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Defect Analysis in Aerospace Systems Using Non-destructive Testing

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Abstract

Defects are anathema, particularly in Aerospace and, if they are controlled by means of non-destructive means, better it is. Defect analysis using Non-destructive Testing (NDT) is an expedient way for controlling defects in Aerospace Systems. Defect Analysis means identifying, locating, interpreting, evaluating and generating corrective and preventive actions. Defect Analysis in Aerospace consists of the following:

1. Capturing the defects,
2. Analyzing the defects,
3. Developing defect mitigation plan, and
4. Implementing defect mitigation plan.

Although historically nondestructive techniques have been used almost exclusively for detection of macroscopic defects in structures, yet in aerospace, research has increasingly shown that it is practical to expand the role of nondestructive evaluation to include all phases of materials production. In aerospace both accredited and non-accredited NDT Methods are used. Commonly used accredited NDT methods in aerospace are Visual Testing (UT), Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), Eddy Current Testing (ET), Ultrasonic Testing (UT), Radiography Testing (RT) and Leak Testing (LT). Some of the advanced non-accredited NDT techniques used in aerospace are ultrasonic phase array, optical holography, X-ray computed tomography, X-ray Diffraction Imaging and infrared thermography. Generally, 90% Probability of Detection (POD) criteria may be used for selection of an NDT Technique.

Detectable size of the defect that an NDT method should detect can be estimated by the use of fracture mechanics. And based on this, the required NDT method may be decided. Defectology, Defect Analysis and the needed knowledge of Nondestructive Testing is used for controlling the defects in Aerospace Systems.

Defect Mitigation Plan consists of corrective and preventive actions. Based on this information corrective and preventive actions may be implemented. Corrective actions consist of repair and salvage actions. And preventive actions ensure that the defects are not repeated.

1. Introduction

Quality mantra is to ensure that defects in the products are within acceptable limits for end use. The top management is ever on the hot pursuit to realize this quality mantra. They have installed quality system based on ISO 9000 or QS 9000 or AS 9100 etc, towards this end. Lately, they are pursuing Six Sigma or beyond

Programmes to achieve the same goal. Defects are anathema, particularly in Aerospace and, if they, are controlled by means of non-destructive means, better it is. Defect analysis using Non-destructive Testing (NDT) is an expedient way for controlling defects in Aerospace Systems.

Defect Analysis means identifying, locating, interpreting, evaluating and generating corrective and preventive actions. Many a time evaluation of a defect means understanding the defect and its cause and development of corrective and preventive actions. Defect analysis may be used for controlling the defects.

The control of the defects is obtained in three steps:

1. Production of the proper indication of the defect,

2. Interpretation of the defect, and

3. Evaluation of the defect.

The first step i.e. production of the proper indication of the defect may be obtained with the help of nondestructive or destructive methods. It is always valuable, if it is realized through nondestructive means rather than through destructive ones. Thus, in aerospace, for this purpose, Nondestructive Testing (NDT) is very expedient.

In aerospace, NDT can make the difference between success and failure, and life and death. For example, aerospace systems, like space shuttle, aircraft, missiles etc., are designed to be as light as possible while still performing their intended function. This generally means that aerospace components carry very high loads relative to their material strength and small defects can cause a component to fail. Aerospace Systems are cycled (loaded and unloaded) as they fly, land, taxi, and so on, therefore, many components are prone to fatigue cracking in due course of time. After they are used for a while, fatigue crack start growing in some of their parts. Cracking can also occur due to other things, like a lightning strike.

NDT techniques are increasingly applied to components/systems for the detection and characterisation of defects, stresses and microstructural degradation to ensure the continued safety and performance reliability of components in aerospace. NDT techniques improve the performance reliability of components through periodic in-service quality control, by way of preventing premature and catastrophic failures. NDT also provides valuable inputs to determine which components are the most likely to fail and then to ensure that those have easy maintenance access for repair or replacement. In in-service scenario, it is rather difficult to stop the formation of defects and the growth of the defects already formed.

Another problem with aerospace systems is corrosion. For example, when an aircraft lands and the door is opened, the inside of the plane often fills with warm moist air. When the plane takes flight, and reaches altitude, the skin of the aircraft becomes very cold due to the temperature of the outside air. This causes the moisture held by the air inside the cabin to condense on the inside of the aircraft skin. The water will collect at low areas and serve as the electrolyte needed for corrosion to occur.

