Chapter 21 – NON-DESTRUCTIVE TESTING FOR CORROSION

David S. Forsyth
Texas Research International, TRI/Austin
Austin, Texas
USA

21.1 INTRODUCTION

Non-Destructive Testing (NDT) is defined by the American Society for Non-destructive Testing (ASNT) as: "The determination of the physical condition of an object without affecting that object's ability to fulfill its intended function. Non-destructive testing techniques typically use a probing energy form to determine material properties or to indicate the presence of material discontinuities (surface, internal or concealed)." For the purpose of this article, the terms non-destructive testing, Non-Destructive Inspection (NDI), and Non-Destructive Evaluation (NDE) will be considered to be equivalent.

In the modern NDT paradigm, the uses of NDT can be broken into several categories where it plays an important role:

- Material property measurements;
- Process design for materials manufacturing;
- Online process control; and
- Quality control as various stages of manufacturing are completed.

In addition, NDT plays an important role in the continued safe operation of physical assets. For instance, NDT is being used in conventional inspections and in health monitoring, where NDT sensors are embedded or attached to the system being inspected or monitored for defects or damage. In all cases, the customer must define the requirements of the test, such as the minimum level of acceptability for the property being measured and the characteristics of the material discontinuities to be identified. Given this information, the NDT engineer or experienced technician can choose the appropriate method and develop an appropriate technique for the inspection requirements.

21.2 NON-DESTRUCTIVE TESTING METHODS

An NDT method is classified according to its underlying physical principle. For example, the common methods are:

- Visual and optical Testing (VT);
- Radiographic Testing (RT);
- Electromagnetic Testing (ET);
- Ultrasonic Testing (UT);
- Liquid Penetrant Testing (PT);
- Magnetic particle Testing (MT);
- Acoustic Emission testing (AE); and
- Infrared and thermal testing (IR).

An NDT technique defines all the parameters for the application of a specific method to a specific problem. These parameters include the instruments, probes, acceptance criteria, calibration specifications, and much more. ASNT offers a series of handbooks that are a key reference for the practical implementation of NDT. In addition, AMMTIAC (Advanced Materials, Manufacturing, and Testing Information Center) has a number of state-of-the-art reports and technology assessments that provide in-depth reviews of specific topics. A listing of these reports is available on the AMMTIAC website. The following sections will briefly describe each of the common methods listed above.

21.2.1 Visual NDT

By far, the most common NDT method is visual and optical testing. In many instances, a trained inspector armed with simple tools, such as a flashlight and magnifying glass, can perform a very effective inspection. In quality control, as well as in maintenance operations, visual testing is the first line of defence. When deciding upon whether to use visual testing, it is important to understand its potential as well as its limitations. If the visual method is not sufficient for the problem at hand, more complex methods must be considered. Using the visual inspection method for enclosed systems can be challenging and possibly ineffective. To enable a technician or engineer to inspect these difficult-to-see areas, a device known as a borescope is often used. Borescopes are essentially miniaturized cameras that can be placed on the end of a fiber optic cable. The camera can then be inserted into regions that are obstructed from direct visual inspection, and the resulting images are viewed in real-time on a video screen by the inspector.

21.2.2 Enhanced Visual/Optical NDT

There are a variety of enhanced visual/optical NDT methods available. In terms of corrosion NDT, these methods are generally used to detect and measure deformations on surfaces. These deformations may be caused by pitting on the exposed surface, or by sub-surface corrosion damage in built-up structure. There are a number of implementations of instruments based on Moire, Electronic Speckle Pattern Interference (ESPI) and digital speckle correlation [1], and holography. Other optical surface topography systems have been used for characterization of corrosion damage [2],[3]. Direct optical metrology methods such as laser interferometry and triangulation-based methods have been used in laboratory type situations for measuring pillowing caused by corrosion in thin aluminum structures [4].

21.2.3 Ultrasonic NDT

Ultrasonic testing employs an extremely diverse set of methods based upon the generation and detection of mechanical vibrations or waves within test objects. The test objects are not restricted to metals, or even to solids. The term ultrasonic refers to sound waves of frequency above the limit of human hearing. Most ultrasonic techniques employ frequencies in the range of 1 to 10 MHz. The velocity of ultrasonic waves traveling through a material is a simple function of the material’s modulus and density, and thus ultrasonic methods are uniquely suited to materials characterization studies. In addition, ultrasonic waves are strongly reflected at boundaries where material properties change, and thus are often used for thickness measurements and crack detection. Recent advances in ultrasonic techniques have largely been in the field of phased array ultrasonics, now available in portable instruments. The timed or phased firing of arrays of ultrasonic elements in a single transducer allows for precise tailoring of the resulting ultrasonic waves introduced into the test object.

