical fiber sensors can also be designed to detect water, corrosion, or metal ions in otherwise inaccessible regions of aircraft. Optical fibers also allow for a distributed sensor network within a given structure. Several of the methods employed for structural health monitoring applications are outlined here and include evanescent field sensors (A3.1, A3.16, A3.17, A3.19), fluorescent sensors (A3.9, A3.12, A3.20), grating based sensors (A3.4, A3.5, A3.9, A3.18) and intensity based sensors (A3.3, A3.6, A3.10, A3.11).
  - Pros: (i) Signal capacity. Optical signals can carry much more information than electrical ones. (ii) Transmission reliability. Optical signals do not suffer electromagnetic interference and present a much smaller bit error rate compared to electrical systems. (iii) Size and weight. The weight of 1km of optical fiber is about 6kg while the same length of coaxial cable could weigh as much as 1000kg.
  - Cons: (i) Physical Constraints. Optical fibers cannot be bent too much or they lose some light reflecting properties. Also, optical fibers can be damaged much more easily than copper cables, and the associated cost and complexity of the repair is much higher. (ii) Optical switching. Optical fibers are very efficient in point-to-point data transmission, however, they are limited in terms of switching or data routing applications.

1.1.4 Miscellaneous optical methods

- Some “non-conventional” optical corrosion monitoring methods [51-58] are presented in this section. One of the more interesting methods uses infra-red radiation (light emitting diodes) for detecting corrosion under paint (A4.4).

1.1.5 X-ray methods

- In general, x-ray corrosion and crack detection methods [59-63] involve the use of tomograms or tomography in which the surface under inspection is “sliced” by the x-ray scanner and the image(s) is/are reconstructed from the various slices taken. The method is particularly effective in detecting intergranular corrosion (A5.2, A5.3, A5.4) defined as the phenomenon where the edges of a crystal lattice are more susceptible to corrosion than the inside of the lattice itself. For aluminum and other alloys this could be due to the degradation of a corrosion protection material such as chromium, for example).

  - Pros: (i) Can evaluate corrosion on small parts and/or hidden enclosures. (ii) An x-ray radiograph can quantify the type and degree of corrosion. (iii) Pits and thinning can also be deduced from the radiograph. (iv) Minimal part preparation is required.
  - Cons: (i) Narrow cracks parallel to radiation source are difficult to detect. (ii) Limited to detecting 1-2% (of sample thickness) thickness variation. (iii) Interpretation of radiographs can be problematic. (iv) Possible safety hazard if not handled carefully. (v) Costly.

1.1.6 Microwave methods

- Corrosion and material thickness (A6.3) can be monitored by employing microwave radiation methods [64-68]. This approach is also good for detecting corrosion under paint and other materials (A6.1, A6.2, A6.4, A6.5).
  - Pros: (i) Contact or non-contact capability. (ii) Can be applied to curved and complicated structures (iii) Microwaves penetrate dielectric materials. (iv) Surface can be covered in paint dirt and corrosion. (v) Polarization properties of microwaves can provide information of crack orientation.
  - Cons: (i) Microwaves do not penetrate through metal. (ii) Resolution is limited by the dimensions of the open-ended waveguide.

1.1.7 Linear polarization methods

- Linear polarization resistance (LPR) is an electrochemical technique that is the only corrosion monitoring method that allows corrosion rates to be measured directly, in real time [69-74]. The method is however limited to ionic conducting liquids, where the electrical conductivity (or inversely the resistance) of a given fluid can be related to its corrosiveness (it can also be applied at the interface between a given metal and its environment). A particularly interesting example is given in (A7.2) in which a stamp-sized LPR sensor is used to measure the corrosion and corrosion rate under a paint layer.
  - Pros: (i) Current (or potential) based measurements. (ii) Rapid response technique. (iii) Can be used to quantify pitting depth. (iv) Can provide information on the state (passive or active) of the metal (when in active state more susceptible to corrosion).
  - Cons: (i) Several measurements may be needed for valid data. (ii) External environment can influence LPR measurements. (iii) Must operate in the linear regime.

1.1.8 Eddy current methods

- Eddy current methods [75-93] are quite common for corrosion and thickness monitoring in aerospace structures. In this regard, pulsed eddy current may be used to detect corrosion in multi-layered structures. Papers of particular interest in this section include (A8.3, A8.4, A8.8, A8.9, A8.10, A8.14, A8.17, A8.18, A8.19).
  - Pros: (i) Non-contact measurements. (ii) High resolution. (iii) High frequency response.
  - Cons: (i) Only “close range” measurements are possible. (ii) Materials must be conductive and sufficiently thick. (iii) Requires calibration.

1.1.9 Thermography methods

- Thermography [94-107] is used to “sense” variations in temperature from a surface (A9.14). The variations, if any, can be due to corrosion (A9.3, A9.4, A9.5) and/or other surface defects (A9.11, A9.12). Pulsed thermography is one approach used to characterize aircraft skin and structures (A9.7, A9.10).
  - Pros: (i) Rapid detection capability (of corrosion) in single layer structures. (ii) Contactless testing.
  - Cons: (i) Expensive. (ii) Power requirements for infrared heater. (iii) Poor penetration. (iv) Low signal-to-noise ratio. (v) Layered structures are a problem.

1.1.10 Ultrasonic methods

- Ultrasonic transducers and sensors come in a variety of shapes and sizes. They can be applied in-situ to monitor corrosion in hidden or hard to reach locations [108-117]. The principle of operation is based on ultrasonic frequencies that can be made to propagate over or through a given structure. The detected return signal, that is bounced or deflected back, can be used to deduce material characteristics such as surface defects, corrosion, and material thickness. Typical ultrasonic signals range from the low kilohertz right up into the megahertz frequencies, depending on the given application. Some particularly good examples and applications are given in (A10.1, A10.2, A10.4, A10.6, A10.7, A10.9).
  - Pros: (i) Uses sound waves which make ultrasonic measurements especially suitable for dirty or wet environments. (ii) Suitable for object and surface deformation detection.
  - Cons: (i) Susceptible to temperature changes. (ii) Cross-talk issues. (iii) Ghost reflections. (iv) “Blind zone”. (v) Several measurements required to obtain reliable data. (vi) Relatively expensive.

1.1.11 Piezoelectric methods

- A piezoelectric material is one from which an electrostatic potential can be obtained simply by deforming or stressing the material in some manner. The changes in the electrical output of the material can be employed either sensor/actuator applications. Piezoelectric materials are often found in ultrasonic applications. All the works cited herein (A11.1-A11.5) give interesting background for piezoelectric sensing for structural health monitoring [118-122].

  - Pros: (i) Small size.
  - Cons: (i) Piezoelectric ceramic materials can be brittle.

1.1.12 Micro-electro-mechanical-systems (MEMS) based methods

- MEMS sensors offer small size and weight, low power consumption and a small footprint. As their name implies, MEMS devices are integrated electro-mechanical components fabricated on a single chip. In general, MEMS sensors operate in the mechanical domain and respond in the electrical domain, whereas MEMS actuators tend to operate in the electrical domain and respond mechanically. However, thermal, chemical and surface stress related actuation/sensing is also possible depending on the particular application. Some suggested papers include [123-128] (A12.1, A12.3, A12.4, A12.6).
  - Pros: (i) Integrated mechanics and electronics. (ii) Can be sensitized to many different applications. (iii) Can be combined with microfluidics and micro-optics. (iv) Low cost. (v) Small size.
  - Cons: (i) Packaging related challenges. (ii) At present limited to low level harsh environments.

1.1.13 Miscellaneous papers

- The papers reviewed in this section do not generally fall into one of the categories above. However, they are nonetheless important as they demonstrate the vast amount of work outside "standard" methods in the field of corrosion sensing and monitoring [129-190]. Papers of interest include (A13.1, A13.7, A13.8, A13.9, A13.12, A13.16, A13.18, A13.21, A13.22, A13.25, A13.27, A13.29, A13.31, A13.34, A13.39, A13.57, A13.58).

1.2 Future Work

This literature review is being performed in preparation for the planned development of a MEMS-based corrosion sensor that will be a component of DRDC Project 13pl, "Advanced Health Monitoring Capability Development". This work is currently scheduled to occur over two years commencing at the start of FY 09/10.

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Annex A A selection of papers dedicated to corrosion monitoring and characterization

A.1 Spectroscopic Methods

A.1.1 Bedekar et al. (2008): Detection of corrosion using impedance spectroscopy

In this work the effect of corrosion damage of aluminum on the impedance response of a piezoelectric sensor attached to the aluminum is studied. Here the corrosion damage is effectively quantified and detected in its early stages for aluminum 6061 alloy. The damage caused in the basic sodium hydroxide (NaOH) environment was studied by the impedance spectroscopy based piezoelectric wafer sensor. A systematic variation in the real part of the electromechanical impedance was found as the specimen corrosion proceeded. The results also indicate that there is an optimal distance between the piezoelectric sensor and the location where damage is occurring that provides highest damage index. [1]

A.1.2 Jafarzadeh et al. (2008): EIS study on pitting corrosion of AA5083-H321 aluminum-magnesium alloy in stagnant 3.5% NaCl solution

In the research described here, an electrochemical impedance spectroscopy (EIS) technique was used to study the pitting corrosion behaviour of AA5083-H321 aluminum-magnesium alloy in a 3.5% sodium chloride (NaCl) solution. Impedance spectra were obtained during 240 hours of exposure of the sample to the solution. The surface and cross-section of the samples were studied by scanning electron microscopy (SEM) and energy dispersive analysis of x-ray (EDAX) analysis. This paper aims to establish an electrical interpretation using an equivalent circuit model. The circuit model serves to analyze the behaviour of the passive layer, pits and the substrate of AA5083-H321 aluminum-magnesium alloy, exposed to aerated and non-aerated NaCl solutions in order to assess the ideality in the behaviour of capacitors with the proposed model. [2]

A.1.3 Jakab et al. (2008): Measurement of CPC performance using EIS based sensor methods – laboratory and field studies

This paper addresses the laboratory and field studies of an electrochemical impedance spectroscopy (EIS) based sensor that utilizes wireless, mote based technology. The ability of the coating degradation sensor to assess coating failures in real and simulated coastal environments is demonstrated. Mote based sensor technologies are capable of wireless data transmission. They are also equipped with an on-board operating system allowing the direct, localized control of each sensor resulting in efficient data collection and transmission as well as power conservation. Detailed electrochemical impedance studies were carried out in order to further optimize the sensor design. It was found that in most cases there was a good correlation between sensor output and coating performance. The sensor output of the fielded sensors was found to correlate well with both coating performance and laboratory studies. [3]

A.1.4 Mendoza-Canales and Marin-Cruz (2008): EIS characterization of corrosion processes of titanium and alloy UNS N10276 in sour environments

In this work, two commercially manufactured metals, titanium UNS1-R50400 and alloy UNS-N10276, were electrochemically analyzed in order to determine their corrosion susceptibility in sour environments. Electrochemical impedance spectroscopy (EIS) was used to characterize the corrosion processes for each metal–environment combination. Electrochemical impedance spectroscopy was also used to determine the effects of environmental pH on the corrosion phenomena and to identify the consequences of hydrogen sulfide (H_2S) on them. [4]

A.1.5 Quej-Aké et al. (2008): EIS evaluation of the effect of neutralizing and inhibitor compounds on corrosion process of 1018 carbon steel in acid solutions typical of atmospheric distillation plants

Presented in this paper is the effect of mono-ethanol amine (MEA) as a neutralizing and a corrosion inhibitor on carbon steel corrosion processes found in environments of petroleum refineries. Corrosion was evaluated using electrochemical impedance spectroscopy (EIS). The results of the EIS analysis showed that the carbon steel corrosion process in hydrogen chloride (HCl) solution was favored by the presence of hydrogen sulfide (H_2S). However, an important inhibition effect was observed when the inhibitor compound was added to the sour solution. The authors surmise that this could be associated with the formation of a passive film composed by corrosion products and inhibitor molecules on the steel surface. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) analysis confirmed the EIS results that were obtained. [5]

A.1.6 Zhang et al. (2008): Mechanistic aspects of electrochemical corrosion of aluminum alloy in ethylene glycol-water solution

In this work, the electrochemical corrosion behavior of a 3003 aluminum alloy in an ethylene glycol–water solution was investigated. Several other electrochemical measurements, including corrosion potential, polarization curves and electrochemical impedance spectroscopy (EIS), and surface analysis techniques, including scanning electrode microscopy (SEM) and energy-dispersive x-ray analysis (EDXA), combined with theoretical analysis of EIS data, were used to determine the anodic and cathodic behavior of the aluminum alloy. [6]

A.1.7 Li et al. (2007): Exfoliation corrosion and electrochemical impedance spectroscopy of an Al-Li alloy in EXCO solution

The purpose of the work presented in this paper was to study the exfoliation corrosion susceptibility of an aluminum-copper-lithium-zirconium (Al-Cu-Li-Zr) alloy containing small amounts of magnesium (Mg), zinc (Zn) and manganese (Mn). An electrochemical impedance spectroscopy (EIS) approach was used to characterize its corrosion progression in an exfoliation corrosion (EXCO) solution and to try to find some relationship between the exfoliation corrosion and the EIS features. [7]

A.1.8 Castelli et al. (2006): Optical reflection spectroscopy of thick corrosion layers on 304 stainless steel

Presented in this paper are the results of optical reflectivity (specular and diffuse) measurements as well as the implications of various approaches to modeling optical properties. In this respect, thick and thin layers of corrosion on stainless steel are investigated. For thin layers, it was determined that scattering is negligible and the interference fringes are clearly visible. However, for thick (thickness >1000nm) corrosion layers, scattering from large ferrite crystallites dominates the reflected signal for times greater than a few thousand hours and leads to a relatively flat reflectivity spectrum. Variation of the aperture for reflected signal collection can reveal what fraction of the signal is scattered. An optical model that includes thin film interference effects, particle forward and backscattering, and surface roughness is also presented. The authors presented analytical spectra results are in good agreement with the experimentally measured spectra. [8]

A.1.9 Su et al. (2006): Exfoliation corrosion of Al-Li alloy 2090-T6 in EXCO solution: A study of electrochemical noise and electrochemical impedance spectroscopy

In this paper, the initiation and propagation characteristics of the exfoliation corrosion of 2090-T6 aluminum-lithium (Al-Li) alloy in exfoliation corrosion (EXCO) solution has been studied using electrochemistry impedance spectroscopy (EIS), electrochemical noise (EN), and optical microscope techniques. Two equivalent circuit models were developed to fit the EIS data of the initiation and propagation stages of the exfoliation corrosion according to their corresponding physical-chemical properties, respectively. The authors also show that the wavelet transform based on the EN analysis can be used as a more efficient method than other traditional electrochemical techniques to characterize exfoliation corrosion and to identify various localized corrosion stages. [9]

A.1.10 Shi et al. (2005): EIS study on 2024-T3 aluminum alloy corrosion in simulated acid rain under cyclic wet-dry conditions

The aim of this work is to study the atmospheric corrosion of 2024-T3 aluminum alloy using the electrochemical impedance spectroscopy (EIS) technique. Wet/dry cycle corrosion processes under different pH environments were investigated using EIS in conjunction with scanning electron microscope (SEM) method. The results obtained by the authors show that, during the dry period of each cycle, the electrode potential remained relatively stable. [10]

A.1.11 Srinivasan et al. (2005): Miniature wireless full spectrum EIS corrosion sensor

In this work, alternating-current (AC) impedance, which is also known as electrochemical impedance spectroscopy (EIS), sensor is presented and characterized. The authors attest that the EIS method is one of the more versatile tools available to measure corrosion rates, corrosivity, coating integrity and reaction mechanisms. During a typical measurement, the EIS technique uses a voltage or current signal to perturb the system, measures the response and reports the results.