The rigorous process used to design aerospace systems either allows for a certain amount of damage to occur before a part fails, or in many cases, a part can fail completely and its performance will not be affected. The jobs of defect analysis using NDT is to find the damage while it is within acceptable limits and take corrective and preventive action.

2. Defect Analysis in Aerospace

It is the Defect Analysis, which mostly helps in realizing highly reliable aerospace systems and NDT only aids. Defectology, Defect Analysis and the needed knowledge of Nondestructive Testing is used for controlling the defects in Aerospace Systems.

Defect Analysis in Aerospace consists of the following:

1. Capturing the defects,
2. Analyzing the defects,
3. Developing defect mitigation plan, and
4. Implementing defect mitigation plan.

2.1 Defects and Their Detectable Size

Defect is any anomaly, discontinuity, flaw, imperfection, non-conformance and so on. Nevertheless, defect per se is not issue. Defect - pre-service or in-service - is an issue if it leads to failure. Pre-service defects are either inherent or processing defects and in-service defects are the defects introduced during the operating cycle of the material, component or the system. The size of the defect that may lead to failure may be estimated by using fracture mechanics. Defects present in the materials, components or the system, lead to failure when they grow to a critical, self-propagating size. The fracture mechanics allows one to estimate the critical size of the defect as a function of their depth, length, stress intensity and properties of the material, such as, modulus of elasticity, yield strength and fracture toughness. Using this, detectable size of the defect that an NDT method should detect can be estimated. And based on this, the required NDT method may be decided. If the critical defect size is greater than the smallest detectable size that can be reliably detected, then the selected NDT method may be used.

2.2 Defectology

Items based on metals and alloys are very commonly used in Aerospace. Control of defects in such items determines the success of Aerospace Systems. Defects start creeping in from the metallurgy stage of metals and alloys itself and keep on multiplying on further processing till the final product is reached. Control of these defects is essential throughout the process of product realization from the raw material to the finished product.

Raw materials are made in various forms, such as, sheets, wires, plates, rods, forgings, castings etc. Further during the process of product realization they pass through the processes of fabrication, heat treatment, plating, surface coatings, etc. The control of defects during the product realization process demands thorough understanding of the various defects that may crop-up during various phases. This is the subject matter of Defectology. Defectology deals with the defects that affect all the stages of product realization, starting from raw material to finished product.

3. Capturing the Defects

Obtaining the proper indication of the defect with the help of nondestructive or destructive methods may capture defects. It is always valuable, if it is realized through nondestructive means rather than through destructive ones. Thus, for capturing the defects, Nondestructive Testing (NDT) is very expedient. NDT is used with three different philosophies, each having a different principal objective.

The first philosophy is to use NDT to find defects before the finished product goes to the customer and into the service. Finished product should be free from all defects that would interfere with the satisfactory performance. This objective alone would justify a large effort, particularly, R&D effort, and expenditure on NDT facility, systems and equipment.

The second philosophy does not reject the first but further strengthen it by applying NDT at various strategic stages during processing. The basic principal of this second approach is to apply NDT for locating defective material as soon as the defect is formed in it. Thus, product realization phase is devoted to produce usable product and not a product that would have to be rejected as scrap on final inspection.

The third philosophy which results in substantial returns, simply makes systematic use of the information developed under the first two by tabulating and analyzing the nature and times of occurrence of the various discontinuities found during product realization. This would result in continual improvement - raw materials may be better selected, designs improved and processes corrected to the end that the incidences of discontinuities are reduced, production cost lowered, and the service life of the product extended. It is this philosophy of NDT that finds favour in aerospace. And quality system for defect analysis in aerospace systems is designed with this philosophy.

3.1 Role of NDT in Aerospace

NDT contributes considerably in quality control of aerospace systems. Control is a basic concept in aerospace. For example, while producing a product from forging blanks use of NDT rather that Destructive Testing better controls the defects such as seams, large inclusions or cracks during the product realization process. Generally, NDT techniques are applied in aerospace for one or more of the following:

1. Evaluation of the discontinuities in the materials or processed Materials,
2. Mechanical properties of materials,
3. Analysis of the geometry of components,
4. Non-contact Measurements,
5. Material condition throughout the life cycle, and so on.

