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MILITARY HANDBOOK

NONDESTRUCTIVE ACTIVE TESTING TECHNIQUES FOR STRUCTURAL COMPOSITES

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FOREWORD

1. This military handbook is approved for use by all Activities and Agencies of the Department of the Army and is available for use by all Departments and Agencies of the Department of Defense.

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data that may be of use in improving this document should be addressed to: Commander, US Army Armament Research, Development, and Engineering Center, ATTTN: SMCAR-BAC-S, Picatinny Arsenal, NJ 07806-5000, by using the self-addressed Standardization Document Improvement Proposal (DDForm 1426) appearing at the end of this document or by letter.

3. This handbook was developed under the auspices of the US Army Material Command's Engineering Design Handbook Program, which is under the direction of the US Army Management Engineering College.

This handbook should serve as a guide to designers concerned with the technology associated with the nondestructive testing of advanced composites. It deals with the basic concepts of nondestructive testing and the specific tests that can be used at various stages during production and in-service inspections. The data can be used by designers to aid in selecting the nondestructive test equipment best suited for a particular application.

It is hoped that an understanding of the various available nondestructive test concepts will enable even the cautious designers of Army material to make use of the many advantages of advanced composites in designing reliable, durable, and maintainable components.

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LIST OF ABBREVIATIONS AND ACRONYMS

AE = acoustic emission
AMS = Aerospace Materials Specifications
ASTM = American Society for Testing and Materials
CRT = cathode-ray tube
DIN = Deutsches Institute for Normung e.u.
EDAX = energy-dispersive X ray
ISO= International Organization for Standardization
NASA = National Aeronautics and Space Administration
NDE = nondestructive evaluation
NDI= nondestructive inspection; nondestructive investigation
NDT = nondestructive testing
NTIAC = Nondestructive Testing Information Analysis Center
PAN = polyacyrlonitrile
PMR= polymerization of monomer reactants
RP = reinforced plastics
SAE = Society of Automotive Engineers
SAMPE = Society for the Advancement of Materials and Process Engineering
SEM = scanning electron microscope
SMC= sheet molding compounds
SNDT = shearographic nondestructive testing
SPI = Society of the Plastics Industry
SQUINT = Surface Quality Unit for Inspection by Nondestructive Testing
STEM = scanning transmission electron microscope

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CHAPTER 1

INTRODUCTION

The purpose and scope of this handbook are discussed. The term composite materials is defined, and the roles of components of these materials—reinforcements, glass fibers, graphite fibers, aramid fibers, and polymeric matrices—are discussed. Solid laminates and sandwich constructions are discussed and discussed.

1-1 PURPOSE

The purpose of this handbook is to educate the reader as to the nature of nondestructive testing of fiber-reinforced polymeric materials. Metal-matrix composite materials are another subject and will not be addressed here. The intent is to advise the reader about the various techniques available for use during the inspection of the raw materials and incoming component materials, for inspection during fabrication, and for final inspection and in-service monitoring to detect damaged and/ or degraded structures.

1-2 SCOPE

Nondestructive testing is the testing of materials or structures without causing failure of the item being tested. There are three acronyms that are in general usage: nondestructive testing (NDT), nondestructive evaluation (NDE), and nondestructive inspection (NDI) (or nondestructive investigation (NDI)). These terms are used by various authors to describe the same basic types of testing. NDT is the more general term, NDI (inspection) is preferred by the quality control engineer, and NDE and NDI (investigation) are preferred by the research scientist.

This handbook briefly describes the materials of interest, namely, the organic or polymeric matrix-fiber-reinforced composites. The various nondestructive techniques available are described in a manner that outlines the techniques, However, this handbook is not intended for use as an operator's manual for the techniques discussed.

This handbook covers the testing that can and should be carried out on (1) incoming materials, such as prepregs, resins, and fibers, to help build quality assurance into the subsequent parts, (2) the types of tests that can be used during fabrication and on the final product, and (3) in-service use of NDT. In-service use of NDT covers the problems related to in-service testing in evaluating such properties as reliability. durability, and life expectancy of a fiber-reinforced composite by nondestructive means.

Further, an attempt will be made to alert the reader to new and promising techniques that are being developed.

1-3 DEFINITIONS

1-3.1 COMPOSITE MATERIALS

Composites are defined as material systems consisting of two or more constituents, each of which is distinguishable at a macroscopic level. The constituents retain their individual identities in the composite and are separated by a detectable interface. Generally, one of the constituents acts as a reinforcing agent, and the other serves as the matrix or binder. The properties of the composite material are derived from the combination of the properties contributed by the constituents but modified by their synergistic effects.

The composite materials of interest in this handbook will be limited to polymeric matrix materials with "advanced" high-modulus or high-performance reinforcements. The reinforcements will include fiberglass, graphite, and aramid fibers in continuous or discontinuous forms. Boron filament, due to its limited use, will not be discussed. The type of composite structures considered will include solid laminates and sandwich constructions.