21.2.4 Eddy Current NDT

Electromagnetic Testing (ET), especially eddy current testing, is commonly used to inspect objects throughout their life cycle. Eddy current techniques employ alternating currents applied to a conducting coil held close to the test object. In response, the test object generates eddy currents to oppose the alternating current in the coil. The eddy currents are then sensed by the same coil, separate coils, or magnetic field sensors. Changes in the induced eddy currents may be caused by changes to a material's electromagnetic properties and/or changes in geometry, including the abrupt changes in current flow caused by cracks. Thus ET methods are highly effective for the detection of cracks present on or below the surface of metallic objects. ET equipment has become extremely portable and is relatively inexpensive. It is the second most common method specified for NDT of aircraft. Recent advances in eddy current technology include multi-channel portable instruments, allowing faster inspections of large areas, and new magnetic sensors, such as the Giant Magnetoresistive (GMR) sensors developed for computer hard drives, instead of coils.

21.2.5 Thermographic NDT

Infrared and thermal testing methods are characterized by the use of thermal measurements of a test object as it undergoes a response to a stimulus. Thermal imaging cameras are the most common sensing method. Passive imaging of machinery or electronics may be used to detect hot spots indicative of problems. Imaging of test objects after the application of energy can be used to monitor the flow of heat in the object, which is a function of material properties as well as boundaries. Flash thermography techniques have been very successful in imaging disbonds and delaminations in composite parts, for example. The high cost of quality thermal cameras was previously a drawback of the IR method, but recently these have become significantly less expensive. Another significant recent advancement is the use of mechanical energy to stimulate localized heating at sub-surface discontinuities, such as cracks in metals, opening up a new field of application for the IR method.

21.2.6 Radiographic NDT

Historically, radiography is the next most common NDT method. Significant activity in the field occurred almost immediately after Roentgen's discovery of X-rays in 1895 [5]. Early literature notes the ability of radiographs to detect discontinuities in castings, forgings, and welds in metals. Discontinuities such as pores or inclusions in metals are readily detected in many cases. Cracks may also be detected using radiographic techniques, but attention must be paid to orientation and residual stress issues. Radiography continues to be widely used despite the expense and safety implications of the equipment. Recent advances in digital radiography have helped reduce the cost of employing this method by eliminating the use of film.

21.2.7 Additional NDT Methods

There are a number of other NDT methods that have been used for corrosion NDT. These include the Magneto-Optic Imager (MOI), a commercial device that images magnetic fields induced by a sheet current [6]. Microwave NDT methods have been used to find corrosion under paint layers [7]. Terahertz imaging is being used to find corrosion damage under thermal insulation tiles on the space shuttle [8].

Health monitoring for corrosion is a growing field, with the potential to reduce the impact of disassembly and reassembly of aircraft to enable traditional NDT. Some of the sensor types are direct evolutions of NDT methods, and are simply attached to the structure to be left in place. This topic is covered elsewhere in this book.

21.3 DATA FUSION

A simple definition of data fusion is the combination of multiple inputs into one output. Thus data fusion includes basic systems such as voting (if a majority of inputs are true, the output is true) as well as highly complex systems such as military target tracking or remote sensing using multiple band radars operating in different locations. There are three general categories used to describe the level at which data fusion takes place: Pixel level data fusion describes applications where little or no pre-processing is applied to the data, and the fusion operation acts on the lowest level of the data. Feature level fusion refers to cases where feature extraction has been performed on the data before fusion. Finally, decision level fusion refers to the fusion of data that is carried out after feature extraction and identification on the data inputs. The results reported in this work use pixel-level fusion algorithms. Some applications of data fusion to NDI have been published, most of which are of moderate complexity (for example Gros [9],[10] and involve pixel or feature level fusion. One of the authors has previously applied simple data fusion methods on NDI results to identify and measure corrosion in aircraft structures [11], but the work presented in this paper uses NDI from commercially available inspection equipment and applies more advanced fusion techniques to yield quantitative estimates of the thicknesses of individual layers of a two-layer lap joint.

The generic steps required to perform data fusion on NDI data are:

- Inspection pre-processing;
- Registration of individual inspections on a common coordinate system; and
- Data fusion.

It is important to note that the steps of pre-processing and registration are in themselves value-added steps. Even before any data fusion operation has been performed, the NDI data from disparate sources have been brought together on one software platform, and registered on a common coordinate system. This is a significant improvement over most current practices for handling NDI data, and greatly facilitates the use of databases for maintenance planning. It also allows improved inspector interpretation by making comparison between NDI data much simpler. Often the pre-processing step can be used to transform a single NDI data source from the NDI domain to a quantitative measure; for example, Edge of Light images can be transformed from brightness levels to images of maximum pillowing deformation [12].