While doing NDT in aerospace, a reasonable balance between type-I and type-II errors should be achieved. Reducing the defect size decreases the frequency of type-I errors (acceptance of defective parts). However, this often increases the frequency of type-II errors (rejection of sound parts). Hence, a judicious balance is called for.

In aerospace two types of NDT Methods are used : accredited and non-accredited. NDT bodies, like ASNT, CINAE and ISNT have listed more than twenty accredited NDT methods, however, in India only five or six are very popular. In aerospace, however, it is the non-accredited methods and techniques, such as phase array based ultrasonics, X-ray Tomography, Holography and many more, that are getting better reception, because of unconventional defects /problems faced and solutions evolved. And, the use of accredited and non-accredited method will depend upon the type, size and severity of defect.

NDT is employed, in aerospace, for myriad purposes, such as, for locating the flaws, discontinuities, leaks, imperfections in materials, and for determining contamination, thermal anomalies in materials, components or subsystems or systems without impairing their integrity or function. NDT is also utilized for real-time monitoring during measurement of properties such as hardness and internal stress and in-service monitoring of defect growth for determining the maintenance requirements and to assure the reliability and continued safe operation. NDT is becoming increasingly important in design-through-service phases and for quality management.

Innovations in NDT are coming up to meet the new challenges of materials and applications in aerospace. Advances in the use of lasers and imaging technology (both optical and thermal) have led to non-contact NDT for materials including composites and electronic and embedded systems. Quality of the information that may be obtained from new NDT methods is greatly enhanced because of the developments in digital signal processing techniques.

3.2 NDT Techniques in Aerospace

In aerospace, surprisingly, more than 50 percent of NDT is done by using visual tests. Quality control looks at various components for signs of damage at regular intervals. For example, during heavy overhaul, most of the interior of the aircraft is stripped out so that quality control can look for damage on the inside surface of the fuselage. However, not all areas of the aircraft can be accessed for visual testing and not all damage can be detected by visual means. This is where NDT plays a critical role in thoroughly inspecting airplanes.

NDT methods allow quality control of the aerospace systems that would otherwise be not possible without disassembling. NDT methods also allow detection of damage that is too small to be detected by visual means. Eddy current and ultrasonic testing methods are used extensively to locate tiny cracks that would otherwise be undetectable. These techniques are also used to measure the thickness of the skin from the outside and detect metal thinning from corrosion on the inside surface of the skin. X-ray techniques are used to find defects buried deep within the structure and to locate areas where water has penetrated into certain structure.

The success of the aerospace industry is highly dependent on NDT. Without NDT, the safety of flying would decrease. When people step into an airplane they trust that it will get them to their destination with as little turbulence as possible. NDT plays a vital role in keeping air travel one of the safest modes of transportation.

3.3 Accredited and Non-accredited NDT Methods

In India, commonly used accredited NDT methods in aerospace are Visual Testing (UT), Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), Eddy Current Testing (ET), Ultrasonic Testing (UT), Radiography Testing (RT) and Leak Testing (LT).

Liquid Penetrant Testing does detection and analysis of surface defects. It is a method that is used to reveal surface breaking flaws by bleed out of a colored or fluorescent dye from the flaw. This technique is based on the ability of a liquid to be drawn into a "clean" surface-breaking flaw by capillary action. Hence PT is applicable only for non-porous materials and it is applicable to detect even a very sharp surface cracks and their sizes may be the order of micrometer or nanometer level. In general, Penetrant Testing are more effective at finding (a) small round defects than small linear defects, (b) deeper flaws than shallow flaws, (c) flaws with a narrow opening at the surface than wide open flaws (d) flaws on smooth surfaces than on rough surfaces

(e) flaws with rough fracture surfaces than smooth fracture surfaces.

Magnetic Particle Testing is a cost effective and expedient NDT method for determining discontinuities in ferromagnetic materials. This method is useful for detection and analysis of surface and sub-surface defects such as cracks, laps, seams, and inclusions etc. This technique utilizes the principle that magnetic lines of force (flux) are distorted by the presence of a flaw in a manner that will reveal its presence. The flaw is located from the "magnetic flux leakage".

Eddy Current Testing uses the principal of "electromagnetic induction". The defects such as cracks are detected when they disrupt the path of eddy currents due to differential conductivity and permeability and weaken their strength. Hence this method is useful for detection and analysis of surface and sub-surface defects only for materials which posses electrical conductivity. The signal indications in various eddy current testing is done based on (a) impedance approach (b) phase analysis approach and (c) modulation approach.