Since it utilizes a very small perturbation signal (1-3μA), and the measurements are conducted at or close to the open circuit voltage of the system, the technique is essentially non-destructive. However, its limitations are the size and complexity of the electronics, and the power demand of the instrument; by comparison, linear polarization resistance (LPR) instruments are far less complex. The complexity of the electronics also makes EIS instruments relatively more expensive than LPR instruments to procure and maintain. The sensor operation is validated by using two independent conventional instruments, and in three different types of corrosive mediums. The corrosivity and coating health data obtained using the wireless EIS sensor matched well with the data obtained using conventional bench-top EIS and LPR instruments. The wireless EIS sensor is small, requires very little power to operate and is hermetically sealed. [11]

A.1.12 Zelinka and Rammer (2005): The use of electrochemical impedance spectroscopy (EIS) to measure the corrosion of metals in contact with wood

This paper discusses the effect of wood-metal contact on the corrosion process of metal fasteners. The goal of this study is to determine the viability of electrochemical impedance spectroscopy (EIS) as an accelerated testing procedure for determining the corrosion rate of metals in water-saturated wood. [12]

A.1.13 Cao et al. (2004): Exfoliation corrosion of aluminum alloy AA7075 examined by electrochemical impedance spectroscopy

For the research presented in this work, aluminum alloy AA7075 was immersed in an exfoliation-corrosion (EXCO) solution and its corrosion properties during different immersion times were measured using electrochemical impedance spectroscopy (EIS). Also, the EIS data was simulated using an equivalent electric circuit model. It was determined that at the initiation of the immersion, and for up to 9 hours, charge transfer resistance gradually decreases (acceleration of the corrosion rate), and the proton concentration decreases steeply, indicating that the cathodic process is dominant. Then the corrosion rate decreases gradually corresponding to the exhaustion of available proton ions. The authors state that the results also indicate that the exfoliation corrosion is developed from pitting corrosion through intergranular corrosion to general corrosion at the end. [13]

A.1.14 Hayez et al. (2004): Micro-Raman spectroscopy for the study of corrosion products on copper alloys: setting up of a reference database and studying works of art

The overall objective of this work is to explore the possibilities offered by Raman spectroscopy for the detection and characterization of atmospheric corrosion of metallic alloys, taking into account different types of atmospheric conditions. Aspects such as corrosion identification, and distribution (lateral and depth), are studied. In this paper, however, only the results obtained during the identification of the corrosion products appearing in specific sulfur-bearing atmospheres on copper (Cu) alloys is reported. In this regard, micro-Raman spectroscopy is an interesting technique for the local identification of atmospheric corrosion products on Cu alloys. [14]

A.1.15 Kachurina et al. (2004): Laser-induced electrochemical characteristics of aluminum alloy 2024-T3

In this work, an excimer laser (ultraviolet laser) was used for the surface modification of 2024-T3 aluminum alloys. Environmental scanning electron microscopy (ESEM) was used to characterize the alloy surface structure and modification. Potentio-dynamic scan (PDS) and electrochemical impedance spectroscopy (EIS) were used to analyze the corrosion resistance properties of the pre- and post laser treated alloys. The laser ablation process resulted in the removal of second phases and the growth of the barrier aluminum oxide layer on the surface. The thickness of the oxide layer was determined using EIS data. The authors found that these two complementary effects enhance the corrosion resistance properties of the aluminum alloy surface. [15]

A.1.16 Meng and Frankel (2004): Effect of Cu content on corrosion behavior of 7xxx series aluminum alloys

The research in this paper was focused on the corrosion behavior of 7xxx aluminum alloys with various copper (Cu) contents. The effects of corrosion were investigated using both polarization and electrochemical impedance spectroscopy (EIS) techniques. The authors determined two breakdown potentials in Cu containing alloys in a de-aerated chloride solution, and that the values increased logarithmically with increasing Cu content. However, in an aerated chloride solution, polarization resistance as determined by EIS decreased with increasing Cu content. The first breakdown potential corresponded to transient dissolution associated with attack of the fine hardening particles and the surrounding solid solution in a thin surface layer. The second breakdown potential was associated with combined intergranular and selective grain attack. The correlation between the microstructure, especially the Cu content, and corrosion behavior was made by composition analysis of the grain boundary regions including precipitate free zone and grain boundary precipitates as well as the matrix by scanning transmission electron microscopy. The corrosion potential increased with increasing alloy Cu content in aerated chloride solutions because of enhanced rates of oxygen reduction. This degraded the corrosion resistance despite the increase in the breakdown potentials with Cu content. [16]

A.1.17 Lavaert et al. (2002): An EIS study of the influence of imperfections on the corrosion behaviour of an organic coated steel system

In this work, three different coating conditions influencing the quality of a silicon-polyester galvanized steel system were investigated by means of electrochemical impedance spectroscopy (EIS). The first objective was to investigate the influence of different types of pores or discontinuities on the corrosion resistance of the above mentioned coating-system. A second objective was to study the influence of mechanical deformation and damage of the coating on the corrosion behaviour of the coating-system. Finally, degradation due to ultraviolet exposure was also investigated by the authors. In each of these investigations the authors found that it was possible to distinguish different time constants for different electrochemical events (Bode phase diagrams). From the build up of the coating-system, and the number of time constants deduced from the EIS measurements, it was possible to model the system. From the model, the physical and electrochemical phenomena occurring during the service life of an imperfect organic coating system were explained. [17]

A.1.18 Davis et al. (2000): *In-situ* corrosion sensor for coating testing and screening

In this paper, an in-situ corrosion sensor capable of detecting coating deterioration and substrate corrosion underneath a paint coating is described. The sensor is based on the method of electrochemical impedance spectroscopy (EIS) and is sensitive to early stages of material degradation (before any visual damage is present). Two versions of the in-situ sensor have been developed (a permanently attached sensor and a portable hand-held sensor). The permanently attached in-situ sensor is well suited for corrosion sensing in inaccessible areas or for automatic or semi-automatic inspection of a particular area of both test specimens and real structures. [18]

A.2 Terahertz Radiation Methods

A.2.1 Kawano and Ishibashi (2008): An on-chip near-field terahertz probe and detector

In this work, the authors present an integrated detection device for terahertz (THz) near-field imaging. The device consists of an aperture, a probe and a THz detector all integrated on one semiconductor chip that is cryogenically cooled. This particular scheme allows highly sensitive, high-resolution detection of the evanescent field (evanescent-field sensors are based on the principle of total internal reflection at the interface between two media with different indices of refraction) alone and promises new capabilities for high-resolution THz imaging. The main property of THz waves, such as their transmission through objects opaque to visible light, is attracting attention for imaging applications. [19]

A.2.2 Madaras et al. (2008): Application of terahertz radiation to the detection of corrosion under the Shuttle's thermal protection system

This paper discusses the use of terahertz (THz) radiation for detecting corrosion under the space Shuttle heat barrier tiles. NASA is investigating new nondestructive evaluation (NDE) methods for detecting hidden corrosion such as might be found underneath the heat barrier tiles. In this regard, time domain THz radiation has been applied to corrosion detection under heat barrier tiles in samples ranging from small lab samples to an actual space Shuttle. This method has been able to detect corrosion at thicknesses of 5 mils or greater, under 1 inch thick Shuttle tiles, and 7-12 mils or greater, under 2 inch thick Shuttle tiles. Tests have been performed to evaluate the ability of electromagnetic (EM) radiation at THz frequencies to detect corrosion hidden under the thermal protection materials used on the space Shuttles. Several measurements indicate that corrosion greater than five mils deep in the aluminum substrate is detectable under one inch thick tiles. Further measurements indicate that corrosion detection is limited to about seven to twelve mils under two inch thick tiles. Measurements on a relatively high fidelity structural mock up of the space Shuttle with tiles indicate that the THz EM waves had enough image resolution to identify numerous structures under the tiles. [20]

A.2.3 Stoik et al. (2008): Nondestructive evaluation of aircraft composites using terahertz time domain spectroscopy

In this work, terahertz (THz) time domain spectroscopy was used for nondestructive evaluation of aircraft glass fiber composites stressed with bending and heating damage. Refractive index and absorption coefficients were measured for both damaged and undamaged composites. The two dimensional extent of the heat damage could be shown with either a simple phase or amplitude THz imaging technique. [21]

A.2.4 Zimdars et al. (2008): Rapid time domain terahertz axial computed tomography for aerospace non-destructive evaluation

In the work presented herein, a rapid time domain terahertz (THz) computed axial tomography system is described. The THz system is used to reconstruct three dimensional structures of aerospace components. In this work the authors demonstrate a rapid THz system to reveal the 3D structure and internal flaws of larger aerospace structures such as Kevlar, silica thermal protection tiles, and foam thermal insulation. [22]

A.2.5 Chan et al. (2007): Imaging with terahertz radiation

This paper gives a comprehensive description of the various techniques which have been employed for terahertz (THz) image formation. Several examples which illustrate the potential uses for these emerging technologies are also discussed. Many of these proposed applications exploit the unique capabilities of THz radiation to penetrate common packaging materials and provide spectroscopic information about the materials within. This list has grown in parallel with the development of new technologies and new paradigms for imaging and sensing. [23]

A.2.6 Anastasi and Madaras (2006): Terahertz NDE for metallic surface roughness evaluation

In the research presented in this work, terahertz (THz) non-destructive evaluation (NDE) is described as a method capable of inspecting metallic surfaces. The THz frequency regime is between 100GHz and 10THz and has a free space wavelength of 300μm at 1THz. Pulsed THz radiation, can be generated and detected using optical excitation of biased semiconductors with femto-second laser pulses. Metallic surface roughness in a smooth surface is a potential indication of material degradation or damage. When the surface is coated or covered with an opaque dielectric material, such as paint or insulation, inspecting for surface changes becomes almost impossible. In this work, samples are inspected with a commercial THz NDE system that scans the sample and generates a set of time-domain signals that are a function of the signal reflected from the metallic surface. Post processing is then performed in the time and frequency domains to generate C-scan type images that show scattering effects due to surface non-uniformity. [24]

A.2.7 Anastasi and Madaras (2006): Terahertz NDE for under paint corrosion detection and evaluation

In this work**,** terahertz (THz) nondestructive evaluation (NDE) imaging under paint for corrosion was examined as a method to inspect for corrosion by examining the THz response to paint thickness and to surface roughness. If corrosion under paint causes the paint to swell and increase in thickness or changes a nominally smooth surface to an uneven and irregular surface, then THz NDE may be able to inspect for corrosion. Terahertz NDE response to paint thickness shows that as the paint became thin, an individual paint surface echo could not be resolved from substrate echoes, but signal amplitude continued to be influenced by paint thickness. Limits of surface roughness detection are examined using surface-roughness comparator-plates. These plates are scanned and examined in the time and frequency domains and at normal and angled incidence. [25]

A.2.8 Zimdars et al. (2006): Large area terahertz imaging and non-destructive evaluation applications

In this work, the method of terahertz (THz) imaging is described for non-destructive evaluation (NDE) in aerospace and other settings. As an example, NASA is currently employing THz reflection NDE to examine the space shuttle external tank foam insulation for voids and disbonds. Other THz imaging applications include homeland security, such as the inspection of personnel, the detection of concealed explosives, biological agents, chemical weapons, flammables, metallic and non-metallic weapons, and other potentially dangerous items. Unfortunately, the advancement of many of these applications has been limited by slow imaging speed, small scan areas and in many cases the requirement that the sample itself be mechanically scanned. In this paper, the authors report on the development and applications of a high speed large area time domain THz NDE imaging system. [26]

A.2.9 Kersting et al. (2005): Terahertz microscopy with sub micrometer resolution

The research described here presents a terahertz (THz) near-field microscope that can serve as a contactless probe for identifying the dielectric properties of individual quantum systems. Spatial resolutions down to 150nm have been achieved. In this regard, THz images obtained of organic and inorganic structures demonstrate the applicability of the technique on objects of submicron size. [27]

A.2.10 Chen et al. (2003): Terahertz imaging with nanometer resolution

In this paper, the authors report on the application of scanning near-field optical microscopy for terahertz (THz) imaging. They were able to obtain a spatial resolution of 150nm for 2THz pulses. Their experiments show the potential of submicron THz microscopy for imaging of biologic tissues at the cellular level or for the investigation of individual submicron semiconductor devices. [28]

A.2.11 Mueller (2003): Terahertz radiation: applications and sources

A brief discussion on terahertz (THz) technology is presented in this paper including possible emerging applications for THz imaging as well as efficient THz radiation sources. [29]

A.2.12 Mittleman et al. (1999): Recent advances in terahertz imaging

In this work, the authors review recent progress in the field of terahertz (THz) imaging. This imaging technique, based on THz time-domain spectroscopy, has the potential to be the first portable far-infrared imaging spectrometer. The authors provide several examples illustrating possible applications of this technology, using both amplitude and phase information contained within the THz waveforms. They describe the latest results in tomographic imaging, in which waveforms reflected from an object can be used to form a three-dimensional representation. Advanced signal processing tools are exploited for the purposes of extracting tomographic results, including spectroscopic information about each reflecting layer of a sample. [30]

A.3 Fiber-Optic Methods

A.3.1 Börner et al. (2009): Evanescent field sensors and the implementation of waveguide nanostructures

In this work, a fiber optic evanescent-field sensor is presented for the online and in-situ monitoring of carbon dioxide (CO_2) for detection during sequestration in aquifers. The results demonstrate the suitability of the sensor for CO_2 detection in both the gas phase as well as in the fluid phase. The paper also discusses the detection of the explosive TNT by a fiber optic evanescent-field sensor with a highly sensitive polymer coating. Zinc oxide (ZnO) nano-wires are studied for implementation in a conventional evanescent-field sensor to increase the interacting surface area and usability of waveguiding effects of the nanostructures. Analytical and experimental results show promising properties that are useful for enhancing the sensitivity of the sensor. [31]

A.3.2 Leung et al. (2008): A novel optical fiber sensor for steel corrosion in concrete structures

In this paper, the authors present a new fiber optic based technique for detecting the onset of steel corrosion under a certain environment, with special application on concrete structures. In this regard, the underlying physical principle is first explained. The sensor was tested in sodium chloride (NaCl) solution and embedded in cement mortar with NaCl to illustrate the feasibility of corrosion sensing. Additional tests were conducted on a fully packaged sensor to study its performance. First, the sensors were installed inside holes drilled in hardened cement mortar blocks with different NaCl content to verify the capability to detect corrosion activity in existing structures. Second, the sensors were glued to embedded steel reinforcements under corrosive environment and the sensor output will be compared to existing corrosion measurements. Third, packaged sensors are embedded in cement mortar blocks with the sensing tip at different distances from the surface. With these blocks placed inside a salt water bath, the feasibility to monitor the penetration of chloride into a concrete member can be assessed. [32]

A.3.3 Wade et al. (2008): A fibre optic corrosion fuse sensor using stressed metal-coated optical fibres

In this work, a novel optical fiber-based corrosion sensor is presented. The sensing mechanism is based on the mechanical failure of stressed metal-coated optical fibers when exposed to a corrosive environment. The work discusses proof-of-principle tests carried out using commercially available aluminum-coated optical fibers. Tests have been undertaken in a non-corrosive environment, in aqua regia (a mixture of hydrochloric acid and nitric acid) and in sea water. The failure times of stressed aluminum-coated fibers were found to correlate with the corrosivity of the test environment. The results are discussed in relation to microscopic investigations of the metal coatings in these corrosive environments and also as a function of immersion time. The sensor uses a stressed metal-coated optical fiber which transmits light to indicate that no corrosion is present. When the fiber is exposed to a corrosive solution the metal coating of the fiber corrodes away. After a certain amount of time the metal jacket corrodes to the extent that the glass cladding of the optical fiber is exposed. Once the glass is exposed the fiber will fracture at a rate dependant upon a variety of factors including the level of stress and the amount of moisture present. After the fiber has broken it will no longer transmit light, and the loss of signal can be used to indicate the presence of corrosion. [33]