The final data fusion algorithm to be used will be specific to the application. Development of these algorithms will only be cost-effective for repetitive inspection situations, such as the common lap splice joint. However, the preliminary steps of data handling, pre-processing, and registration are likely to become more commonly used as fleet maintenance practices are modernized, reducing the costs of implementing data fusion in practical situations.

21.4 RELIABILITY OF NDT FOR CORROSION

When NDT is used as part of the management of risk in the life cycle maintenance of an aircraft, it is imperative to know what is the probability of finding (or equivalently of missing) discontinuities of interest in an inspection. This is usually called the Probability Of Detection (POD). The development of the POD metric was originally directed towards fatigue cracks, but it is important to note that the POD approach is not limited to cracks, and has in fact been applied to other discontinuities such as corrosion loss, impact damage, or delaminations (see for example Komorowski et al. [13], Forsyth et al. [14], Ashbaugh et al. [15], Hoppe et al. [16]. The current POD approaches present POD as a function of a single metric of damage, for example crack length, as shown in Figure 21-1 below. In cases where the corrosion damage of interest can be characterized by a single metric, the conventional POD approaches will be suitable. This may be the case for intergranular cracking and pitting on an exposed surface. In other cases, multi-dimensional damage is not well characterized by a single metric, and a number of approaches have been developed.

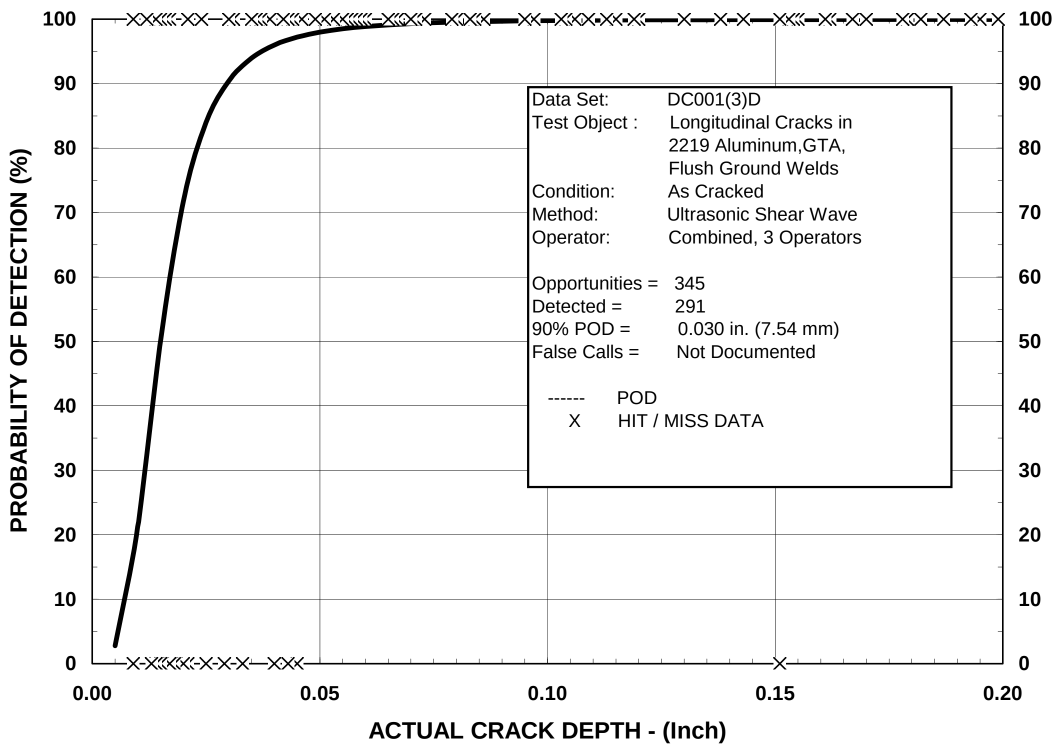

Figure 21-1: An Example of a POD Curve, from the Ultrasonic Inspection of Welds in Aluminum for Cracks (from Rummel and Matzkanin, [17], used with permission).

Both the USAF [18] and the United States Federal Aviation Agency (FAA) [19]-[21], have published guidelines that describe in detail the experiments required to estimate the POD of an inspection system. These documents are in the public domain, and can be obtained for free from the respective government agencies as well as the Department of Defense's Advanced Materials, Manufacturing, and Testing Information Analysis Center (AMMTIAC) (see http://ammtiac.alionscience.com).