Ultrasonic Testing is used for the detection and analysis of internal defects. In this technique, the beam of high frequency acoustic energy are transmitted into the material and the detection of flaw is based on the reflection or refraction or transmission of the signal due to difference in acoustic impedance exist at the site of discontinuity. Ultrasonic Testing uses contact and non-contact techniques (immersion method) and various types of probes and the scanning mechanism, which include A-Scan, B-Scan, C-Scan, D-Scan, S-Scan, etc.

Radiography Testing is used for the detection and analysis of internal defects. Here the higher level penetration power of X-rays and Gamma rays are utilized for detection of flaw due to their differential absorption at the site of discontinuity.

Although historically nondestructive techniques have been used almost exclusively for detection of macroscopic defects in structures, yet in aerospace, research has increasingly shown that it is practical to expand the role of nondestructive evaluation to include all phases of materials production. Some of the advanced NDT techniques used in aerospace are ultrasonic phase array, optical holography, X-ray computed tomography, X-ray Diffraction Imaging and infrared thermography.

Ultrasonic phased arrays are similar in principle to phased array radar, sonar, and other wave physics applications. Phased arrays use a collection of elements, all individually wired, pulsed and time-shifted. These elements can be a linear array, a 2-D matrix array, a circular array, or some more complex forms. Most applications use linear arrays, since they are the easiest to program.

Ultrasonic phased arrays are a relatively new method of generating and receiving ultrasound. Phased array testing is a specialized type of ultrasonic testing that uses sophisticated multi-element array probes and powerful software to steer high frequency sound beams through the test piece and map returning echoes, producing detailed images of internal structures.

Phased arrays offer significant technical advantages over conventional single-probe ultrasonics, such as, Electronic Scanning (for rapid coverage of the components), Beam Forming (for orienting the beam perpendicular to the predicted) defects, Beam Steering (for mapping of components at appropriate angles to enhance POD) and Electronic Focusing (for optimizing the beam shape and size at the expected defect location).

Holographic techniques can be used for nondestructive testing of materials (HNDT). There are two types of holographic techniques : Optical and Non-optical Holographic techniques. Non-optical Holography techniques include Acoustical, Microwave, X-Ray and Electron beam Holography.

HNDT essentially measures deformations on the surface, sub-surface and internally in metallic and composite specimens. In HNDT techniques, the test sample is interferometrically compared with the sample after it has been stressed (loaded). A defect can be detected in an object if by stressing it an anomalous deformation is observed around the defect.

Computed x-ray tomography (CT) permits retrieval of three dimensional information inside an object. To make a CT measurement, several radiographic image of an object are acquired from different angles, and the information collected by the detector is processed in a computer. The final three-dimensional image, generated by mathematically combining the radiographic images, provides the exact locations and dimensions of the internal features of the object. X-ray CT is the only nondestructive technique which can reveal the internal structure of these metals.

Active Infrared Thermography has emerged as a widely used method for nondestructive testing. It offers noncontact, wide area detection of subsurface defects, and can be used as an alternative or complement to conventional NDT techniques. IR thermography can be divided into two approaches, the passive approach and the active approach. The passive approach tests materials and structures which are naturally at different (often higher) temperature than ambient while in the case of the active approach, an external stimulus is necessary to induce relevant thermal contrasts. In both the approaches, abnormal temperature profiles indicate a potential problem.

Contrary to the passive approach, in the active approach, an external stimulus is required to generate relevant temperature differences not present otherwise. Depending on the external stimulus, different approaches of active thermography have been developed, such as pulse thermography (PT), step heating (SH), vibrothermography (VT). The active approach finds numerous applications in NDT.

4. Analyzing the Defects

First step of capturing the defects gives only the indication of the defect, however, analysis of the defects require the remaining steps too i.e. analyzing the defect, developing defect mitigation plan, and implementing defect mitigation plan.

Analysis and interpretation of data is a serious problem in NDT. It requires sound grounding in the NDT technique under use and test results should not be taken for granted.

4.1 Selection of NDT Technique

Generally, 90% Probability of Detection (POD) criteria may be used for selection of an NDT Technique. Basically in NDT process, it is quite often more than one test to be conducted for thorough testing of the part, based on the properties and geometry of the test part. Further, complex techniques are required for finding tight surface cracks and internal discontinuities.