A.3.4 Abi Kaed Bey et al. (2007): Long period grating pair chloride ion sensor for early corrosion prevention

In this paper, an approach for chloride ion monitoring in aqueous sodium chloride (NaCl) solutions using a long period grating pair (LPGP) is reported (two long period grating (LPG) fibers with a center-to-center separation of 30mm). The refractive index change due to the presence of the chloride ion was monitored, with the sensor having previously been calibrated using solutions of known refractive index (n). A test comparison with the response of a single LPG under similar testing conditions was also carried out, and the results demonstrate that the LPGP could measure a change in n of ±0.003, achieving an improvement in the precision obtained using a single LPG. The focus of the work is on the underpinning technology for early stage corrosion monitoring in structures arising due to salt and water ingress. [34]

A.3.5 Corres et al. (2007): Design of pH sensors in long-period fiber gratings using polymeric nanocoatings

In this paper, two different pH sensors based on polymeric nano-coatings on long-period fiber grating have been studied and compared. An electrostatic self-assembled method was used to create pH sensitive films. In this regard, two types of sensors have been designed, (i) the first one is based on polyallylamine hydrochloride (PAH), and polyacrylic acid (PAA), and (ii) the second one incorporated a Prussian blue (PB) pigment in the PAH/PAA matrix. A theoretical model of multilayer cylindrical waveguides based on coupled-mode theory was used to predict the position of the attenuation bands as a function of the overlay thickness. Both sensors were tested and compared in terms of sensitivity and response time. A faster response was obtained with the introduction of PB particles in the polymeric matrix. Linear sensors in the pH range 4–7 were obtained, showing good repeatability and high sensitivity. [35]

A.3.6 Qiu et al. (2007): The formation of pure aluminium corrosion sensing film on fiber and its electrochemical performance

In this paper, an aluminum corrosion sensing film was directly deposited on the core of an optical fiber (where the cladding had been removed) using a vacuum sputtering method. Metallographic microscope and scanning electron microscope (SEM) were used to analyze the structure of the aluminum film. Measurements taken indicate that the thickness of the aluminum corrosion sensing film was 14.65μm, and that the sputtered film was evenly distributed. Galvanic measurements were used to evaluate the corrosion resistance in sodium chloride (NaCl) solution of different concentrations. The results obtained show that the corrosion resistance of the sensing film is similar to that of industrial pure aluminum in NaCl solution. The work in this paper contributes to the research of fiber optical corrosion sensor for monitoring corrosion of aluminum. [36]

A.3.7 Martins-Filho et al. (2007): Fiber-optic-based corrosion sensor using OTDR

In this work, an optical sensor using an optical time domain reflectometry (OTDR) technique was proposed for the characterization of the corrosion process in aluminum. The proposed sensor system consists of several sensor heads connected to a commercial OTDR by a single mode optical fiber and fiber couplers. Each sensor head consists of an optical fiber having the cleaved end coated with an aluminum film. For laboratory measurements, the corrosion action was simulated by controlled etching of the aluminum film on the sensor head. The OTDR detects the light reflected by each sensor head. As the aluminum is etched the reflection decreases. The proposed sensor system is multipoint and can detect the corrosion rate for each head several kilometers away from the OTDR. [37]

A.3.8 Collins (2006): Optical fibre sensors: an Australian perspective

This paper presents an overview of optical fiber sensor research and development within Australia. [38]

A.3.9 Sinchenko et al. (2006): Optical fibre techniques for distributed corrosion sensing

In this work, several different approaches are examined to assess the suitability of optical fiber sensors to detect corrosion or its precursors. In this respect, the research includes coating an optical fiber with a special compound that will fluoresce in the presence of corrosion products or other species that may be responsible for initiating corrosion. The performance of optical fibers containing long period gratings (LPGs) with a moisture sensitive cladding layer has also been tested. This paper reviews the different approaches that have been investigated and discusses the engineering problems that remain to be overcome before an effective system can be developed for distributed sensing in the field. This work investigates techniques that could potentially be applied via optical fiber sensors to detect changes in the local environment that are associated with corrosion or can lead to the initiation of corrosion. In this regard, two techniques for corrosion sensing are examined, (i) sensing changes in the local moisture content and (ii) changes in the local cation concentration. The authors state that the (ii) technique appears more attractive than humidity detection, although other possible indicators for moisture presence still need to be investigated and might provide better results. The detection of aluminum cations in solution was demonstrated with an optical fiber point sensor. While the ability of this sensor to be embedded in inaccessible areas and interrogated remotely offers a significant advantage over conventional corrosion inspection techniques, the sensor needs to be in close proximity to the corrosion affected area. The production of a distributed sensor is the ultimate goal, as it will increase the probability of detecting corrosion in large structures. [39]

A.3.10 Dong et al. (2005): Intensity-based optical fiber sensor for monitoring corrosion of aluminum alloys

The work presented in this paper consists of a method based on the shift of light power, or intensity, transmitted through a fiber to measure the corrosion of aluminum. A portion of the cladding of a multimode fiber was metalized with aluminum. The transmitted light signal is dependent upon the integrity of the cladding and may therefore be a measure of the degradation or corrosion of the aluminum cladding. [40]

A.3.11 Dong et al. (2005): Sensing of corrosion on aluminum surfaces by use of metallic optical fiber

In the research described in this paper, the normal cladding of the optical fiber is removed in the sensor region and replaced with an aluminum alloy of the same material as the structure being monitored. The excellent reflecting property of aluminum prevents total internal reflection, and therefore there is a significant attenuation of the higher-order modes through the aluminum-coated sensor region. However, as the aluminum alloy coating corrodes, the cladding around the core is removed. As a result, the core is then surrounded by air, water, or corrosion products, which have lower indices of refraction than the core, and the attenuation decreases significantly; hence the output light increases. This increase in the optical output of the fiber should give an indication of the amount of corrosion taking place at the corrosion-sensing location along the fiber sensor to be monitored. Because the light throughput increases with corrosion, it should be relatively immune to false calls caused by dirt on connectors, micro-bending, fiber damage, and other mechanisms that decrease the intensity of light. [41]

A.3.12 McAdam et al. (2005): Fiber optic sensors for detection of corrosion within aircraft

In this work, fluorescent fiber optic sensors that detect aluminum cations from the early stages of the corrosion process are proposed as a means for providing an early warning of corrosion in aging aircraft. This paper discusses the results for two different carriers of an aluminum-sensing fluorophore and some of the key technical issues that need to be resolved for the development of an effective fiber optic sensing system. [42]

A.3.13 Morison et al. (2005): Solving common corrosion problems with non-intrusive fiber optic corrosion and process monitoring sensors

In this paper, a non-intrusive long gage length FOX-TECH FT fiber-optic sensor system which, in addition to monitoring wall loss, can also monitor pressure and temperature profiles is demonstrated. The sensor is based on the principle of the coherence of reflected light recombining (either in phase or out of phase) from two different optical paths (one reference and one probe). These sensors can be used to measure wall loss in real time to increase safety and to allow more efficient planning of turnarounds. [43]

A.3.14 Benounis and Jaffrezic-Renault (2004): Elaboration of an optical fibre corrosion sensor for aircraft applications

In this work, an optical fiber corrosion sensor is developed to characterize corrosion in aeronautical structures by electrochemical measurement. Here, corrosion is deduced from the optical signal. The kinetics of corrosion are monitored by the optical fiber corrosion sensor (OFCS). Also, uniform or preferential corrosion can be deduced from the optical signal. The results demonstrate the feasibility of using the sensor for the detection of corrosion in different environmental conditions. For high acid concentration, concentrated acid attacks on preferential places occur. Therefore, the hydrogen pressure is sufficient to cause the blister cracks. For low concentrations, the aluminum corrosion is done in an homogeneous way. This OFCS can be used for the detection of corrosion effects or for the detection of humidity in structures. [44]

A.3.15 Maalej et al. (2004): Fiber optic sensing for monitoring corrosion-induced damage

This paper reports on the feasibility of using embedded Fabry-Pérot fiber optic sensors to detect and monitor the propagation of cracks and delamination within concrete beams induced by corrosion of the reinforcing bars. This technique demonstrates the possibility of detecting corrosion-induced damage in reinforced concrete structures, particularly those where visual inspection is not possible. The optical sensing mechanism is based on transverse tensile strains associated with the longitudinal crack along the reinforcing bars. [45]

A.3.16 Wong et al. (2003): Plastic optical fiber sensors for environmental monitoring: Biofouling and strain applications

In the work presented herein, two long-term environmental monitoring plastic optical fiber (POF) sensors are described. The sensing mechanism is based on light intensity modulation. An evanescent field bio-fouling sensor was developed and characterized with sensitivity of ±0.007 refractive index units. A tapered POF was developed and tested as a strain sensor, which demonstrated excellent linearity and exhibited good agreement with measured strain values. The POF strain sensor appeared to be well-behaved in that it showed little data scatter and was able to monitor strains up to 1.4% without failure. These two applications demonstrate the potential POF sensors have for cheap, on-line continuous environmental monitoring. [46]

A.3.17 Ghandehari and Vimer (2002): An evanescent-field fiber optic sensor for pH monitoring in civil infrastructure

Presented in this work are fiber optic pH sensors based on the evanescent field spectroscopic technique. Portions of the poly-methyl methacrylate (PMMA) cladding of polymer clad silica (PCS) optical fibers are replaced with a new cladding composed of PMMA doped with a pH sensitive chromophore. Methyl-Red, Thymol-Blue, and Thymolphtalein are used for sensing pH at the acid, neutral and base levels, respectively. Changes in the pH of the sensing environment are detected by measuring the absorption spectrum of the new cladding in the sensing region of the optical fiber. [47]

A.3.18 Cooper et al. (2001): Optical fiber-based corrosion sensor systems for health monitoring of aging aircraft

This paper discusses the precursors that typically preclude the initiation of corrosion or reveal its propagation as a way to monitor corrosion. In this work, new optical fiber-based sensors for real-time in-situ detection of corrosion precursors and by-products have been developed for health monitoring of aging aircraft. The sensor-system consists of optical fiber long-period grating (LPG) sensors multiplexed using an optical switch and a miniature spectrum analyzer. The LPG sensors operate based on specially designed hydrogel coatings which cause a measurable change in the refractive index measured by the LPG in the presence of specific target species. Application of optical fiber-based chemical sensors for the detection of water ingress in lap joints, and metal- ion detection are presented and discussed. [48]

A.3.19 Fitzgerald et al. (2001): Evanescent microwave sensor scanning for detection of sub-coating corrosion

In this paper, the method of evanescent microwave probe (EMP) scanning spectroscopy is presented. This method has the capability to image sub-surface features through poorly conducting or dielectric materials, such as aircraft paint. This makes EMP scanning a valuable option for detecting corrosion of aircraft primary structural members without removing paint from the area to be inspected. Evanescent microwave probes measure resonance frequency shift and power loss as functions of the conductivity, dielectric response, and topography of a material. Because each of these materials properties can be changed locally by surface and near surface defects, a change in measured parameters occurs when the probe passes over an area of corrosion. This new nondestructive evaluation technique produces sensitive and highly resolved spatial measurements of corrosion on aircraft structures through layers of paint, thus saving time and money on aircraft maintenance. [49]

A.3.20 Panova et al. (1997): In situ fluorescence imaging of localized corrosion with a pH-sensitive imaging fiber

In the research described in this paper, a fiber-optic pH-imaging sensor array capable of both visualizing remote corrosion sites and measuring local chemical concentrations at these sites was applied to real-time corrosion monitoring. The imaging fiber’s distal face, containing an immobilized pH-sensitive fluorescent dye, was brought into contact with metal surfaces submerged in aqueous buffers and fluorescence images were acquired as a function of time. Heterogeneous fluorescence signals were observed due to both pH increases at cathodic surface sites and pH decreases at anodic surface sites. These fluorescence signals showed both localization and rates of corrosion activity. Three corrosion processes were investigated, galvanic corrosion at a copper/aluminum interface and crevice corrosion and pitting at a stainless steel surface. The spatial resolution of the technique was limited by proton/hydroxide diffusion and the diameter of the individually clad optical fibers comprising the imaging bundle. [50]

A.4 Miscellaneous Optical Methods

A.4.1 Andrés et al. (2008): Fast visualization of corrosion processes using digital speckle photography

The purpose of the work presented in this paper is to propose digital speckle photography (DSP) as a technique to obtain relevant information about corrosion processes. The analysis of the correlation coefficient in the digital image is used to obtain information about corrosion rates of iron in different sulfuric acid (H_2SO_4) solutions. The results are compared with those obtained from a linear sweep voltammetry technique. An analysis of the images recorded with DSP provides a detailed quantitative corrosion map with information on the corrosion process at each point on the surface. [51]

A.4.2 Hung et al. (2007): Review and comparison of shearography and pulsed thermography for adhesive bond evaluation

In this paper, two techniques are compared to address a common set of aerospace applications such as delaminations or skin-to-core disbonds in composite structures. These approaches use different flaw detection mechanisms, (i) shearography measures a sample's mechanical response to mechanical stresses (shearography measures structural deformation), and (ii) pulsed thermography measures a sample's thermal response to an instantaneous thermal excitation. If stresses similar to the service stresses can be applied, defects that are detrimental to the service life of the object can be revealed. Thermography can also provide some degree of material characterization, such as diffusivity, depth, or thickness measurement. Both shearography and thermography also have the ability to go beyond identifying disbonds; they can also be employed for evaluating other types of defects such as cracks and corrosion. [52]

A.4.3 Webster and Thevar (2007): Remote optical non-destructive inspection technique for metal and composite structures

This paper presents and describes a non-contact laser based nondestructive inspection (NDI) technique for metals and composites. An acoustic device is used to remotely excite the material under inspection while a scanning laser vibrometer is employed to measure the resulting vibrations. The test materials studied, mostly aluminum or composite aircraft structures, have been successfully inspected from a standoff distance of at least a meter. The NDI system clearly shows the defect locations overlaid on the images of the test objects. Metal and composite delamination and subsurface corrosion in aluminum structures are among the defects that were detected. [53]

A.4.4 Zeylikovich et al. (2003): Mid-IR transmission window for corrosion detection beneath paint

In this work, the mid-infrared transmission window between 3.8-5.5µm is used to detect corrosion beneath a paint layer of 80-100µm thickness using low power light emitting diodes (LED). The samples used in the study were made from 2024-T3 aluminum plates. The aluminum plates were chemically corroded by the reaction of potassium hydroxide (KOH) with the surface of the aluminum plate for a period of 24h. The thickness of the corrosion was about 35µm and formed an 8mm circle. The corrosion was either over coated with paint or covered with glass slides that had been prepared with different paint systems of various thicknesses. The authors reveal that the best results were obtained for a 4.8µm wavelength. [54]

A.4.5 Ali et al. (2000): Detection of corrosion beneath a paint layer by use of spectral polarization optical imaging

In this work, the spectral and polarization (far-red and near-infrared spectral polarization imaging) properties of scattered light were used to image corrosion beneath the surface of a painted aluminum plate. The quality of imaging of the corrosion on the metal surface was significantly enhanced by the spectral polarization optical imaging technique. Depolarization scattered light was used to detect and image corrosion beneath the paint layer. [55]

A.4.6 Komai et al. (1996): In-situ nanoscopic visualization of stress corrosion cracking of high-strength aluminum alloy by scanning atomic force microscopy

In this research, an atomic force microscope (AFM) with a three-point bending testing machine was employed for in situ visualization of intergranular stress corrosion (SC) crack growth under a constant displacement. The tests were conducted on 7075-T6 aluminum alloy. The AFM was capable of imaging surface topography of growing SC crack in the order of nanometers and was capable of monitoring slow SC crack growth. The authors determined that the tip of a growing SC crack in laboratory air was very sharp, however, when the environment was changed to a vacuum, the crack tip became blunt, and the crack retarded. When the environment was changed back to laboratory air, the crack growth restarted after some time, and the tip became sharp again. [56]