A solid laminate is a product made by bonding together two or more layers of material. The layers may be oriented in various configurations with respect to the orientation of the fibers in order to obtain the most desirable properties. This will be discussed in further detail in par. 1-3.2.1.

A sandwich structure is made up of two outer skins of composite laminate or other material, such as metal or wood. These skins are bonded to an internal structural material, such as honeycomb, foam, or, more recently, other configurations such as waveformed composites (Ref.1) or tubular structures bonded together in a form similar to honeycomb. Sandwich structures will be discussed in more detail in par. 1-3.2.2.

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1-3.1.1 Reinforcements

1-3.1.1.1 Glass Fibers

In the United States fiberglass generally implies either E-glass (a lime-alumina-borosilicate glass) or S-glass (a silica-alumina-magnesia glass) fiber and is produced as a continuous monofilament bundle by drawing molten glass through a multihole bushing. The size of the holes will determine the diameter of the fiber. The monofilament bundles can then be prepared in different forms such as rovings, multifilament strands, and woven and nonwoven fabrics. A detailed discussion of these materials is given in Ref. 2, and there are numerous reports in the literature on fiberglass. Specific sources are the annual conferences of the Society of the Plastics Industry (SPI), the Society for the Advancement of Materials and Process Engineering (SAMPE), as well as Refs. 3 and 4.

1-3.1.1.2 Graphite Fibers

Most military and aerospace applications requiring high-performance graphite fibers use fibers produced by the pyrolysis of polyacrylonitrile (PAN) fibers under tension at temperatures of 1760 -2760°C (3200-5000° F) in a controlled atmosphere. The properties of the fibers are a function of both the tension and the temperature used during pyrolysis. Graphite fibers are used in a wide range of applications, some of which include aircraft structural components, satellites, missiles and armament components, X-ray equipment, various automotive applications, and sports and recreational equipment. More information on graphite fiber can be found in Refs. 2 and 5.

1-3.1.1.3 Aramid Fibers

Aramid is a generic term denoting a class of polyamide materials. The aramid fibers are produced by conventional textile spinning methods. Kevlar aramid fiber and Nomex aramid paper are two materials in this class. Kevlar 49 is the principal aramid fiber currently used in composite applications. However, recent developments in armor applications are finding a place for Kevlar 29 fibers in composites as well. Aramid fibers are used in composite applications because of their outstanding combination of low density, high strength and high stiffness. The versatility and durability of these fibers, combined with their desirable properties, have design engineers turning to aramid fiber composites in many applications requiring light weight, high strength, and durability. The designer should be careful, however, not to use these composites in applications that will experience high or sustained compressive loads. Many papers have been published on the use of aramid fibers in composites; specific sources are the conferences and journals of SAMPE and Refs. 6, 7, and 8.

1-3.1.2 Matrix Materials

The principal matrix materials used in composites are epoxy, polyester, and vinyl ester resins. These are followed by phenolics, polyamides, and silicone resins, which are generally used in specialty applications. Thermoplastic resin systems, such as polysulfone and polyarylsulfone (Ref. 9), have been used to fabricate high-performance composites, More recently, systems such as the bis-maleimides (Ref. 10), phenyladimides, polymerization of monomer reactants (PMR), polyamides (Refs. 11, 12, and 13), and polyphenyl sulfides (Ref. 14) have been evaluated for fabricating composites with special mechanical and thermal properties. Many other papers have been published on the evaluation of matrix materials for organic composites; specific sources are the conferences and journals of SAMPE and Ref. 2.

The polymeric matrix material used in composites has, as its principal role, the responsibility of absorbing and transmitting loads to the reinforcement fiber. However, secondarily, the matrix material also controls many other properties. such as the viscoelastic behavior, creep, stress relaxation, and in-plane and interlaminar shear. The chemical, thermal, electrical, and environmental aging characteristics (Ref. 15) of the composite are also properties that are controlled by the matrix material.

The matrix material and the fiber material used to fabricate a composite do not generally play a large part in the selection of the nondestructive testing technique used to inspect the final part. However, the orientation or structural shape may influence the interpretation of the results obtained.