Each NDT Technique on has its own limitations. The capability of an NDT Technique depends upon the inherent limitations of the technique or procedure used. For example, Ultrasonic Testing can not reliably detect discontinuities very near to the surface due to the erratic near field effects of the probe. On the contrary, Eddy Current Testing is not expected to reliably detect discontinuities more than a few millimetres below the surface. On the other hand, Magnetic Testing can detect both surface-breaking and volumetric discontinuities of sufficient size.

Though in many instances single NDT technique is sufficient to solve a problem, yet more than one technique may be employed. The additional information obtained, during the test is likely to enhance detection reliability. Further, we should distinguish between effectiveness and efficiency of NDT. Effective NDT finds all the required defects with the required POD. But an efficient NDT, in addition, avoids the unnecessary rejection of minor imperfections.

Indications obtained during NDT need to be interpreted and evaluated. Any indication that is found is called a discontinuity. Discontinuities are not necessarily defects, but need to be identified and evaluated against suitable criteria. Discontinuity could be a false or non or irrelevant indication. These indications should be properly interpreted, evaluated and sifted for relevant discontinuity.

4.2 Advances in NDT

In many types of NDT, the sensitivity of the technique depends upon the ability to distinguish the significant part of the signal from the general background due to electronic noise, or inherent background signal from the material being examined. With the power and speed of modern computers, signal processing methods and modelling numerical methods, remarkable developments took place in research on NDT techniques Significant improvements have been made both in the NDT equipment and in the specific techniques used . Thus, defects that may not have been revealed by NDT performed five or ten years may be detected by more sophisticated NDT equipment or techniques currently available.

The results of reliability studies indicate that the probability of detecting a defect with ultrasonics increases with the degree of sophistication of the system. (manual ultrasonics, without sophistication, can be expected to reject an equal or greater percentage of the discontinuities present than will radiography). Manual ultrasonic systems relaying on 20dB or 6dB drop are known to be inaccurate. The incorporation of computer assisted processing into ultrasonic systems has allowed the easy implementation of potentially better methods for defect detection and sizing such as TOFD.

4.3 Quality of NDT

Quality of an NDT operation is defined as its performance in unambiguously revealing and reporting defects of prescribed characteristics, without jeopardising the component's integrity and repeatability. This idea of Quality of NDT assists in identifying the key elements of the quality system for NDT. However, management commitment is very necessary, as in the final analysis, the ultimate quality is decided by the day-to-day performance and not by the theoretical capability of procedures, equipment, instruments or operators.

Quality assurance is the establishment of a program to guarantee the desired quality level of a product from raw materials through fabrication, final assembly and delivery to the customer. Quality control is the physical and administrative actions required to ensure compliance with the quality system. These functions include physical and chemical tests and non-destructive tests. Growing concern for product quality calls for this kind of quality system.

The important requirements for an effective quality system for ensuring reliable NDT are qualified operators using qualified procedures and qualified equipment and materials; proper supervision and surveillance of operators for minimization of human errors; objective evidence of test results in terms of records in proper media; quality walkthrough for re-examination of methods, audit, review of procedures and system; optimisation of the total organisation by focusing on customer needs, total participation, elimination of non value addition, continuous improvement, training and so on.

5. Developing Defect Mitigation Plan

Analysis or interpretation of the defects will identify the nature, type, size and severity of the defects. Based on this information defect mitigation plan may be formulated. It consists of corrective and preventive actions.

6. Implementing Defect Mitigation Plan

Defect Mitigation Plan consists of corrective and preventive actions. Based on this information corrective and preventive actions may be implemented. Corrective actions consist of repair and salvage actions. And preventive actions ensure that the defects are not repeated.

7. Conclusions

Defect analysis using Non-destructive Testing (NDT) is an expedient way for controlling defects in Aerospace Systems. Defect Analysis means identifying, locating, interpreting, evaluating and generating corrective and preventive actions. Defect Analysis in Aerospace consists of the following :

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First step of capturing the defects gives only the indication of the defect, however, analysis of the defects require the remaining steps too i.e. analyzing the defect, developing defect mitigation plan, and implementing defect mitigation plan.

Analysis and interpretation of data is a serious problem in NDT. It requires sound grounding in the NDT technique under use and test results should not be taken for granted. Quality of an NDT operation is defined as its performance in unambiguously revealing and reporting defects of prescribed characteristics, without jeopardising the component's integrity and repeatability.

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