A.4.7 Hung (1989): Shearography: A novel and practical approach for nondestructive inspection

This paper presents an optical technique referred to as shearography for nondestructive inspection. Shearography is an interferometric method which allows full-field observation of surface displacement derivatives. Both surface and interior flaws can be detected. It reveals flaws in materials by looking for flaw-induced strain anomalies. [57]

A.4.8 Svedung (1986): An in-situ method to study atmospheric corrosion of contact material

In this work an in-situ apparatus to study atmospheric corrosion of contact materials is presented. By using a light reflection-absorption method the corrosion process was studied on gold coated brass in a corrosive atmosphere. The test equipment consisted of a helium-neon (HeNe) laser. The HeNe laser generates 2.0mW polarized light at a 6328Å wavelength. In this regard, the reflection of light from a metallic surface changes when the surface is corroded. The authors followed this process by measuring the decrease in the angular reflected beam intensity during exposure. All corrosion products on the surface absorb and diffusely reflect the incoming light. This method of studying corrosion processes may be useful for the comparison of contact materials in a certain corrosive atmosphere. The study of one material in different environment is also of interest, but it is not possible to obtain completely comparable intensity plots, since different corrosion products have different absorption coefficients and scatter light differently, depending on the appearance of the corrosion products. [58]

A.5 X-Ray Methods

A.5.1 Birt et al. (2006): NDE corrosion metrics for life prediction of aircraft structures

This work discusses corrosion “metrics” that need to be measured so that the remaining life can be calculated from corrosion and fatigue crack growth models. Recent research in nondestructive evaluation (NDE) has led to the development of a number of techniques for detecting and measuring hidden corrosion for aircraft structures. The authors have determined that the first corrosion metric which needs to be established is the type of corrosion taking place. A set of corrosion specimens has been fabricated to demonstrate the ability of various NDE techniques to measure the corrosion metrics. Two types of corrosion were investigated (i) pitting corrosion and (ii) crevice corrosion. The corrosion was produced by placing the samples in a salt-fog chamber for different lengths of time. Ultrasonic, eddy current and x-ray inspection techniques were carried out on the corrosion samples. This paper describes the initial results of the study. [59]

A.5.2 Connolly et al. (2006): X-ray microtomography studies of localised corrosion and transitions to stress corrosion cracking

In this paper, two programs are presented to demonstrate the power of the x-ray microtomography technique. The first one investigates the intergranular corrosion (IGC) of an aluminum alloy and the second investigates the transition from pitting to stress corrosion cracking in steel. The advantages of this technique to provide physical inputs and parameters useful in life prediction modeling and in efforts to understand the underlying mechanisms controlling localized corrosion and stress corrosion crack growth are shown. [60]

A.5.3 Johnson and Storey (2004): Intergranular corrosion of a light aircraft aluminum alloy propeller

In the work presented herein, the examination of the wreckage of a light aircraft revealed that approximately 20cm was missing from one tip of the aluminum alloy propeller. Fractographic and metallographic examination of the remaining portion of the propeller revealed extensive grain-boundary separation in the vicinity of the fracture, and grain edges and corners rounded by corrosion on the fracture surface. Energy dispersive x-ray analysis (EDXA) was used to determine the cause of the corrosion induced fracture. [61]

A.5.4 Zhao et al. (2003): In situ x-ray radiographic study of intergranular corrosion in aluminum alloys

In this work, an in situ x-ray radiography method was used to address localized corrosion kinetics and morphology of AA2024-T3 and AA7178 aluminum alloys. In situ x-ray radiography was used to characterize the intergranular and exfoliation corrosion in high strength aluminum alloys exposed to a sodium chloride (NaCl) solution at a controlled potential, and also to high humidity after an electrochemical pretreatment. Growth kinetics for intergranular corrosion (IGC) sites determined from radiographs of samples encased in epoxy and exposed to the solution were slower than growth kinetics determined by the foil penetration technique. The radiographs clearly visualize the exfoliation corrosion and record the progress of the corrosion. The unencased AA2024-T3 samples that were exposed to the NaCl solution exhibited IGC and then exfoliation corrosion. AA2024 and AA7178 samples that were first electrochemically pretreated in chloride solution and then exposed to 96% relative humidity developed sharp intergranular fissures. [62]

A.5.5 Wallinder et al. (1999): Characterization of black rust staining of unpassivated 55% Al-Zn alloy coatings effect of temperature, pH and wet storage

The aim of this paper is to clarify under which conditions black staining on a 55% aluminum-zirconium (Al-Zn) alloy coating can occur and to provide a possible explanation to why the discoloration takes place. Temperature, wet storage and pH dependence were investigated in the laboratory in terms of time to blackening and corrosion product characterization. Efforts have been made to associate the black rust staining with phases formed in the corrosion layer. The results are mainly based on morphological and quantitative analyses by means of scanning electron microscopy with x-ray microanalyses and crystalline phase identification using x-ray diffraction techniques. [63]

A.6 Microwave Methods

A.6.1 Qaddoumi et al. (2007): Innovative near-field microwave nondestructive testing of corroded metallic structures utilizing open-ended rectangular waveguide probes

In this work, a method employing microwave nondestructive testing and evaluation (NDT-E) techniques for the detection and evaluation of rust under paint was presented. The results obtained show that using a dielectric layer with known physical properties to replace the air-layer results in significant improvement in the measurement sensitivity and resolution for some microwave NDT applications. The goals of this research included using theoretical computer programs to describe the interaction of microwave signals with any layered medium. One of the computer programs calculates the aperture reflection coefficient (simulating measurements), and the other computer program calculates the field distribution in any layered media. The experimental results were obtained using an inspection system that was built according to the results of the theoretical investigation and they confirmed the theoretical results. [64]

A.6.2 Ghasr et al. (2004): Comparison of near-field millimeter wave probes for detecting corrosion pit under paint

In this paper, a comparison between several different millimeter wave probes is made for the detection and evaluation of corrosion precursor pitting under paint at Ka and V-bands. Near-field microwave nondestructive techniques have been successfully used for detection of corrosion under paint. The pittings investigated here are very small in size; hence the spatial resolution and sensitivity of the probes are critical issues. It is shown that modified open-ended rectangular probes namely, tapered waveguide and dielectric slab-loaded waveguide probes provide high resolution and sensitivity for the detection and evaluation of very small pitting under paint. [65]

A.6.3 Saleh and Qaddoumi (2004): Corrosion detection and thickness evaluation utilizing active near-field microwave nondestructive testing techniques

In this work, a method using microwave nondestructive testing techniques for enhanced detection and evaluation of rust under paint has been developed. The results obtained are promising and show that the use of a layer of dielectric material with known properties to replace the standoff layer (air) yields significant improvements in the measurement sensitivity and resolution. [66]

A.6.4 Hughes et al. (2003): Near-field microwave detection of corrosion precursor pitting under thin dielectric coatings in metallic substrate

In this work, a near-field microwave technique is used for corrosion detection under paint, under a dielectric coating and from bare metal. The authors report detecting 500μm pits using an open-ended rectangular waveguide sensor at the V-band (50-75GHz) microwave frequencies. [67]

A.6.5 Hughes et al. (2001): Microwave nondestructive detection of corrosion under thin paint and primer in aluminum panels

The objective of this work was to investigate the potential of near-field microwave testing techniques for detecting corrosion under paint and primer in aluminum substrates. To accomplish this goal, an electromagnetic formulation, simulating detection of corrosion in layered structure using open-ended rectangular waveguide probes, was used to gain an insight into the functionality of measurement parameters such as the frequency of operation and the standoff distance. Also, the dielectric properties of paint, primer, real and chemically produced aluminum oxide were measured in a wide range of microwave frequencies (2.6-18GHz). The results showed that the dielectric properties of paint, primer and aluminum oxide are very similar to each other. A theoretical simulation was carried out in a wide frequency band (8.2-40GHz). The over all result of the simulation was that higher frequencies and standoff distances of a few mm are more optimal for detecting thin corrosion layers under paint. Two specially prepared aluminum panels with induced areas of corrosion and surface pitting were produced as well. Using these panels and several phase sensitive measurement systems, experiments were conducted producing 2-D images of various areas of these panels. The overall results of this investigation indicate the robust capability of near-field microwave nondestructive testing and evaluation techniques, using open-ended rectangular waveguide probes. [68]

A.7 Linear Polarization Methods

A.7.1 Elewady et al. (2008): Anion surfactants as corrosion inhibitors for aluminum dissolution in HCl solutions

The work presented in this paper aims to investigate the efficiency of some surface coatings as corrosion inhibitors for aluminum in acidic media. An attempt is also made to clarify the effects of concentration and temperature on the inhibition efficiency of the studied inhibitors. The investigated coating compounds act as inhibitors for the corrosion of aluminum in hydrochloric acid (HCl) solution. The inhibitors increase the value of activation energy of corrosion and consequently, decrease the rate of dissolution of aluminum in the HCl solution. [69]

A.7.2 Kumar et al. (2007): Sensors for measurement of corrosion rates and detection of corrosion under coatings

This work discusses a stamp-sized corrosion sensor that allows measurement of corrosion rates based on linear polarization resistor (LPR) technology, which outputs an exact corrosion rate for the structure on which it is placed. Corrosion rate measurements can reveal which areas of a structure need immediate maintenance and which ones will need maintenance later, as well as allow an optimal maintenance schedule to be developed. The corrosion rate data can be monitored continuously or stored in a data collection node, and downloaded periodically. This sensor technology is being evaluated in the laboratory under various simulated corrosive field conditions. The sensor is being considered for corrosion monitoring applications on structures for mission critical equipment on military installations in severely corrosive environments. [70]

A.7.3 Albiter et al. (2006): Corrosion behaviour of aluminium metal matrix composites reinforced with TiC processed by pressureless melt infiltration

The aim of this work is to investigate the aqueous corrosion behaviour of aluminum metal matrix composites reinforced with titanium carbide (TiC) particles. The main factors influencing the corrosion of composites include porosity, precipitation of inter-metallic phases within the matrix, high dislocation densities at the particle-matrix interfaces, the presence of an interfacial reaction product and electrical conductivity of the reinforcements. Corrosion rates are calculated in terms of the corrosion current density by using linear polarization resistance (LPR) measurements. [71]

A.7.4 Kouřil et al. (2006): Limitations of the linear polarization method to determine stainless steel corrosion rate in concrete environment

This study discusses the results of polarization resistance for several types of stainless steel in fresh as well as in carbonated concrete pore solutions by means of a linear polarization method. The paper also presents results of the non-linear polarization curves analysis. Linear polarization is a non-destructive method designed for measuring polarization resistance. In this regard, it serves for identification of the corrosion rate at or near the free corrosion potential. The linear polarization technique is based on a continuous change of an electrode's potential in the vicinity of a free corrosion potential. Prior to each measurement, the free corrosion potential must be identified with a reference electrode. Subsequently, a counter electrode makes the working electrode's potential skip in the cathodic direction. Polarization of the working electrode in the anodic direction follows with a constant scan rate up above the value of corrosion potential. [72]

A.7.5 Coates et al. (2004): Improving accelerated corrosion test predictions using linear polarization resistance sensors with neural networks

This work addresses the interpretation of accelerated corrosion data with specific application towards the implementation of a successful condition-based-maintenance (CBM) program. The objectives of this work were to investigate the efficacy of specific linear polarization resistance (LPR) sensors and to develop a greater understanding of interpretation of accelerated corrosion testing. LPR sensors were used to retrieve corrosion data of 1100 aluminum and 1010 steel using accelerated corrosion tests. Data from LPR sensors was compared with physical observations of metal corrosion. Preliminary tests indicated that the LPR sensor resistance varies appropriately with the corrosion rating and humidity. Quantitative standards are achieved using the ASTM G34 corrosion rating. An artificial neural network (ANN) algorithm is developed in MATLAB to test the consistency and efficacy of the LPR sensors. LPR sensors have proven to be reliable indicators of corrosion and provide resistance data that correlate with humidity changes and enable corrosion rate predictions. [73]

A.7.6 Klassen and Roberge (2004): Self linear polarization resistance-theory and examples

In this article a technique is introduced for mathematically extracting polarization resistance as well as for obtaining a measure of the frequency of anodic and cathodic transients from electrochemical noise (EN) data. It is a refinement and further development of the technique introduced as self-linear polarization resistance (SLPR). SLPR theory provides a means of quantifying the frequency of cathodic and anodic transients. The SLPR results for 430 stainless steel electrodes in acidic media were virtually identical to linear polarization resistance (LPR) results. The analysis indicates that an estimation of the polarization resistance is obtainable only if one electrode is generating transients during a given time record. In some cases, this information is of more interest than a measure of the polarization resistance. [74]

A.8 Eddy Current Methods

A.8.1 Lefebvre and Mandache (2008): Pulsed eddy current thickness measurement of conductive layers over ferromagnetic substrates

In this work, a lift-off point of intersection (LOI) based pulsed eddy current method is employed to measure the thickness of a conductive layer over a ferromagnetic substrate. The LOI behaviour is analyzed in terms of its time and amplitude values under various conditions. The main areas investigated in this work include varying the conductivity and thickness of the top layer as well as the permeability of the substrate. [75]

A.8.2 Krause et al. (2008): Diffusion of pulsed eddy currents in thin conducting plates

In this work, pulsed eddy current responses from thin plates of copper, aluminum and brass (<1mm) in thickness were investigated. In the thin plate limit, the characteristic time for diffusion within the plate varied linearly with conductivity and had a magnitude that scaled with the dimensions of the coil and the plate thickness. The results obtained are in agreement with the variation expected for electromagnetic diffusion in thin conducting plates. [76]

A.8.3 Murner and Hansen (2008): Buried corrosion detection in multi-layer airframe structures using pulsed eddy current

The work presented in this paper implements pulsed eddy current technology. Unlike conventional eddy current inspections in which the depth of penetration depends on the frequency of the excitation current, pulsed eddy current (PEC) uses a pulse of electric current through a drive coil to induce a multi-frequency mix of eddy currents. Low frequency eddy currents can penetrate a conductive structure more deeply, providing a basis for buried corrosion detection and extraction of depth related information of such defects. Although demonstrated in a research context, this capability has not been made available in a portable instrument for application to aircraft structures or other industries where corrosion detection outside of a laboratory environment is necessary. This paper reviews the science of PEC technology, with specific focus on advances in commercially available portable instruments and comparison of results to traditional eddy current arrays. [77]

A.8.4 Sicard et al. (2008): Detection and imaging of corrosion and cracks in multi-layered aluminum aircraft structures using pulsed eddy currents

The objective of this paper was to investigate the possibility to detect and separate corrosion and crack type defects in multi-layered aircraft structures using both time and frequency based approaches. This paper presents results obtained for the detection and imaging of such defects in multilayered aircraft structures using pulsed eddy current technology on an automated scanner. Various approaches are presented for independent defect imaging within each layer. [78]

A.8.5 Cacciola et al. (2007): Swarm optimization for imaging of corrosion by impedance measurements in eddy current test

The aim of this paper is to suggest a methodology based on particle swarm optimization (PSO). The PSO method is an iterative evolutionary computation technique with the aim of obtaining an image which can sufficiently describe the profile of the corroded material, for example, a metallic plate in which a circular-shaped corrosion profile is detectable. A comparison with a least square minimization method has also been carried out in order to evaluate performances of the proposed approach. [79]

A.8.6 Mandache and Lefebvre (2007): Electromagnetic enhancement of pulsed eddy current signals

The work presented here employs the crossing-points of the lift-off point of intersection (LOI) of pulsed eddy current signals for overcoming lift-off effects when taking measurements. The LOI is the singular point in the time domain for which the amplitude of transient signals does not change with varying lift-off. The authors propose using the coordinates of the lift-off crossing point as signal features for improved detection sensitivity of metal-loss and thickness measurements of conductive top layers over a ferromagnetic substrate. Its use has been previously proven successful in mapping out corrosion in layered structures, such as those used in the aerospace industry. [80]