There are a number of useful general statements that can be made about estimating POD. The process of POD estimation requires a number of inspections to be performed:

- Using the complete, pre-defined inspection system that is being assessed including representative equipment, procedures, inspectors, and target parts;
- Using parts with discontinuities that represent the discontinuities of interest or a means to assess the difference between the two: for example, using machined notches or flat bottomed holes can provide a useful measure of capability, but should not be assumed to be representative of cracks or other natural discontinuities; and
- Using an inspection procedure and environment typical of the deployed environment. Human factors studies have shown that the relationship of factors such as environment (lighting, temperature, etc.), training, experience, motivation and others is not simple and often not intuitive.

It is key to understand the physical parameters that may affect the response of the NDT system to a discontinuity to be able to execute a representative POD estimate. If parts from service, with discontinuities arising from service, are available; this is the optimal situation. However, in most cases, this is not possible. Therefore every reasonable effort should be made to replicate the service discontinuities as close as possible, or to use engineering judgment as to whether safety factors are needed to account for the difference between the POD experiment and in-service conditions.

Unique approaches to POD for corrosion damage have been developed for the case of corrosion in the internal surfaces of aircraft skin splice joints . Ashbaugh et al. [15] showed that detection of corrosion in this case was a function of both the thickness loss and area affected (see Figure 21-2 below).

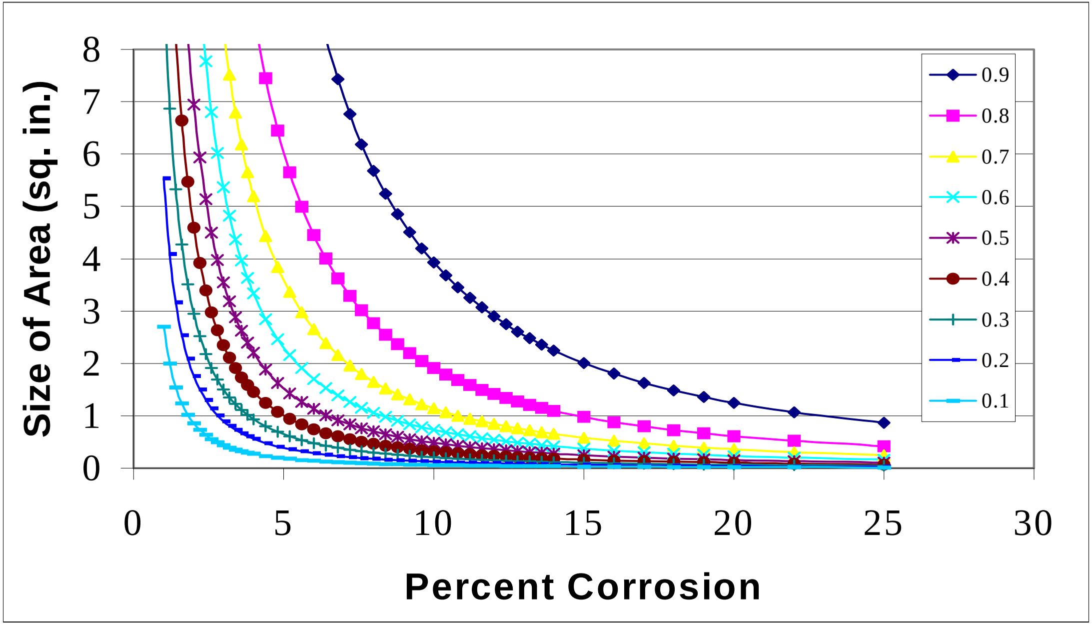

Figure 21-2: Data from Experiment, Showing Contours of POD Values as a Function of Both Area and Thickness Loss of Damage (from Ashbaugh et al. [15], used with permission).

Liao et al. [22] used the error in thickness loss measurement by NDT to calculate the effect of this error on the risk and therefore maintenance actions required, see Figure 21-3. K/C-135 lap splice joints were used as the basis of this case study. As shown in the figure below, increasing error results in increasing uncertainty about the NDT assessment, and therefore more severe maintenance actions are required as NDT error increases for the same estimated thickness loss.