1-3.2 CONSTRUCTION

1-3.2.1 Solid Laminates

Composite materials are generally used in the form of solid laminates, which may be fabricated in either sheet or molded form and are made by bonding together two or more layers of material. In structural composites the materials bonded together to form the composite consist of fibers of reinforcement, as described in par. 1-3.1.1. These fibers may be oriented in various configurations and may vary in size and shape. Among the various forms of fibers used to fabricate solid laminates are rovings or strands, chopped fibers, reinforced mats, and woven and nonwoven fabrics. The various forms are explained in detail in Ref. 2. Laminates are generally formed by use of wet lay-ups or prepregs. The *wet lay-up method* involves the application of the matrix material to the dry reinforcement at the time of the buildup of the part to be fabricated. Care must be taken to insure that the reinforcement material is thoroughly wetted out by the matrix material and that no air is entrapped in the composite because this will result in

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voids. Prepregs are preimpregnated combinations of the reinforcement and the matrix materials in a condition ready for fabrication; they are available as woven or nonwoven fabrics, unidirectional tapes, mats, and rovings coated with the various matrix materials. All of the important reinforcing materials, including fiberglass, graphite, and the aramids, can be prepreged. The detection of defects in composites by NDT may be affected by the form and makeup of the laminate.

1-3.2.2 Sandwich Construction

Sandwich construction consists of two or more laminates of different (dissimilar) materials bonded together with an adhesive, as shown in Fig. 1-1.

The outermost skins (laminations), made up of solid laminate, furnish the strength and stiffness properties of the construction. The inner core separates the skin and prevents buckling of the skin when loaded. The inner lamination or core material may be made of a number of materials, such as honeycomb core, as shown in Fig. 1-1, or foam, wood, composite waveformed material, or bonded composite tubes. Sandwich construction is strong, stiff, and lightweight. It may be flat, simple curved, or compound curved. Because of these useful properties and the ability to form many shapes, the design engineer may choose sandwich construction for many military systems. A basic discussion of bonded sandwich construction is given in Ref. 16,

When selecting the NDT method for inspection, it is important that the quality control engineer be aware of the type of core material that is in the sandwich construction since the type and configuration of the core will affect the type of test method to be selected. The transmission of the signal into the sandwich and the interpretation of the signal response may vary with each type of core material

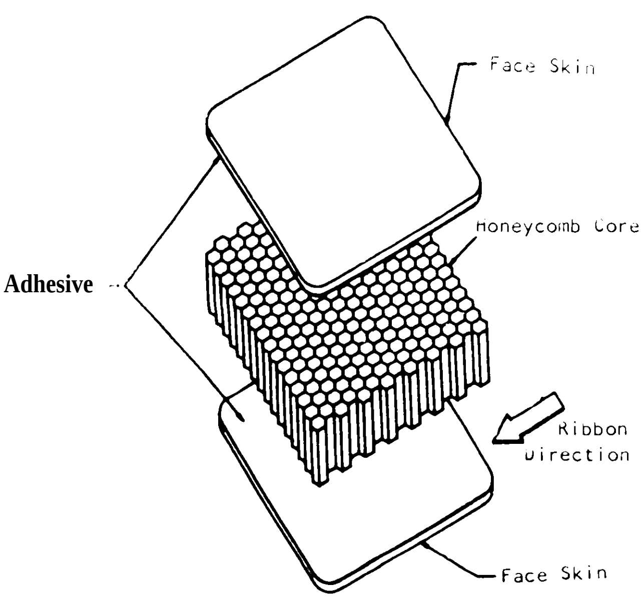

Figure 1-1. Typical Sandwich Construction (Honeycomb)

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CHAPTER 2

NONDESTRUCTIVE TESTING TECHNIQUES: AVAILABILITY AND LIMITATIONS

An overview is presented of the various nondestructive testing techniques that are available for evaluating structural composites with the goal of building in reliability, durability and maintainability. The use of visual, optical, ultrasonic, acoustic, radiographic, thermal, and mechanical methods of inspection is discussed.

2-1 INTRODUCTION

The intent of this chapter is to introduce the various nondestructive testing techniques that are available to the engineer to help build reliability, durability, and maintainability into composite structures. Various concepts of nondestructive testing are discussed in generalities to attempt to describe the techniques and their limitations. However, the detailed nondestructive procedures for the various methods will not be included. Nondestructive testing (in some cases nondestructive inspection might be a more appropriate term) can and should cover the complete range of operations from the raw materials through fabrication to final inspection to in-service inspection.

Some of the areas that the engineer should consider include

1. Chemical analysis
2. Processability evaluations
3. Cure control and monitoring
4. Nondestructive testing
5. Proof testing
6. In-service reliability evaluations.

The first two are techniques that are not nondestructive in nature because they require the removal of a sample of the material and, therefore, will not be discussed in this chapter. However, these techniques should be given serious consideration to insure that the proper raw materials are used. Discussions of these techniques are well presented in Refs. 1 and 2. Ref. 1 also presents a cross reference to the American Society for Testing and Materials (ASTM) and the Deutsches Institute for Normung e.u. (DIN) tests for many of the techniques. Cure control and monitoring, proof testing, and in-service reliability evaluations are covered in Chapter 3.