A.8.7 Crouzen and Munns (2006): Pulsed eddy current corrosion monitoring in refineries and oil production facilities – experience at Shell

In this work, a pulsed eddy current (PEC) method has been adopted to monitor wall thickness in piping of refineries and oil production platforms and is a preferred choice for corrosion monitoring with relative short intervals. As PEC is a non-contact nondestructive testing (NDT) technique, it can also be applied for wall thickness monitoring at high temperatures. Precision wall thickness monitoring allowed for the extension of runtimes. The PEC method has also been applied at crude distillers and high vacuum units of refineries and to verify corrosion inhibition at oil production facilities. [81]

A.8.8 Yang et al. (2006): Pulsed eddy current technique used for non-destructive inspection of ageing aircraft

In this research, a pulsed eddy current (PEC) method is used to quantify cracks found in aircraft structure. The main purpose of the research described here is overcoming the problem of low accuracy of PEC in the classification of defects. Hence, a new feature called the "frequency spectrum separating point" is proposed by the authors for defect classification. Also, the authors propose an array PEC imaging method to detect corrosion appearing in the second layer of an aircraft structure. [82]

A.8.9 Safizadeh et al. (2005): Automated pulsed eddy current method for detection and classification of hidden corrosion

In this work, the authors have investigated the time-frequency analysis of pulsed eddy current (PEC) signals along with feature extraction and classification to automatically characterize and determine the location of material loss in a two-layer structure. In this regard, PEC has been shown to effectively characterize hidden corrosion in aircraft fuselage lap joints. The authors state that two noise sources in the form of probe lift-off and interlayer gap can cause false indications or inaccuracies in quantification. The goal of this study was to develop a software tool to detect and distinguish between first layer and second layer corrosion damage, and describes the development of a modular architecture for analysis of PEC data to enable automatic characterization of hidden corrosion in a typical aircraft fuselage multi-layer structure. [83]

A.8.10 Smith et al. (2004): Enhanced transient eddy current detection of deep corrosion

This paper reports on an investigation on how to determine how the sensitivity can be increased for metal-loss defects deeper than 15mm. The authors indicate that the essential requirement is to increase the contrast between good and defective structure by either reducing noise levels or increasing the strength of the field reflected from the defect. An increase in the reflected field can be achieved by either increasing the incident field strength, or changing its spatial characteristics. Experimental results obtained show that defect sensitivity can be increased using these methods with a considerable improvement in the detection of metal loss in deep defects. [84]

A.8.11 Smith and Harrison (2004): Hall sensor arrays for rapid large-area transient eddy current inspection

This paper discusses the development of an array of Hall-effect sensors in conjunction with a rectangular coil to gather transient eddy current data and form coherent images of metallic specimens. Scanning speeds are up to 10 times faster than with single sensor probes. A discussion is given on the consequence of using a rectangular coil in that double images can occur. Due to the highly directional nature of the current excitation, the detection of cracks depends on their alignment relative to the probe. Therefore, in order for cracks to be detected reliably, their direction must be known in advance. In contrast, the detection of corrosion does not depend on probe alignment. [85]

A.8.12 Katyal and Bowler (2003): Simulation of eddy-current corrosion detection using a sensor array

In this paper, a computer model is presented for the evaluation eddy current probes for the detection and evaluation of hidden corrosion. The main advantage of the simulation approach is that it allows for adjustments to the virtual probe model in order to improve its sensing capabilities (sensitivity, resolution, etc). [86]

A.8.13 Smith et al. (2003): Eddy-current testing with GMR magnetic sensor arrays

This paper discusses the technology of fabricating sensor arrays on giant magneto-resistance (GMR) sensors. In this regard, integrated sensor arrays are described for crack and corrosion detection. The authors indicate that GMR magnetic sensors and GMR sensor arrays with frequency independent sensitivity offer improvements in speed, depth, and resolution with regard to eddy-current testing, and arrays of GMR magnetic sensors allow rapid scanning of an area for defects in a single pass. Arrays have been fabricated with sensor spacing as small as 5µm. The authors describe GMR sensor elements that can be deposited on active silicon substrates facilitating on-chip signal processing and multiplexing and simplifies the sensor/signal-processing interface, minimizes the number of leads, and can reduce the effect of noise. [87]

A.8.14 van den Bos et al. (2003): Automatic scanning with multi-frequency eddy current on multi-layered structures

The purpose of the work presented here was to increase both testing speed and sensitivity by using multi-frequency eddy current testing combined with a scanning system for corrosion detection in multi-layered structures. For this work, the wing of a Saab 2000 aircraft was one example for which several samples were manufactured with artificial (chemically etched) corrosion of various severity and cracks. By using previously determined optimal single frequency as a start, the authors determined suitable frequency combinations to give increased sensitivity for different structures and defects. The influence of different disturbing signals, signals from rivets, thickness variations, noise, and how to reduce them using the multi-frequency technique was studied. Tests results obtained from in-field conditions to evaluate the system are also presented. [88]

A.8.15 Goldfine et al. (2002): Corrosion detection and prioritization using scanning and permanently mounted MWM eddy-current arrays

This paper describes using meandering winding magnetometer (MWM) arrays for the following applications: detection and imaging of corrosion through an insulating layer, detection and imaging of hidden corrosion for a single-layer structure, and detection and imaging of hidden corrosion in multi-layer structures. Specific examples given in this work include: imaging of corrosion and material loss from grinding repairs on a C-130 flight deck plate section, hidden material loss imaging for second-layer lap-joint material loss, and surface pitting and exfoliation/intergranular corrosion imaging for coupons removed from a corrosion test. The MWM technology described here addresses and discusses the need for quantitative, low cost, high throughput corrosion imaging. The examples of corrosion imaging described here include manual scanning, with and without position encoders, as well as automated scanning. [89]

A.8.16 Robers and Scottini (2002): Pulsed eddy current in corrosion detection

An overview of the fundamentals and also the RTD-INCOTEST pulsed eddy current tool for corrosion detection is presented in this work. Several in-field applications other than insulated objects are presented. Practical examples include situations where dirt, corrosion, water, concrete or coating material influence direct surface access. With this method surface coatings can be avoided, the sensor tool can provide a fast and cost-effective solution for corrosion detection. [90]

A.8.17 Smith and Hugo (2001): Detection of deep corrosion and cracks in ageing aircraft using transient eddy-current NDE

The authors report on transient eddy-current sensors for crack and corrosion detection. They describe the effects of new Hall-sensor probe designs for detection of defects within aluminum, and discuss the development of an assessment protocol for the most appropriate probe for a given application. [91]

A.8.18 Lepine et al. (1998): Pulsed eddy current method developments for hidden corrosion detection in aircraft structures

The work in this paper describes the development of a pulsed eddy current (PEC) sensor for corrosion detection in aircraft structures. Experimental tests were carried out on laboratory samples as well as on in-service equipment. The paper also provides an insight into how PEC data can be presented and interpreted. [92]

A.8.19 Siegel and Gunatilake (1997): Remote inspection technologies for aircraft skin inspection

The authors have developed and demonstrated a robotic deployment method for remote eddy current and remote enhanced stereoscopic video instrumentation with the aim of removing human performance problems and workplace hazards in the inspection process. In this work an application to aircraft skin inspection for finding cracks and corrosion is presented. A wavelet-based data interpretation approach is used to determine features around rivets, and then to discriminate between cracks and scratches. [93]

A.9 Thermography Methods

A.9.1 Marcuzzi and Marinetti (2008): Efficient reconstruction of corrosion profiles by infrared thermography

In this paper, a novel algorithm (thermal inverse) is proposed to solve the hidden corrosion estimation problem from experimental data collected from infrared thermography. The algorithm incorporates a predictor-corrector form and uses an adaptive finite element model as the reference model. The adaptation is done in the (linear) predictor step, while the parameter estimation is done in the (nonlinear) corrector step. Experiments with real test data have confirmed the effectiveness of the method. [94]

A.9.2 Vavilov et al. (2008): Thermal control of corrosion in aluminum panels of airplanes

In this work, the sensitivity-threshold of thermal testing was found experimentally during corrosion detection in aircraft aluminum panels. Statistical processing and other algorithms of image processing, such as principal component analysis, polynomial approximation, and correlation analysis, were applied. The authors show that inversion relationships for the quantitative estimation of the material loss demonstrate an acceptable accuracy for corrosion testing in aviation aluminum panels. [95]

A.9.3 Fasino et al. (2007): Corrosion detection in conducting boundaries: II. Linearization, stability and discretization

In this paper, the authors describe and test an algorithm based on the linearization of inverse problems for the nondestructive evaluation of hidden surface damage by means of stationary thermographic methods. [96]

A.9.4 Grinzato et al. (2007): Hidden corrosion detection in thick metallic components by transient IR thermography

The goal of this work is the evaluation of practical corrosion detection limits when a one-dimensional thermal model cannot be used. A heating protocol is also studied by applying both flash and finite-pulse heating. An inversion formula available for a plate with large-size corrosion sites is extended to a cylinder and sphere. For pipes, the usage of the proposed inversion formula improves the evaluation accuracy by about 15%. Heating duration should be optimized in order to provide a maximum signal-to-noise ratio. Maximizing the thermal contrasts requires shorter heating times. But, on the other hand, due to the presence of noticeable noise, the heating is to be long enough to ensure reasonable temperature signals. [97]

A.9.5 Hohage et al. (2007): Detecting corrosion using thermal measurements

This work presented in this paper deals with the inverse problem of detecting the level of corrosion at the interface of an inclusion given thermal measurements at the accessible boundary of the sample. This phenomenon leads to a transmission problem for the heat equation with an unknown coefficient. Both time-harmonic and delta-pulse excitations are considered. In both cases uniqueness results are proven for the inverse problem. To reconstruct the unknown level of corrosion numerically both a non-iterative method and a regularized Newton method are analyzed. The performances are compared in a number of numerical experiments. [98]

A.9.6 Wallbrink et al. (2007): The effect of size on the quantitative estimation of defect depth in steel structures using lock-in thermography

In this paper, an investigation into the effect of size on the estimation of defect depth in a steel specimen has been undertaken using lock-in thermography. Phase contrast measurements over circular defects of varying diameter and depth are presented for a range of excitation frequencies. It was found that the diameter of a defect had an appreciable effect on the observed phase angle which consequently has significant implications with regard to estimating defect depth. Phase contrast measurements for a range of defects in a 10mm steel specimen indicate that an excitation frequency of 0.02Hz is the optimal frequency for defect detection. A finite element analysis (FEA) had good correlation with the experimental data and demonstrates potential for providing improved estimates of defect depth. [99]

A.9.7 Avdelidis et al. (2005): Pulsed thermography: philosophy, qualitative & quantitative analysis on aircraft materials & applications

The main objective of this work was to study the effectiveness of pulsed thermography (PT) to assess various defects/features on representative aerospace materials. The advantages of this technique are that it investigates rapidly large areas for surface or near surface defects and that it generates interpretable results. However, a major disadvantage of PT is that its success is highly dependent on defect depth and size, which restricts its application to near surface defect imaging. [100]

A.9.8 Genest et al. (2005): Shape effect on blind frequency for depth inversion in pulsed thermography

In this paper, a study of blind frequency as a function of surface orientation was performed. Frequencies at which the phase contrast becomes zero are known as blind frequencies. In this regard, the phase contrast refers to the phase difference between the phase angle measured over a defect and the phase angle in the unaffected material. The authors determined that, for orientations of $\theta<30°$, blind frequencies are not affected by orientation. Also, they noted that blind frequencies are also size invariant provided that the defect size-on-depth ratio is sufficiently high (>>1). They present results for both carbon fiber reinforced plastic (CFRP) and glass fiber reinforced plastic (GRFP). They recommended applying a coating on the GFRP due to the semi-transparent nature of this material. [101]

A.9.9 Obbadi and Belattar (2005): Characterization of delamination by a thermal method of non destructive testing

In this work, the authors studied a material containing a circular delamination subjected to a thermal excitation. They set out to analyze the influence of defect parameters on the measurable magnitude, and showed that it is theoretically possible to detect any defect, with the application of sufficient energy and significant contrast in thermal conductivities between material and defect. [102]

A.9.10 Servais and Gerlach (2005): Development of a NDT method using thermography for composite material inspection on aircraft using military thermal imager

This paper describes the steps used for thermography as a new inspection method for composite parts in aircraft maintenance. In this work it is focused on two main topics (i) control of leading edge flaps of Belgian F16, and (ii) inspection of the main and tail rotor blades of Belgian A109 Agusta helicopters. The new idea presented here is to use typical military thermal imagers with a good thermal sensitivity and spatial resolution, and to develop a specific signal processing of the digitized images. [103]

A.9.11 Gupta and Tuli (2004): Electrical approach to defect depth estimation by stepped infrared thermography

In this work, a simplified electrical approach to transient heat conduction is adopted for arriving at a novel one-dimensional electrical analysis for defect depth estimation using stepped infrared thermography. The experimental and simulated results prove the validity of one-dimensional analysis of defect depth estimation even for three-dimensional geometries. The proposed technique can provide a good estimate of defect depth in metals and nonmetals as well as composites. By this technique, defect depth in an unknown material, even having variable surface emissivity, can be estimated from very early-time behaviour of surface temperature evolution. [104]

A.9.12 Ciliberto et al. (2002): Porosity detection in composite aeronautical structures

This paper presents and discusses the identification of porosity level on composite structures by employing thermography. Experimental results obtained in different experimental conditions are reported and the results are compared with findings given by an ultrasonic method. A procedure for porosity classification on carbon fiber reinforced plastics by means of two-dimensional wavelet transform and statistical analysis is also presented. [105]

A.9.13 Rajic (2000): An investigation of the bias caused by surface coatings on material loss evaluation by quantitative thermography

The aim of this work was to examine, analytically and experimentally, the impact of surface coating properties on the temperature response of coated objects subject to thermographic inspection. The work relates mainly to metals and on the corrosion problem particularly with regards to aircraft structural integrity. The article begins with the formulation of an analytical solution to the problem of heat conduction in a two-layered slab subject to surface thermal excitation. The author then draws a comparison between the response predicted by this model and that observed experimentally for a test case involving an aluminum specimen with a coating of paint applied in strips of varying thickness. The experimental data obtained shows that even light coatings can have an observable effect on the measured response. [106]

A.9.14 Shepard (1997): Introduction to active thermography for non-destructive evaluation

This paper provides an introduction to nondestructive evaluation (NDE) applications such as the detection of subsurface defects and/or anomalies. The author states that the ability of infrared (IR) imaging methods to inspect large areas quickly and contactless, make them attractive alternatives to other NDE techniques such as ultrasound, and eddy current. Recent developments in IR camera and computer technology, allow IR imaging methods to be used in applications such as for the measurement of material loss in aircraft skins due to hidden corrosion and measurement of depth of delaminations and voids in composite materials. [107]

A.10 Ultrasonic Methods

A.10.1 Liu et al. (2008): *In situ* ice and structure thickness monitoring using integrated and flexible ultrasonic transducers

In this investigation, two types of ultrasonic sensors are developed for in situ monitoring of ice thickness as well as airframe thickness. In situ monitoring of stabilizer outer skin thickness and ice thickness development from fractions of 1mm to less than 1.5mm are demonstrated. The piezoelectric-film sensors have been fabricated by a sol–gel spray technique and piezoelectric films of thickness greater than 40µm can be deposited directly onto the interior of a 1.3mm thick aluminum alloy control surface of an aircraft wing structure as integrated ultrasonic transducers (IUTs). In the second sensor type, piezoelectric films are coated onto a 50µm thick polyimide membrane as flexible ultrasonic transducers (UTs). The ultrasonic measurements carried out used longitudinal acoustic waves. [108]

A.10.2 Ozolinsh et al. (2007): Some results of ultrasonic detection of uniform corrosion in thin Al2024-T3 sheets