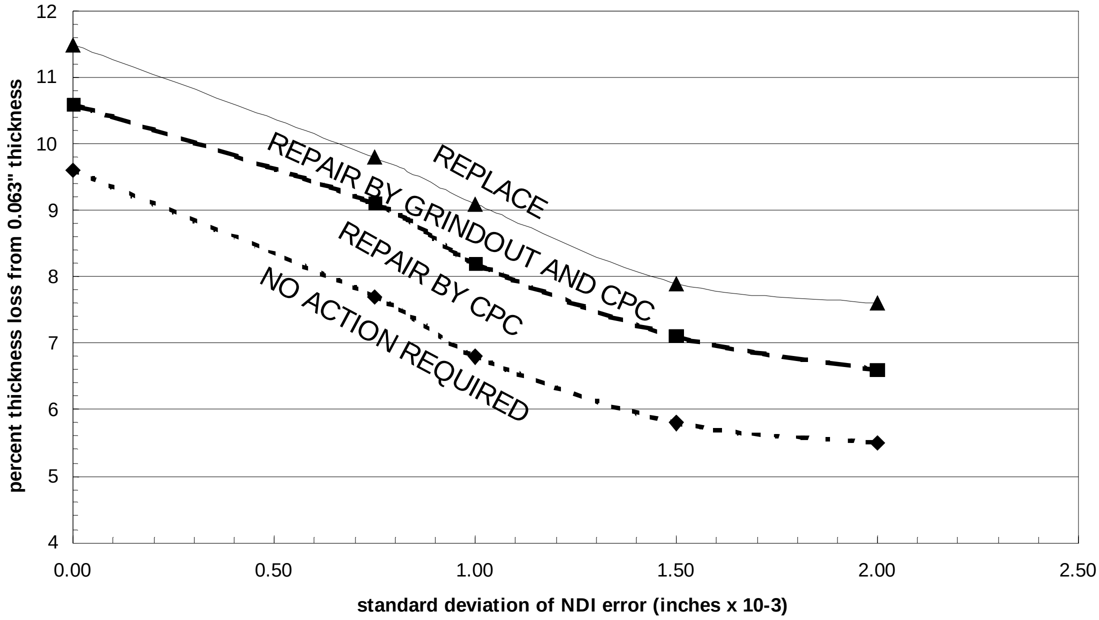

Figure 21-3: A Graph of the Effect of NDT Error on the Level of Damage and Subsequent Maintenance Actions (see Liao et al. [22]).

21.5 CASE STUDIES

21.5.1 Intergranular Corrosion in Thick Section Aluminium Structure

Typical examples of thick section structure are wing skins, ribs, and spars; and complex forgings used for fittings at locations like wing to body attachment points. These structures are commonly manufactured from 7000 series aluminum alloys, 7075-T6 being common on older aircraft. More corrosion resistant alloys are generally used in modern designs.

Because of the materials and product forms typical of these structures, intergranular corrosion attack is a common problem. This attack begins at pitting at exposed grains, and quickly becomes intergranular in nature. If sustained stresses are present, due to residual stresses or even simple “weight on wheels” loads, the phenomenon often called “stress corrosion cracking” can result.

In a number of cases, inspection may be only an interim solution, providing time for material substitution programs. Any pitting on highly loaded forgings of Al 7075-T6 or older vintage 7000 series alloys is capable of nucleating intergranular cracking. If these components are exposed for visual inspection, this may be sufficient to detect pitting and initiate any required maintenance actions. Interesting case studies include the C-130 “pork chop” fitting (see Chapter 5) and the C-141 landing gear hub [23].

Intergranular attack commonly nucleates at corrosion pits on exposed end-grains, Figure 21-4. Holes with steel fasteners are a common site, as fretting eventually wears off the coatings designed to isolate the steel from the aluminum. In severe cases, the material bulges around the fastener due to the corrosion product between multiple intergranular cracks. This is called exfoliation.