In this paper, the ultrasonic detection of uniform corrosion (early stage corrosion damage) in a thin sheet of aluminum alloy 2024-T3 was investigated. An artificially induced corrosion process (corrosive solution) was used and the corrosion damage was relatively small and did not cause significant changes of thickness and fatigue strength. However, it had nonetheless caused significant changes of the intensity of transmitted ultrasonic waves. The main results of the research presented here shows that even small corrosion damage can be reliably detected by the integrated system at an early stage of its development. [109]

A.10.3 Burch et al. (2005): Computer modeling for the prediction of the probability of detection of ultrasonic corrosion mapping

The work in this paper describes a computer model for the prediction of the probability of detection (POD) of ultrasonic corrosion mapping. This technique is widely used in the oil and gas industry for the in-service detection and characterization of corrosion in pipes and vessels. The model has a relatively simple physical/mathematical basis but is a good approximation of the main factors which affect the POD of this inspection technique. The results from the model are compared with those from experiment. [110]

A.10.4 Cole et al. (2005): Octopus – A mid range ultrasonic corrosion-erosion monitor

This paper describes the operation and use of an “octopus” system. The system consists of an ultrasonic corrosion-erosion monitor that uses a main transducer and up to eight secondary transducers. The secondary transducers can be up to one meter away from the main transducer. In this regard, by transmitting a carefully constructed signal from every transducer to every other transducer, and analyzing the received waveforms, it is possible to monitor the average thickness in each transmission path. This approach provides quantitative permanent monitoring of an extended area, and is suitable for remote surveillance situations. [111]

A.10.5 Smith (2004): Advanced ultrasound waveform analysis package for manufacturing and in-service use

This paper gives examples of ultrasonic full-waveform acquisition methods, with a particular emphasis on data analysis. A specific example, using this approach, is presented for corrosion detection from a KC135 aircraft. [112]

A.10.6 Brotherhood et al. (2003): An ultrasonic wheel-array sensor and its application to aerospace structures

This paper describes the development of an ultrasonic wheel-array sensor scanning system. The system operates at 10MHz using a 64-element array transducer located in a fluid-filled wheel (made from a soft, durable polymer with very little acoustic loss). The wheel is coupled to the test structure (either dry or with a liquid coupler). The wheel is rolled over the surface of the test structure and a defect map (C-scan) is generated in real-time. Three application studies are presented, (i) the detection of embedded defects in a thick-section of a carbon composite test block, (ii) the detection of cracking and disbonding in a carbon composite skin-stringer sample and (iii) the inspection of sealant layers in an aluminum aircraft wing structure. In each application, the wheel-array sensor was found to produce C-scans of comparable quality to an immersion system with reduced scanning times. [113]

A.10.7 Silva et al. (2003): Hidden corrosion detection in aircraft aluminum structures using laser ultrasonics and wavelet transform signal analysis

This paper presents a nondestructive and noncontact method for back surface corrosion detection in plate-like structures. The method uses laser generated and detected Lamb waves. It is based on the efficient generation of a Lamb mode near its cutoff frequency to detect the strong attenuation of that mode due to the surface roughness associated with the presence of corrosion. Real corrosion at the back surface of an aircraft aluminum structure is successfully detected in the case of a thickness loss of 5% (0.1mm in a 2mm plate). Since the method detects the change in surface roughness due to corrosion, and not the material loss or thinning of the plate, it is particularly suited for early corrosion detection. The development of a fast wide area inspection technique for corrosion detection in plate-like structures is the first motivation of this work. [114]

A.10.8 de Morais and Brett (2002): Influence of ultrasound on the corrosion of aluminium

In this work, the influence of ultrasound on the electrochemical behaviour of aluminum in chloride solution is studied using an ultrasonic probe placed above the metal surface. Ultrasound can promote pitting corrosion of aluminum by destroying the passive oxide layer. Various parameters are studied using measurements of open circuit potential and polarization curves. [115]

A.10.9 Finlayson et al. (2001): Health monitoring of aerospace structures with acoustic emission and acousto-ultrasonics

The work presented in this paper examines acoustic emission and acousto-ultrasonics for structural health monitoring (aging) aerospace structures. The method is described and an example is given of structural health monitoring of military aircraft. [116]

A.10.10 Grossman (1984): A high resolution *in situ* ultrasonic corrosion monitor

This paper discusses the development of an in-situ ultrasonic corrosion monitor that is able to provide a continuous high resolution indication of corrosion buildup. The monitor is based on the principle that the ultrasonic velocity in a corroding waveguide changes as the corrosion builds up. The monitor has the capability of measuring film thickness increases smaller than 0.1µm. The paper also provides a comparison between theoretical and experimental results. [117]

A.11 Piezoelectric Methods

A.11.1 Yu and Giurgiutiu (2008): Multi-mode damage detection methods with piezoelectric wafer active sensors

This paper presents multiple-modes in situ structural health monitoring (SHM) methods using piezoelectric wafer active sensors (PWAS). Piezoelectric wafer active sensors are small and non-invasive transducers that can be easily affixed to a structure. The sensors are used for damage detection (cracks and corrosion) in metallic plate structures such as aircraft panels. The paper introduces the basic principles of PWAS transducers for impedance measurement and ultrasonic inspection, and then several examples are given to demonstrate the significance of the proposed method. [118]

A.11.2 Xu and Giurgiutiu (2007): Single mode tuning effects on Lamb wave time reversal with piezoelectric wafer active sensors for structural health monitoring

In this work, a theoretical model for the analysis of piezoelectric wafer active sensors (PWAS) is presented. The theoretical model is first used to predict the existence of single-mode Lamb waves. Then the time reversal behavior of single-mode and two-mode Lamb waves is studied numerically. The proposed theoretical model is validated through experimental studies. The authors show that, under certain conditions the use of PWAS-tuned single-mode Lamb waves can greatly improve the effectiveness of the time-reversal damage detection procedure. With this method, certain types of damage can be detected without baseline data. However, the application of this method using PWAS is complicated by the existence of at least two Lamb wave modes at any given frequency, and by the dispersion nature of the Lamb wave modes existing in thin-wall structures. [119]

A.11.3 Zhao et al. (2007): Active health monitoring of an aircraft wing with an embedded piezoelectric sensor/actuator network: I. Defect detection, localization and growth monitoring

In this paper, a guided wave piezoelectric (PZT) sensor/actuator network technique was applied to an aircraft wing section to monitor defect(s). A preliminary test with angle-beam Lamb wave transducers on the wing panel was conducted first to evaluate the wave propagation capabilities. Strong attenuations and scattering from the paint and rivet rows have a negative influence on the wave inspection range. A relatively sparse PZT array with a diameter of 30cm was then bonded to the inner surface of the wing to generate and receive ultrasonic guided waves. Simulated defects such as loose rivets, cracks and material loss on the wing panel were studied. A correlation analysis based algorithm called RAPID is introduced that was specifically developed for defect detection, localization and growth monitoring. [120]

A.11.4 Zhao et al. (2007): Active health monitoring of an aircraft wing with an embedded piezoelectric sensor/actuator network: II. Wireless approaches

The objective of this work was to develop a wireless ultrasonic structural health monitoring (SHM) system for aircraft wing inspection. In the first part of the study, described above, piezoelectric (PZT) disc transducers were bonded to various parts of an aircraft wing for detection, localization and growth monitoring of defects. In this paper, two approaches for wireless-interrogation of the sensor/actuator network are reported. The first method utilizes a pair of reactive coupling monopoles to deliver 350kHz RF tone-burst interrogation pulses directly to the PZT transducers for generating ultrasonic guided waves and to receive the response signals from the PZTs. It couples enough energy to and from the PZT transducers for the wing panel inspection, but the signal is quite noisy and the monopoles need to be in close proximity to each other for efficient coupling. In the second method, a small local diagnostic device was developed that can be embedded into the wing and transmit the digital signals FM-modulated on a 915MHz carrier. Power to the electronics is delivered wirelessly at x-band with an antenna–rectifier array conformed to the aircraft body, eliminating the need for batteries and their replacement. It can effectively deliver at least 100mW of DC power continuously from a transmitter at a range of 1 m. The wireless system was tested with the PZT sensor array on the wing panel and compared well with the wire connection case. [121]

A.11.5 Giurgiutiu et al. (2002): Piezoelectric wafer embedded active sensors for aging aircraft structural health monitoring

The work in this paper aims to show that the electromechanical impedance (E/M) method and the wave propagation approach are complementary techniques and that they should be used simultaneously for damage detection. The first method works in the near field, while the second acts in the far field. The authors state that their simultaneous utilization will ensure the complete coverage of the monitored structure. Concepts for a structural health monitoring system that could be implemented on an aging aircraft structure were also presented. The authors also noted that, in the damage detection process, the signal processing methods and damage-metric algorithms have to be tuned to the specific structural interrogation techniques being used. In the high-frequency E/M approach, pattern recognition methods should be used to compare the impedance signatures and to identify change in these signatures that are indicative of damage presence and progression. In the wave propagation approach, the pulse-echo and acousto-ultrasonic methods identifying the reflections generated from the damage site, and changes in wave phase and velocity, can be used. [122]

A.12 Micro-Electro-Mechanical-Systems (MEMS) based Methods

A.12.1 Hautefeuille et al. (2008): A MEMS-based wireless multisensory module for environmental monitoring

This paper introduces and outlines the use of Tyndall's 1.5µm surface micromachining process to fabricate a micro-electro-mechanical-systems (MEMS) based multifunctional wireless environmental monitoring chip. Preliminary results from integrated temperature, humidity and gas sensor prototypes are presented. The authors state that it is planned to incorporate additional sensing functionalities such as corrosion and gas flow velocity in later sensor models. The integration of these MEMS sensors with a communicative data-logging platform is also described in this paper. [123]

A.12.2 Bogue (2007): MEMS sensors: past, present and future

This paper provides insight into the applications for micro-electro-mechanical-systems (MEMS) sensor technology. The author identifies high growth areas for innovative developments in MEMS sensor technology. The author also illustrates the greatly differing impacts exerted on physical, gas and chemical sensing by MEMS technology. Current industry developments are discussed which suggest strong market prospects for MEMS sensor/actuator devices with analytical capabilities such as micro-optics, micro-fluidics, lab-on-a-chip and bio-MEMS. [124]

A.12.3 Hautefeuille et al. (2007): A miniaturized MEMS-based multi-parameter sensing module

This paper describes the design and fabrication of a MEMS-based multi-sensor array for temperature, shock, pressure, humidity and gas detection. The authors declare that due to the size and cost generally associated with a sensor array, there is a requirement to integrate and miniaturize sensors wherever possible. The primary focus of this research was been the integration, optimization and (further) development of MEMS sensors. The platform designed to hold the resultant sensor layer is the Tyndall 25mm mote, that provides a completed sensing module with wireless capability. A data logging unit has also been developed, including an on-board serial memory. [125]

A.12.4 Cole et al. (2004): Some recent trends in corrosion science and their application to conservation

This paper reviews recent progress in corrosion science. Particular interest is given to the areas of meta-methodology consisting of a holistic approach based acquired learning through sensor integration, models of degradation covering transport, chemical, moisture, etc, and corrosion sensors for studying corrosion including MEMS. [126]

A.12.5 Jain et al. (2002): A MEMS phased array transducer for ultrasonic flaw detection

In this work, the authors describe and characterize a micro-electro-mechanical-systems (MEMS) ultrasonic transducer that can be used fro structural health monitoring applications. [127]

A.12.6 Varadan and Varadan (1998): Wireless smart conformal MEMS-based sensors for aerospace structures

This paper discusses the integration of smart materials, micro-electro-mechanical-systems (MEMS) and smart electronics in the form of a smart skin for aerospace structures. The smart skin developed from this integration is designed for health and condition monitoring of existing (and aging) and future aircraft, drag sensing and control, ice sensing and anti-icing and also for sensing and control of noise and vibration of aircraft structures. The smart sensors were developed using standard microelectronics and micromachining in conjunction with novel smart electronics or wireless communication systems suitable for condition monitoring of aircraft structures in-flight. The other application areas of this investigation includes monitoring of (i) structural integrity of aging aircraft, (ii) fatigue cracking, (iii) corrosion, (iv) deflection and strain of aircraft structures, wings, and rotor blades, (v) impact damage, (vi) delamination, (vii) location and propagation of cracks, (viii) the quality of conventional bonds and “kissing bonds” in composite structures. [128]

A.13 Miscellaneous Papers

A.13.1 Dante et al. (2008): RF system for corrosivity monitoring

In this paper, an environmental radio-frequency (RF) sensor using radio frequency identification (RFID) and capable of detecting cumulative environmental severity is presented. Experimental measurements of the coupling efficiency between a reader antenna and an RFID tag correlate with the observed degradation of a metallic parasitic element deposited on the RFID sensor. The sensor responds to heterogeneous changes in the thickness of the parasitic element deposited on the surface. The authors show that sensor data was successfully acquired both in free space and while the sensor was mounted on a metal back plane. [129]

A.13.2 DeWeese et al. (2008): Stress-corrosion cracking in aluminum beverage can ends – issues, observations, and potential solutions

The work in this paper presents and analyzes the current status of stress-corrosion cracking (SCC) of 5182 aluminum beverage can ends. In this respect, SCC associated with the easy-open ends is an undesirable failure with filled beverage containers. The authors report a change in SCC failure mode from transgranular to intergranular SCC in 5182 aluminum beverage can ends due to higher stress associated with new container designs. The transition of cracking mode is attributed to both anodic dissolution and hydrogen embrittlement. In this paper, these mechanisms are discussed including fractography evidence, identifying the probable causes and solutions. [130]

A.13.3 Dey et al. (2008): Effect of temper on the distribution of pits in AA7075 alloys

In this work, a comparative study of the pitting severity in T6 and T73 tempers of aluminum alloy AA7075 in a sodium chloride (NaCl) is presented. It was found that the pitting was more severe for T6 tempers as compared to the T73 tempers. The authors state that this could be due to the higher pit nucleation sites in AA7075-T76 alloys. These differences in pit distribution are explained on the basis of the role of constituent as well as strengthening particles and the role of grain boundary precipitates. [131]

A.13.4 Kral and Horn (2008): Detection of damage in metal lap joint by combined passive and active methods

The purpose of the work presented herein was to implement an in-situ structural health monitoring (SHM) system that can be employed to monitor damage during flight in real time. The proposed system was given the additional requirements of having to be automated and use nondestructive evaluation (NDE) to determine damage, and without disrupting the function of the structure being monitored. As aircraft skins have an average thickness of around 2-3mm, damage can easily become a problem. Cracks and corrosion have been discovered to initiate and grow around joint regions, due to metal contact and pre-existing holes for rivets to attach multiple layers. This study looks at analyzing the abilities of acoustic emission (AE) and fiber Bragg gratings (FBG) sensors to work as both passive and active systems. The results obtained with these two methods are compared. Due to temperature problems in skewing responses of guided waves, a network of sensors is formed as well to use a correlation in baseline approach, negating this effect, and is tested for fatigue damage on a metal lap joint configuration over cyclic loading. FBG sensors are found to be more directional based and can work in replacing strain gages, while AE sensors can be used well in conjunction with active ultrasonic testing. [132]

A.13.5 Moffat et al. (2008): Failure mechanisms of legacy aircraft wiring and interconnects

This paper introduces an extensive list of the causes and modes of failure and aging in legacy aircraft wiring and interconnects. A failure modes effects and analysis (FMEA) method is conducted to categorize the most serious failures. In order to help advance the understanding of failure mechanism in wiring and interconnects, an in depth classification of the causes and modes of failure in cable harnesses and a FMEA of these systems is presented. [133]

A.13.6 Schneider et al. (2008): Anodic oxide formation on AA2024: electrochemical and microstructure investigation

In this work, the microstructure of aluminum alloy AA2024-T351 was characterized by light and scanning electron microscopy combined with energy dispersive x-ray spectrometry. The anodic oxide formation on AA2024 was studied by electrochemical measurements in sulfuric and citric acid based electrolytes. Oxide layers formed in sulfuric acid showed a common disordered pore structure while oxide layers formed in citric acid are completely free of pores. [134]

A.13.7 Tormoen et al. (2008): Field deployed corrosion sensors on USMC vehicles to measure CPC performance

This paper evaluates the data taken from sensors on actual USMC vehicles. Several storage options (covered, dehumidified or exposed on the lot), and different climates are investigated. Effects of vehicle type, mote placement and storage options on CPC performance are addressed.

Wireless networks of coating degradation sensors to monitor the integrity of applied CPC coatings were successfully deployed at two storage sites. The sensor packages were able to autonomously record impedance data and wirelessly transmit this data to a web portal. The sensors were able to detect the occurrence of wetting incidents, and the overall effect on the integrity of the coating was noted over time. Sensors placed in dehumidified storage at both facilities were found not to degrade over the monitoring period. [135]

A.13.8 Trnkova et al. (2008): Amperometric sensor for detection of chloride ions

The work in this paper describes a sensor for the detection of chloride ions which can be associated with corrosion. In this regard, chloride ion sensing is important in many fields such as clinical diagnosis, environmental monitoring and industrial applications. [136]

A.13.9 Birt et al. (2007): Correlation of fatigue life with potential NDE corrosion metrics

The authors discuss the efforts being made to move away from “find-and-fix” methods to manage corrosion damage in aircraft. They state that this will only be possible if effective nondestructive evaluation (NDE) methods are available to detect, characterize and monitor the corrosion that is present within the airframe and that analytical models exist to predict the interaction of corrosion and fatigue from the characterized corrosion damage. In this work, a set of test specimens were fabricated from unclad 2024-T3 aluminum alloy. The specimens were corroded in a salt-fog chamber for a range of time intervals to induce both pitting and crevice corrosion. They were then characterized using ultrasonic and eddy current inspection techniques. Ultrasonic inspection was carried out at three frequencies (10, 22 and 50MHz) using focused immersion transducers. Amplitude and depth scans at each frequency were obtained. Eddy current inspection was carried out at a single frequency of 10kHz. The authors calculated several parameters from the scans and correlated them with the fatigue life. [137]

A.13.10 Flinn (2007): Thin-film sensors monitor defects

This paper discusses the development of a flexible thin film magnetostrictive sensor for the USAF. The author states that these sensors can efficiently detect and monitor defects in aircraft without the need for costly teardowns or unnecessary inspections. The aim of the overall research is the development of a magnetostrictive multilayer thin-film sensor that could be deposited onto a structure and used at high temperatures with wireless communication. [138]

A.13.11 Gupta et al. (2007): Fusion of multimodal NDE data for improved corrosion detection

The authors present a data-fusion method for combining nondestructive evaluation (NDE) data for detecting surface and subsurface corrosion. This approach is aimed towards limiting false corrosion detections. Experimental results are presented using NDE techniques, including microwave, eddy current, ultrasound, and radiography for a lap-joint structure. [139]

A.13.12 Pfeiffer and Wevers (2007): Aircraft integrated structural health assessment – Structural health monitoring and its implementation within the European project AISHA

This paper reviews some general issues related to state-of-the-art of structural health monitoring in aircraft and gives some information on the European project "aircraft integrated structural health assessment (AISHA)" [140]

A.13.13 Rashkeev et al. (2007): Hydrogen-induced initiation of corrosion in aluminum

In this paper, quantum-mechanical calculations are performed in order to provide atomic scale understanding of the initiation of corrosion in aluminum (Al). It is shown that atomic hydrogen can penetrate into the oxide film and cause structural damage and initiate corrosion in environmentally exposed aluminum systems. Also shown is that an accumulation of several hydrogen atoms within a single cation vacancy breaks bonds between surrounding atoms thus transforming the vacancy into a bigger void. The formation of molecular hydrogen in these voids facilitates the formation of hydrogen blisters. The authors also found that interfacial damage is significantly enhanced when interfacial structural defects (such as those resulting from interfacial lattice mismatch) are initially present. The pit formation is initiated by the oxide damage that starts at sub-interfacial Al vacancies and then gradually propagates into the oxide layer thus opening additional channels for interaction between the unprotected Al metal and the environment. [141]

A.13.14 Sun et al. (2007): Magnetic carpet probe for large area instant crack/corrosion detection and health monitoring

This paper discusses the advent of a recent nondestructive evaluation (NDE) tool called "magnetic carpet probe (MCP)", developed by Innovative Materials Testing Technologies, Inc. for large area crack and corrosion detection and health monitoring. The MCP consists of a two-dimensional coil array on a piece of very thin flexible printed circuit board. A two-dimensional electromagnetic scan is used for crack and/or corrosion identification. [142]

A.13.15 Zheng et al. (2007): Hydrogen permeation behavior and corrosion monitoring of steel in cyclic wet-dry atmospheric environment

In this work, the authors describe hydrogen permeation of steel under cyclic wet-dry conditions. Weight loss from the steel sample was measured for each wet-dry cycle. The results obtained show that the hydrogen permeation current changes with respect to the surrounding atmospheric environment (distilled water, seawater, seawater containing hydrogen sulfide (H_2S)). The surface potential change and the pH change of the metal surface control the hydrogen permeation current. In this regard, a linear relationship was obtained between the amount of hydrogen permeated through the steel and the corresponding weight loss. Based on the linear relationship, the corrosion rate was obtained by monitoring the hydrogen permeation current. [143]

A.13.16 Fawaz and Andersson (2006): Statistical fatigue and residual strength analysis of new/aging aircraft structure

In this work, a data analysis system for analyzing multiple crack fatigue growth was designed and tested on large computer arrays. The objective of this work was to demonstrate that these types of computations may be performed effectively and reliably on large computer systems having thousands of processors with aim of cutting computational time and making analysis of this type practical. [144]

A.13.17 Iannuzzi et al. (2006): Aluminum alloy corrosion inhibition by vanadates

The main objective of this work is to understand which vanadate oligomer imparts the best corrosion protection for AA2024-T3. Vanadate speciation as a function of pH and concentration is investigated by ^{51}V nuclear magnetic resonance (NMR). The influence of decavanadate formation, solution aging, and bulk pH on corrosion inhibition of AA2024-T3 is also discussed. [145]

A.13.18 Ishihara et al. (2006): Prediction of corrosion fatigue lives of aluminium alloy on the basis of corrosion pit growth law

In the research presented here, tension/compression and rotating/bending fatigue tests were carried out on aluminum alloy 2024-T3 samples in a 3% sodium chloride (NaCl) solution. The corrosion pit growth characteristics, and also the fatigue crack initiation and propagation behaviour were then investigated. The estimated (predicted) fatigue results obtained by the authors agree well with the experimental data. [146]

A.13.19 Kermanidis and Pantelakis (2006): A fracture-mechanical model for the prediction of the corrosion dependent local fracture toughness of aluminium alloy 2024

In this work, the corrosion-induced reduction in the tensile ductility of aluminum alloy 2024 is correlated to the reduction in fracture toughness. For the prediction of the local fracture toughness value of the corroded material (crack tip), a fracture-mechanical model has been developed by the authors using a multi-scaling technique. This approach aims to relate tensile degradation due to exfoliation corrosion to local material properties in the vicinity of the crack tip. Predicted analytical values were used to estimate the experimentally observed embrittlement of 2024 panels exposed to exfoliation corrosion. [147]

A.13.20 Lynch and Loh (2006): A summary review of wireless sensors and sensor networks for structural health monitoring

This paper is intended to serve as a summary review of the collective experience the structural engineering community has gained from the use of wireless sensors and sensor networks for monitoring structural performance and health. The authors provide a substantial reference list. [148]

A.13.21 Park et al. (2006): Wireless structural health monitoring using an active sensing node

In this work, the development of an active sensing node (ASN) is discussed. The ASN consists of a miniaturized impedance measuring device, a microcontroller, and a radio frequency (RF) transmitter. A macro-fiber composite patch is used to analyze a given test structure (aluminum beam or loose bolt) by using a self-sensing technique of the miniaturized impedance measuring device. The structural analysis, data acquisition, signal processing, and damage diagnostic was performed at the sensor location by the microcontroller. The RF transmitter is used to transmit the current status of the test structure. [149]

A.13.22 Speckmann and Roesner (2006): Structural health monitoring: a contribution to the intelligent aircraft structure

This paper provides a discussion of structural health monitoring (SHM) practices at Airbus, and about its uses for new aircraft maintenance and design concepts. As the major European aircraft manufacturer, the authors state that Airbus has been leading this kind of development. They also state that maintenance cost reduction, increased aircraft availability and weight savings are principle aims which will be reached by SHM. [150]

A.13.23 Abbott and Kinzie (2005): Aircraft corrosion sensing and monitoring program

This work used a specially designed test-package for the purpose of obtaining atmospheric corrosion rates of a standard test matrix of metals. The test-packages include silver (for chloride determination), copper, aluminum alloys (2024, 6061, and 7075), and a low carbon steel (1010). The authors describe the work as having progressed from ground based corrosion studies to a growing flight test program in support of the Air Force, Air Vehicle Health Management (AVHM) program. Additionally, a statistically based algorithm was developed to relate corrosion rates for these metals to critical environmental variables. [151]

A.13.24 Cole and Watson (2005): Acoustic emission for corrosion detection

This paper describes the use of acoustic emission from the corrosion process, for corrosion detection in storage tanks, reinforced concrete structures, and process equipment. The process of corrosion causes acoustic emission as a result of the fracture and disbonding of expansive corrosion products. In this regard, the method may be used for corrosion detection and quantification of corrosion rate. [152].

A.13.25 Goldfine et al. (2005): Corrosion and fatigue monitoring sensor networks

This paper introduces and discusses a new approach that combines interdigitated dielectrometer (IDED) and meandering winding magnetometer (MWM) sensors. The aim of this research is to detect metal loss, corrosion products and moisture ingress. The MWM is an inductive eddy current sensor and the IDED is a capacitive sensor. Meandering winding magnetometer sensors are suitable for metals, graphite fiber composites, and reinforced carbon composites, while the IDED is suitable for characterization of glass fiber composites, corrosion protection coatings, sealants, glass, paint, and wood, as well as for detection/monitoring of corrosion products, moisture ingress and monitoring of cure states of epoxies and adhesives. [153]

A.13.26 Jander et al. (2005): Magnetoresistive sensors for nondestructive evaluation

This paper presents a review of the state of the art in magnetoresistive (MR) sensors and applications in nondestructive evaluation (NDE). The physical principles, manufacturing process, and performance characteristics of the three main types of MR devices, anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR) are discussed. Their performance is compared to other magnetic sensor technologies for NDE applications. The authors also provide a comprehensive review of the literature on NDE applications of MR sensors. [154]

A.13.27 Lu and Kaxiras (2005): Hydrogen embrittlement of aluminum: The crucial role of vacancies

The main objective of the work presented here was to determine and understand the mechanisms of hydrogen (H)-vacancy interaction in aluminum at the atomic level. The authors introduce first-principles calculations demonstrating that vacancies can combine with H impurities in bulk aluminum and that they play a significant part in aluminum embrittlement. In this regard, calculations were made to determine the total energy of a single H atom near a vacancy site and the authors found that a large number of H atoms (up to 12) can be trapped at a single vacancy. In the presence of trapped H atoms, three nearest-neighbor single vacancies form a tri-vacancy and act as starting points for micro-voids and cracks. [155]

A.13.28 Muster et al. (2005): Establishing a physical basis for the in-situ monitoring of airframe corrosion using intelligent sensor networks

This paper presents the physical relationships that could support an intelligent sensing network for airframe maintenance in hidden areas. The main idea of the health monitoring system described herein is based on the principle of network intelligence utilizing autonomous sensing agents, and is comprised of sensing, communications, multi-agent data analysis and diagnostics, and prognostics with intelligent objects. Galvanic sensors have been employed in this work. Relationships have been developed between measurable corrosion damage parameters, sensed damage and causes of sensed damage. Corrosion damage for two aluminum alloys (7075-T6 and

2024-T3) have been investigated and relationships have been established to link test panel damage to the output data of galvanic corrosion sensors. [156]

A.13.29 Crawford et al. (2004): The effect of pitting corrosion on the position of aircraft structural failures

This paper presents a Monte-Carlo model for pitting corrosion. This model concentrates on the effect of pit spatial density and position on the endurance of a fatigue coupon designed to mimic a simple aircraft component. The results obtained show that pitting increases the area of the coupon over which failures can occur. [157]

A.13.30 Industry Canada (2004): Aircraft systems - diagnostics, prognostics and health management – technology insight document

This work reports on the collaboration between Industry Canada, the Canadian aerospace industry and the Aerospace Industries Association of Canada (AIAC). The objective of this activity is to enhance Canadian Aerospace and Defence sector competitiveness through coordinated and focused government/industry strategic interaction in the area of Diagnostics, Prognostics and Health Management (DPHM) for aircraft and aircraft systems. This activity builds on existing Canadian industry sector strengths to support a number of national and international legacy as well as advanced technology programs, most notably the Joint Strike Fighter (JSF). While the JSF is not the sole focus of this report, that program has substantively advanced DPHM technology concepts into an integrated systems approach beginning at the earliest design stages. Annex A to this document provides a listing and website references for a number of relevant DPHM R&D activities or organizations and programs that are supporting DPHM related activities. [158]

A.13.31 Juzeliũnas et al. (2004): Remote sensing of aluminum alloy corrosion by SQUID magnetometry

In this work, superconducting quantum interference device (SQUID) magnetometry was used for the detection of macroscopic magnetic fields on corroding aluminum alloy 2024. Magnetic images were obtained by a SQUID magnetometer operating in liquid helium with a spatial resolution of approximately 1mm. The magnetic fields originated from corrosion reactions due to asymmetric sample geometry, electrolyte flow and differences in surface activity. The results presented show the capability of SQUID for corrosion sensing, and the potential of SQUID magnetometry for practical corrosion detection in locations not easily accessed (hidden corrosion). [159]

A.13.32 Mackerle (2004): Finite-element modelling of non-destructive material evaluation, an addendum: a bibliography (1997-2003)

This paper gives a bibliographical review of finite-element methods (FEM) applied to the nondestructive evaluation (NDE) of materials. The bibliography in this paper contains references to papers, conference proceedings and dissertations on this topic that were published between 1997 and 2003. In this regard, the following FEM NDE topics are covered, (i) electrical, magnetic and electromagnetic methods, (ii) sonic methods, (iii) mechanical methods, (iv) optical methods, (v) condition monitoring and other methods. A total of 858 references are listed. [160]

A.13.33 Abolikhina and Molyar (2003): Corrosion of aircraft structures made of aluminum alloys

In this paper, the authors describe the causes of corrosion, types of corrosion, removal methods, and its influence on the service life of aircraft structures. The authors state that for extended operation, the following kinds of corrosion were detected, (i) pitting, (ii) exfoliation, (iii) inter-crystalline, (iv) crevice, and (v) contact and corrosion cracking (CC). Pitting and exfoliation corrosion are the most characteristic of structural elements made of aluminum alloys, and that CC is the most dangerous phenomenon. The authors investigate and discuss corrosion effects on a 20 year old aircraft component [161]

A.13.34 Howard et al. (2003): Corrosion detection devices

In this paper, a discussion of some of the latest developments in the detection of corrosion is presented. Also described are some of the nondestructive examination devices in use at the Department of Energy's Savannah River Site. The corrosion detection devices most frequently used are automated ultrasonic mapping systems, digital radiography imaging devices, infrared imaging, and eddy current mapping systems. Other types of anomalies such as cracks have also been quantified. Examples of actual corrosion that has been detected are discussed along with the NDE systems that were used. [162]

A.13.35 Komorowski (2003): New tools for aircraft maintenance

In this paper, an overview is given of the advances in understanding the impact of corrosion on structural integrity and the specific tools available for inspection, assessment and repair. A comprehensive set of these tools would allow for a significant shift in aircraft maintenance concepts. [163]