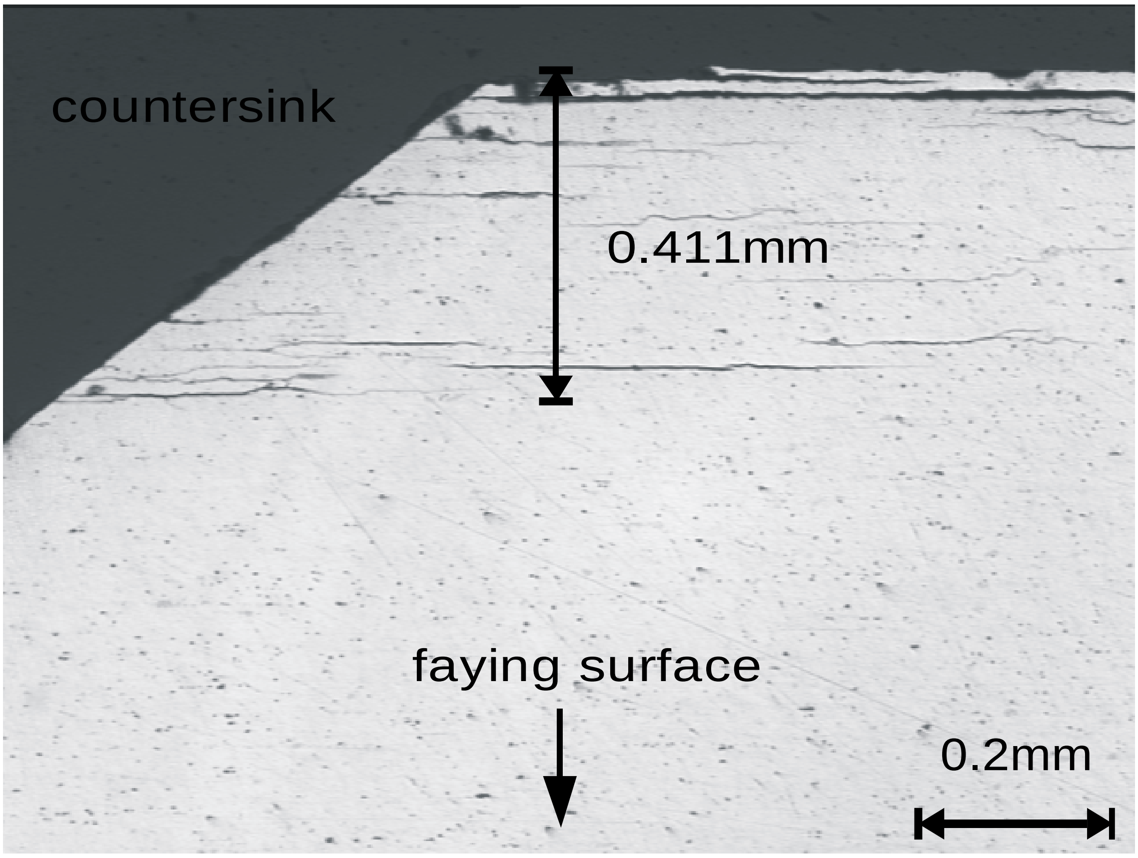

Figure 21-4: Metallographic Section Around a Fastener Hole in a Boeing 707 Wing Skin Plank, Showing Multiple Layers of Intergranular Attack from Pits in the Countersink – the material is 7178-T6 aluminum (from Forsyth et al. [24]).

This type of damage is relatively easy to detect, especially once it has progress beyond the countersink of the fastener. Even before it is visible as exfoliation, UT and IR methods can readily detect it, but will only measure the top layer and any layers beneath which extend beyond the top layer, Figure 21-5 [24].

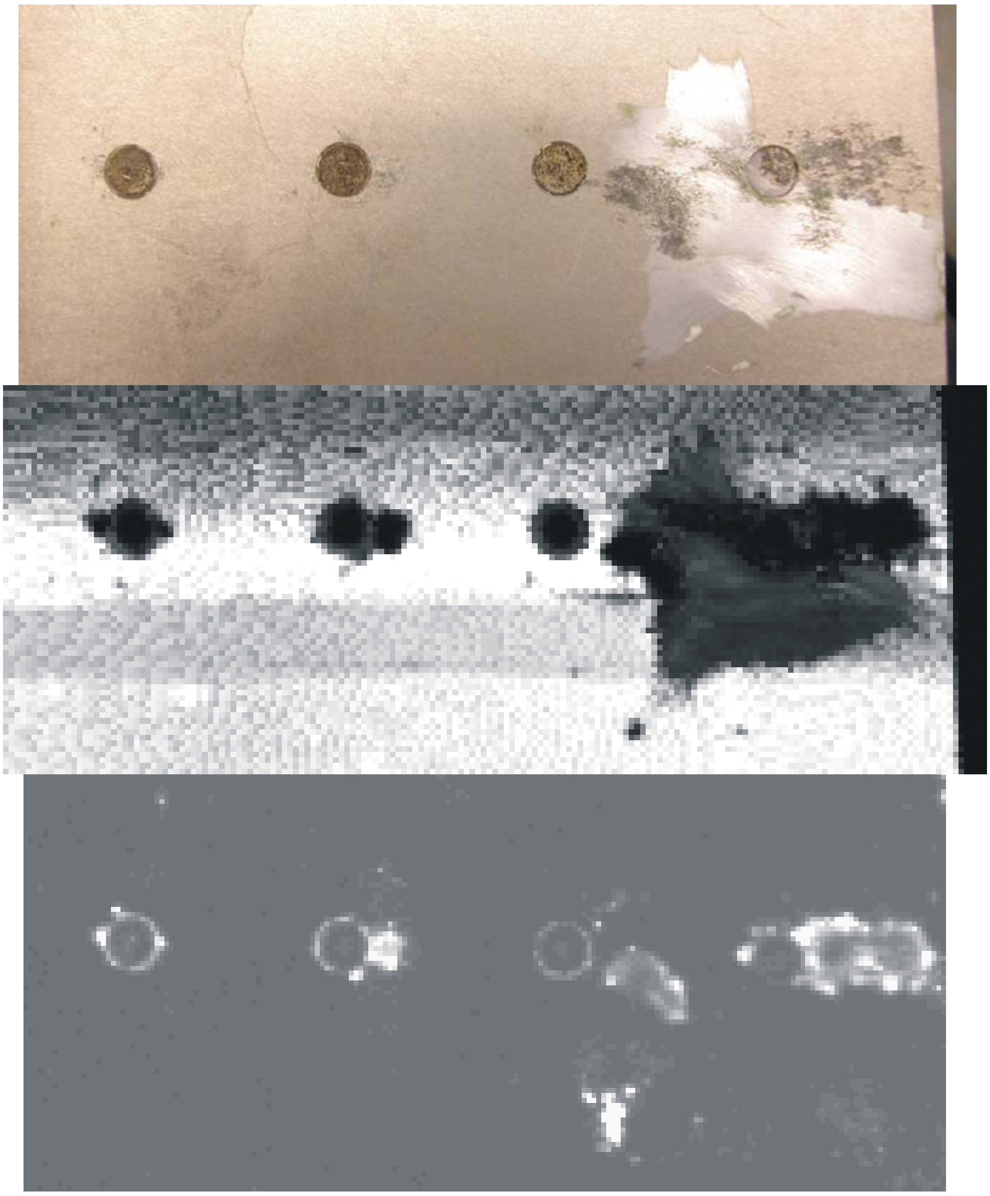

Figure 21-5: From Top to Bottom: A Photograph, a UT Image, and an IR Image of a Section of Wing Plank from a Boeing 707, Showing Exfoliation Damage and Grinding Marks from Repairs – the material is 7178-T6 aluminum (from Forsyth et al. [24]).

More advanced UT methods use surface waves or reflections to interrogate the volume obscured by fasteners, and can detect smaller areas of exfoliation. These methods are still subject to the phenomenon of top or bottom layers obscuring exfoliation occurring between them.

As described above, using UT techniques, it is relatively simple to determine the depth of the first layer of exfoliation that extends beyond fasteners. Accuracy in thick sections should be 0.127 mm (0.005”) or better in depth. More advanced UT techniques can interrogate the bottom of the fastener hole and locate the bottom layer. Accuracy of 0.254 mm (0.010”) is probably achievable under well-controlled situations.

Exfoliation that extends beyond the fastener head can be detected by simple UT and IR methods, as well as enhanced visual methods. Sizing for all these methods is limited by probe sizes and in the case of IR methods, diffusion. UT is the most accurate sizing method, and a measurement accuracy of 0.254 mm

(0.010”) should be achievable. The sensitivity of IR methods is more affected by the depth at which the exfoliation occurs, and this is not well known.

21.6 REFERENCES

[1] Jin, F. and Chiang, F.P., “ESPI And Digital Speckle Correlation Applied To Inspection Of Crevice Corrosion On Aging Aircraft”, R. NDE., Vol. 10 (2), pp. 63-73, 1998.

[2] Komorowski, J.P., Bellinger, N.C., Gould, R.W., Marincak, A. and Reynolds, R., “Quantification of Corrosion in Aircraft Structures with Double Pass Retroreflection”, CASJ, Vol. 42 (2), pp. 76-82, 1996.

[3] Forsyth, D.S., Komorowski, J.P., Marincak, A. and Gould, R.W., “The Edge of Light Enhanced Optical NDI Technique”, CASJ, Vol. 43 (4), pp. 231-235, 1997.

[4] Eastaugh, G.F., Merati, A.A., Simpson, D.L., Straznicky, P.V. and Krizan, D.V., “The Effect of Corrosion on Durability and Damage Tolerance Characteristics of Longitudinal Fuselage Skin Splices”, in USAF Aircraft Structural Integrity Program Conference 1998, San Antonio, TX, USA, 1-3 December 1998.

[5] Bossi, R.H., Iddings, F.A., Wheeler, G.C. and Moore, P.O., “Radiographic Testing, Nondestructive Testing Handbook”, 3rd. Ed., Vol. 4, American Society for Nondestructive Testing, Columbus, OH, USA, 2002.

[6] Thome, D.K., Fitzpatrick, G.L. and Skaugset, R.L., “Aircraft Corrosion and Crack Inspection Using Advanced MOI Technology”, in Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware, SPIE Proceedings Vol. 2945, Scottsdale, AZ, USA, pp. 365-373, 3-5 December 1996.

[7] Hughes, D., Zoughi, R., Austin, R.K., Wood, N. and Engelbart, R., “Near-Field Microwave Detection of Corrosion Precursor Pitting under Thin Dielectric Coatings in Metallic Substrate”, in Thompson, D.O. and Chimenti, D.E., Review of Progress in Quantitative Nondestructive Evaluation: Vol. 22, AIP Conference Proceedings, 657, pp. 462-469, 2003.