A.13.36 Labeas et al. (2003): Assessment of widespread fatigue damage in the presence of corrosion

In this work, the authors present a methodology based on finite-element methods (FEM) (sub-structuring) to treat fatigue damage. The effect of corrosion is also taken into account. Experimental results presented in this paper indicate that crack growth characteristics are not strongly affected by corrosion at the early and medium stages of initiation, and they are in good agreement with the theory. [164]

A.13.37 Wang et al. (2003): Evaluation of the probability distribution of pitting corrosion fatigue life in aircraft materials

The objective of the work presented in this study is to develop a model based on a probability distribution to predict pitting and corrosion fatigue life of aircraft alloys. The probabilistic model considers the key random nature of the pitting initiation and growth, and the transition from a pit to a critical crack (as well as the crack propagation). The probabilistic model investigated considers the uncertainties in the initial pit size, corrosion pitting current, and material properties due to the scatter found in the experimental data. Simulations (Monte Carlo) were performed to define the failure probability distribution. The results obtained are compared with existing probabilistic models and experimental data, and predicted cumulative distribution functions of fatigue life agreed reasonably well with the existing experimental data. [165]

A.13.38 Boller (2002): Structural health management of ageing aircraft and other infrastructure

This work gives an in depth discussion on structural health monitoring with a particular emphasis on aging aircraft and the implementation of design and maintenance strategies. [166]

A.13.39 Jaeger (2002): A novel corrometer sensor for monitoring and identifying atmospheric corrosion of electronics and critical components that can aid in optimizing military periodic maintenance, readiness and the reliability of such equipment

In this work, an electrical resistance atmospheric corrosion sensor is described. The sensor was tested in situ with a printed circuit board (PCB). Electrical resistance changes due decreasing electrode thickness are indications of losses due to corrosion. The test conditions consisted of cycled temperatures between ambient and 50°C along with the respective relative humidity between 60 and 100% in a hydrogen sulphide (H_2S) atmosphere. [167]

A.13.40 Klyatis (2002): Establishment of accelerated corrosion testing conditions

The author of this work developed techniques for accelerated corrosion testing (ACT) and implemented them. The main goal of ACT is rapid product improvement, lower warranty costs, lower life cycle costs, and improved reliability through accelerated corrosion testing. [168]

A.13.41 Meyendorf et al. (2002): Early detection of corrosion in aircraft structures

This paper summarizes results on nondestructive characterization of corrosion using thermal techniques and presents concepts for the prediction of remaining lifetime of corroded parts. In order to study aluminum airframe structures covered with corrosion protective coatings, the authors used scanning acoustic microscopy (SAM) and developed fan thermography (heating method), which made it possible to detect adhesion defects and local corrosion. For quantification of corrosion defects, such as corrosion pits or cracks, and for detection of corrosion activity, white light interferometry and a scanning vibrating electrode technique were used. [169]

A.13.42 Boller (2001): Ways and options for aircraft structural health management

This paper addresses the different means of how aging aircraft can be inspected and maintained, starting with conventional inspection methods and gradually moving to state-of-the-art and finally damage monitoring techniques. [170]

A.13.43 Clark (2001): Management of corrosion in aging military systems

This paper discusses ongoing research in Australia (Australian Defence Force) on the impact of corrosion on structural integrity with the aim of improving the capability to manage corrosion in aircraft. Some of the methodologies adopted for this come from fatigue sensing techniques, and the paper discusses some of the implications of absorbing corrosion into structural integrity management approaches. However, the research has progressed to the point of assessing the impact of some types of corrosion. [171]

A.13.44 Kinzie (2001): Improved corrosion maintenance practices

This paper provides a discussion on corrosion detection and prevention practices within the USAF. [172]

A.13.45 Komorowski et al. (2001): Life and damage monitoring-using NDI data interpretation for corrosion damage and remaining life assessments

This paper discusses corrosion in airframes and the current techniques used for its detection. Also, this paper gives an overview of current nondestructive inspection (NDI) practices for corrosion in airframes. [173]

A.13.46 Mahadevan and Shi (2001): Corrosion fatigue reliability of aging aircraft structures

The objective of this paper is to review advanced methodologies for aging aircraft structure life-cycle engineering. Aspects of design, maintenance and management, failure mechanisms and probabilistic analysis are discussed. The paper presents design approaches and programs adopted by the aircraft industry to ensure aircraft structural integrity and safety. Corrosion fatigue failure mechanisms in aging aircraft structures and life prediction methods are also discussed. Probabilistic methods to simulate corrosion fatigue damage (single/multiple site) are reviewed. Numerical examples are presented to illustrate the reliability evaluation of aircraft fuselage lap joints under corrosion and fatigue. [174]

A.13.47 Sisson (2001): Hydrogen embrittlement and electroplating

This paper discusses the effect of hydrogen embrittlement on high strength fasteners as might be found in aerospace applications. The paper presents the triggering mechanisms associated with this phenomenon and discusses possible solutions. [175]

A.13.48 Blemel (2000): Reactive prognostic management of corrosion with autonomous sensors

This paper presents a new technology for in-situ corrosion detection for naval environment. The author states that the U.S. Government spends up to $125B per year to detect, protect, and repair damage caused by corrosion. This paper presents a report on how the US Naval Air Systems Command (NAVAIR) has initiated several health usage monitoring (HUM) and Sentient health management (SHM) programs to study and combat chemical corrosion. Because of the corrosive nature of the naval environment, NAVAIR is looking for new ways to detect, prevent, eliminate, and deal with corrosion using smart prognostic (Sentient) sensors for HUM and prognostic health management (PHM). Sentients are networked and autonomous reactive sensory computers enabled by microcomputer technologies and are considered a first line of defense against corrosion. [176]

A.13.49 Garosshen and Mukherji (2000): On the correlation of bimetallic corrosion sensor output to actual corrosion damage

This paper presents an evaluation of a corrosion sensor for real-world corrosion damage. The corrosion behaviour of several aerospace aluminum alloys was compared to the sensor output. The objective of this paper was to present the results of evaluations of the ability of this corrosion sensor system to detect the real world corrosion damage and to suggest further improvements to make the system more versatile and valuable. The results of weight loss measurements are presented along with the results of experiments aimed at determining the sensitivity and durability of the sensor system. [177]

A.13.50 Giurgiutiu et al. (2000): Active sensors for health monitoring of aging aerospace structures

The authors discuss a project to develop non-intrusive active sensors that can be applied on existing aging aerospace structures for monitoring the onset and progress of structural damage (fatigue cracks and corrosion). The state of the art in active sensors structural health monitoring and damage detection is also reviewed in this work. Methods based on (i) elastic wave propagation and (ii) electro-mechanical impedance technique are briefly discussed. The signal processing and damage interpretation algorithms are tuned to the specific structural interrogation method used. In the high-frequency impedance approach, pattern recognition methods are used to compare impedance signatures taken at various time intervals and to identify damage presence and progression from the change in these signatures. In the wave propagation approach, the acousto-ultrasonic methods identifying additional reflection generated from the damage site and changes in transmission velocity and phase are used. Both approaches use artificial intelligence neural networks algorithms that can extract damage features. [178]

A.13.51 Kempe et al. (2000): An advanced atmospheric corrosion measurement system

The purpose of this paper is to demonstrate that metal loss under atmospheric conditions can be continuously monitored with an atmospheric corrosion probe, that corrosion rates under atmospheric conditions can be quickly and accurately determined, and that the dew point can be easily detected. An atmospheric corrosion probe is developed to measure corrosion rates under atmospheric conditions. The continuing development of this new metal-loss sensor permits rapid measurements of corrosion rates in atmospheric conditions. The performances of this new technology are evaluated with experiments that alternate between wet and dry exposure conditions. These different measurements show the high sensitivity and high accuracy of the atmospheric corrosion probes. The capabilities of these corrosion probes to measure low values of corrosion rate are also demonstrated. [179]

A.13.52 Shi and Mahadevan (2000): Probabilistic corrosion fatigue life prediction

This paper discusses the effects of corrosion fatigue due to pitting corrosion. In this regard, the fatigue damage process induced by pitting corrosion is composed of seven stages, (i) pitting nucleation, (ii) pit growth, (iii) transition from pit growth to short crack, (iv) short crack growth, (v) transition from short crack to long crack, (vi) long crack growth and (vii) fracture. The authors present a comprehensive mechanics-based probabilistic model for pitting corrosion fatigue life prediction by including all these stages. An analytical first-order reliability method (FORM) and Monte Carlo simulation are implemented with the proposed model. A numerical example is given for the application of the proposed method for the corrosion fatigue life prediction of aluminum alloys. [180]

A.13.53 Ford (1999): Corrosion detection and control

This paper considers the history of corrosion in metallic aircraft and summarizes the different types of corrosion which affect aircraft and the methods for monitoring and measuring this corrosion. [181]

A.13.54 Marcy et al. (1999): Wireless sensor networks for area monitoring and integrated vehicle health management applications

This paper provides a discussion on wireless sensor networks, particularly distributed microsensor networks, for military and commercial applications. In this regard, wireless distributed microsensor networks consist of a collection of communicating nodes, where each node incorporates the following (i) one or more sensors for measuring the environment, (ii) processing capability in order to process sensor data and (iii) a radio to communicate information to/from neighboring nodes and (eventually) to external users. [182]

A.13.55 Steyer (1999): A framework for corrosion prediction and management

The work presented in this paper examined and outlined the steps needed to develop a framework for corrosion prediction. The author also provides suggestions for a corrosion management concept. In this respect, the challenges for corrosion prediction and management include, (i) reduction of the cost of ownership for current and future aircraft, and (ii) to provide cost effective sustainment of aging aircraft. Technological advancements and the implementation of newer technologies are also presented. [183]

A.13.56 Andrieu et al. (1998): Aluminium alloy corrosion detection by magnetic measurements

The aim of the work presented here was to evaluate aluminum alloy corrosion using magnetometric techniques, particularly the detection of pitting corrosion in aluminum alloys using a superconducting quantum interference device (SQUID) magnetometer and a nuclear magnetic resonance (NMR) magnetometer probe. In this regard, pitting corrosion of aluminum alloys was detected through magnetic field measurements, without electrical connection to the sample and without reference or auxillary electrodes in the corrosion cell. A sodium chloride (NaCl) solution containing hydrogen peroxide (H_2O_2) or a solution of potassium hydroxide (KOH) was used for the corrosion tests. The SQUID provided information on spatial distribution and direction of the currents. The NMR magnetometer was better for studying the development of the corrosion over time. [184]

A.13.57 Bar-Cohen et al. (1998): Smart sensor system for NDE of corrosion in aging aircraft

In this work, a sensing method is presented that takes advantage of accumulated knowledge and understanding of material degradation with respect to and caused by flaws. A knowledge-base system (mathematical transformation model) combined with a series of sensors that monitor the variations in the material state supported by computing power is used to simulate the process of degradation and to establish a health monitoring system. While this paper concentrates on corrosion, the concept is generic and can be adapted to other type of flaws. The authors determined that data fusion of sensor signals and artificial neural network algorithms could enhance the accuracy of the damage characterization and reduce the effect of uncertainties and nonlinearities. [185]

A.13.58 Zieliński (1998): Hydrogen-enhanced stress-corrosion cracking of aluminum alloys

Presented in this work are the results of the investigation into stress corrosion cracking of aluminum-zinc-magnesium and aluminum-zinc-copper-magnesium (Al-Zn-Mg and Al-Zn-Cu-Mg) alloys in sodium chloride (NaCI) solutions. The contribution of hydrogen (H) to the process of stress-corrosion cracking is analyzed by taking into account the influence of the admixtures of arsenic trioxide (As_2O_3) and residual H on the susceptibility of metals to this kind of cracking. A mechanism of H-assisted stress-corrosion cracking is suggested on the basis of the concept of critical concentration of H. [186]

A.13.59 Kelley et al. (1997): Embeddable microinstruments for corrosion monitoring

In this work, the design and development of an embeddable corrosion measurement microsystem which takes advantage of the increased availability of application specific integrated circuit (ASIC) and very large scale integrated (VLSI) circuit manufacturing is described. The key components of the system include, (i) micropotentiostat with zero resistance ammeter (ZRA) and (ii) analog-to-digital (ND) and digital-to-analog (D/A) converters. The micropotentiostad ZRA combination was tested on steel electrodes exposed to, (i) sodium chloride (NaCl) solution, (ii) saturated calcium hydroxide $Ca(OH)_2$, and (iii) saturated $Ca(OH)_2$ + NaC1. Comparisons of polarization resistance data generated and commercially available systems, demonstrated that the two systems performed equivalently. The authors also provide future directions for the development of the embeddable corrosion measurement microsystem. [187]

A.13.60 Polyanskii (1985): Role of hydrogen embrittlement in the corrosion cracking of aluminum alloys

This paper provides an overview of the effect of hydrogen embrittlement on the corrosion of aluminum alloys. The author presents and discusses accumulated experimental and theoretical data related to the hydrogen embrittlement of aluminum alloys and how metallurgical factors might inhibit the progression of corrosion cracking. [188]

A.13.61 Marichev (1983): The mechanisms of crack growth in stress corrosion cracking of aluminum alloys

In this review, the possible mechanisms of crack growth in corrosion cracking of aluminum alloys immersed in various corrosion media is presented. The author gives special emphasis to new methods of determining the effect of local anodic dissolution and hydrogen embrittlement in crack growth, and the effect of cathodic polarization on crack growth. The experimental data used as a basis to conclusions about the mechanisms of corrosion cracking in aluminum alloys are also critically examined. [189]

A.13.62 Stanley (1972): Stress corrosion cracking and hydrogen embrittlement of high-strength fasteners

This paper presents a discussion on the physical nature of hydrogen stress cracking (HSC) and stress corrosion cracking (SCC) on high strength aerospace fasteners. The author states that although there is a distinct difference between SCC and HSC phenomena within a laboratory environment, it is often difficult if not impossible to differentiate between the two mechanisms in the field. In this regard, the author ascertains that corrosion theory is not sufficiently advanced (1972) to be able to predict dangerous stress environment structure combinations that could lead to failure. Examples given of fastener failures on the Titan III rocket illustrate the nature of the problem and can be divided into three categories, (i) by ultimate tensile strength level, (ii) by metallurgical type, and (iii) by relative susceptibility to salt solutions or marine environments. Fracture toughness analysis offers the best hope of obtaining data on SCC or HSC. [190]

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3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C, R or U) in parentheses after the title.) A Literature Review of Corrosion Sensing Methods		
4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used) Rinaldi, G.		
5. DATE OF PUBLICATION (Month and year of publication of document.) September 2009	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 94	6b. NO. OF REFS (Total cited in document.) 190
7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.) Technical Memorandum		
8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.) Defence R&D Canada – Atlantic 9 Grove St, PO Box 1012 Dartmouth, NS B2Y 3Z7		
9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)	
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.) DRDC Atlantic TM 2009-082	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)	
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Corrosion monitoring, detection and remediation are of particular importance for military vehicles and infrastructure due to the long operational life-cycle of these assets. In this regard, corrosion is a problem that is growing not only because of the increasing number of military assets, but also due to the increasing number that are aging and nearing the end of their operational life-cycle. Even for newer equipment, corrosion can be a significant problem because of the harsh operational environments often encountered. Hence, as military systems age, corrosion becomes one of the largest cost inflators in the life-cycle costs of military systems. Therefore, cost effective life-cycle management of military assets requires a systematic health monitoring approach to prevent and control corrosion. In this respect, nondestructive evaluation (NDE) and nondestructive inspection (NDI) play important roles in this effort, particularly by monitoring, detecting and reporting the early signs of corrosion before the damage becomes significant. This report presents a literature review of corrosion monitoring technologies and applications with a particular emphasis on aerospace materials and structures.

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Corrosion, Structural health monitoring, Sensors, NDT, NDE