[8] Anastasi, R.F., Madaras, E.I., Seebo, J.P., Smith, S.W., Lomness, J.K., Hintze, P.E., Kammerer, C.C., Winfree, W.P. and Russell, R.W., “Terahertz NDE Application for Corrosion Detection and Evaluation Under Shuttle Tiles”, Proc. SPIE Int. Soc. Opt. Eng. 6531, 2007.

[9] Gros, X.E., “NDT Data Fusion”, Arnold, 1997.

[10] Gros, X.E., “Applications of NDT Data Fusion”, Kluwer Academic Publishers, 2001.

[11] Forsyth, D.S. and Komorowski, J.P., “The Role of Data Fusion in NDE for Aging Aircraft”, in Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware IV, SPIE Proceedings Vol. 3994, pp. 47-58, 2000.

[12] Forsyth, D.S., Gould, R.W. and Komorowski, J.P., “Correlation of Enhanced Visual Inspection Image Features with Corrosion Loss Measurements”, in Maldague X P V, TONE Volume 3: III International Workshop – Advances in Signal Processing for Non Destructive Evaluation of Materials, ASNT, Columbus, OH, USA, pp. 365-372, 1998.

[13] Komorowski, J.P., Forsyth, D.S., Simpson, D.L. and Gould, R.W., “Corrosion Detection in Aircraft Lap Joints: Proposed Approach to Development of POD Data”, in RTO Workshop on Airframe

Inspection Reliability under Field/Depot Conditions, Brussels, Belgium, RTO-MP-10, AC/323 (AVT)TP/2, pp. 8-1 – 8-8, 13-14 May 1998.

[14] Forsyth, D.S., Komorowski, J.P. and Gould, R.W., “Double Pass Retroreflection Versus Visual POD of Impact Damage in Composites”, Presented at RTO Workshop on Airframe Inspection under Field/ Depot Conditions, Brussels, Belgium, RTO-MP-10, AC/323(AVT)TP/2, pp.18.1 – 18.6, 13-14 May 1998.

[15] Ashbaugh, D.M., Bode, M.D., Boyce, K.L. and Spencer, F.W., “Corrosion Structured Experiment”, in Thompson, D.O. and Chimenti, D.E, Review of Progress in Quantitative Nondestructive Evaluation: AIP Conference Proceedings, Vol. 21, p. 615, 2001.

[16] Hoppe, W., Pierce, J. and Scott, O., “Automated Corrosion Detection Program Final Report for 07 April 1997 – 06 October 2001”, United States Air Force Report AFRL-MP-WP-TR-2001-4162, 2001.

[17] Rummel, W.D. and Matzkanin, G.A., “Nondestructive Evaluation Capabilities Databook”, NTIAC-DR-95-02, Advanced Materials, Manufacturing, and Testing Information Center, operated by Alion Science & Technology on behalf of US DoD, Rome, NY, USA, 13440, 1996.

[18] Anon, MIL-HDBK-1823a, United States Air Force, 2009.

[19] Spencer, F.W., Borgonovi, G., Roach, D., Schurman, D. and Smith, R., “Reliability Assessment at Airline Inspection Facilities Volume I: A Generic Protocol for Inspection Reliability Experiments”, DOT/FAA/CT-92/12, I, 1993.

[20] Spencer, F.W., Borgonovi, G., Roach, D., Schurman, D. and Smith, R., “Reliability Assessment at Airline Inspection Facilities Volume II: Protocol for an Eddy Current Inspection Reliability Experiment”, DOT/FAA/CT-92/12, II, 1993.

[21] Spencer, F.W. and Schurman, D., “Reliability Assessment at Airline Inspection Facilities Volume III: Results of an Eddy Current Inspection Reliability Experiment”, DOT/FAA/CT-92/12, III, 1995.

[22] Liao, M., Forsyth, D.S., Komorowski, J.P., Safizadeh, S., Liu, Z. and Bellinger N.C., “Risk Analysis of Corrosion Maintenance Actions in Aircraft Structures”, in the Proceedings of the 22nd Symposium of the International Committee on Aeronautical Fatigue, ICAF 2003, Lucerne, Switzerland, May 2003.

[23] Brooks, C., Honeycutt, K., Prost-Domasky, S. and Peeler, D., “Monitoring the Robustness of Corrosion & Fatigue Prediction Models”, in 2001 United States Air Force Aircraft Structural Integrity Program (ASIP) Conference, Williamsburg, VA, USA, 11-13 December 2001.

[24] Forsyth, D.S., Liu, Z., Hoffmann, J. and Peeler, D., “Data Fusion for Quantitative Nondestructive Inspection of Corrosion Damage in Aircraft Wing Structures”, in United States Air Force Aircraft Structural Integrity Program (ASIP) Conference, Savannah, GA, USA, 10-12 December 2002.