2-2 DISCUSSION OF NONDESTRUCTIVE TEST TECHNIQUES

The nondestructive test (NDT) techniques used to evaluate composite materials include

1. Visual NDT
2. Optical NDT
3. Ultrasonic NDT
4. Acoustic NDT
5. Radiographic NDT
6. Thermal NDT
7. Mechanical NDT.

Combinations or adaptations of these techniques may also be effective in the inspection of composite materials. Each of the techniques is discussed in the paragraphs that follow.

2-2.1 VISUAL NDT

Visual NDT is one of the most important and simplest forms of inspection. It is the observation of the material or product to detect gross imperfections or defects. The visual technique is used to determine that the proper materials are used and involves reading of the identification label on the raw material; observation of the gelation and cure of the matrix material; physical measurement for size, shape, and flatness; and observation of visible defects or delaminations. This technique is operator interpretive but of such significant value that the operators should be trained to know what they are looking for and what any variation might mean to the reliability of the final product.

When adhesive bonding is used in conjunction with composites, visual inspection often can aid in detecting porous adhesive fillets, lack of filleting, lack of adhesive, edge voids, and lack of or incomplete cure of the adhesive.

Discussions of visual inspection can be found in Refs. 3 and 4.

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2-2.2 OPTICAL NDT

2-2.2.1 Microscopy

Optical methods such as the optical microscope, the scanning electron microscope (SEM), and the scanning transmission electron microscope (STEM) often are valuable research tools to study the mechanisms of adhesion of the fibers and the matrix materials, surface analysis, and failure analysis. However, in general, these instruments are of little or no value as nondestructive tools to be used in the production control of composite materials or structures. Kaelble (Ref. 1) points out that the scanning electron microscope with energy-dispersive X ray (EDAX) is an excellent tool for such evaluations as coating durability, surface coating uniformity, fiber curvature, and thickness uniformity in evaluating surface characterization methods for reinforced fiber coating. The limitations to this method include the loss of volatiles during test and the small size of the sample studied. The method may cause charging of the sample surface and generally requires metallized coatings.

The optical microscope requires very little sample preparation, can scan large areas, and photographic attachments can record color and birefringence. However, this microscope is limited by its low resolution (approximately 1μm ($3.9X10^{-5}$in.)), by its depth of focus at the higher magnifications, and by its inability to resolve curved surfaces.

2-2.2.2 Holography

Holography is a system that is capable of storing three-dimensional information on a two-dimensional recording plane for future observation in the original three-dimensional form. The system uses a process known as the interferometric process. This process records the intensity pattern, which is related to the amplitude and phase of the light waves reflected from the object under study. The recorded pattern is called a *hologram*. The image is reconstructed from the hologram by a process during which the hologram is illuminated with monochromatic, coherent light. The hologram diffracts the light into waves that are indistinguishable from those that were reflected from the original object.

Holography was first developed in 1948 by Gabor (Ref. 5). Interferometric holography is a technique of detecting minute surface deformations induced by stress by comparison of each point on the surface before and after stressing. The surface deformations are examined in the holographic reconstruction as a means of interpreting the structural integrity of the component. The application of stress to study defects in composite laminates is generally accomplished by either acoustic or thermal means. Holographic NDT is limited by size, cost, and the complexity of the equipment required. Isolation tables capable of isolating all vibrations are required to insure that any movement on the surface of the item under study is that induced by the applied stress. Furthermore, the fringe pattern produced can be extremely complex, and it is questionable whether it is possible to detect all of the important defects with reliability and repeatability. There have been numerous reports published on holographic nondestructive testing; some of these are given in Refs. 6 through 11.

2-2.3 ULTRASONIC NDT

Ultrasonic nondestructive testing uses a pulsed ultrasound at 2.25 to 10 MHz. The ultrasonic methods generally are divided into immersion and contact techniques, and these can be further subdivided into immersion through transmission or immersion-reflector plate, and contact through transmission or contact-pulse echo. These methods may be further refined or automated to produce visual recordings of the defects by using C-scans. The reflector-plate techniques are easier to use than the pulse-echo technique when attempting to produce C-scan recordings of flat laminate surfaces. Special equipment is required for large panels. Contour followers are needed for contoured parts and special squirters are available for parts that cannot be immersed into a water tank. These squirters are described in Chapter 3. The ultrasonic methods are adversely affected by destructive wave interference, which is caused by varying adherend, or adhesive, thickness. Destructive wave interference may cause an appearance of voids in a structure where there are none. Further discussion on ultrasonics can be found in Ref. 12.

Modification of the ultrasonic techniques includes systems that operate on the principle of resonance impedance. In these systems an ultrasonic transducer is coupled to the part by use of a liquid coupling agent. The instrument is calibrated to respond to a shift in frequency and amplitude or only to amplitude shifts. These instruments will respond to flaws, bond failures, and sometimes to porosity. The limitations of this type of equipment are that the part being tested must be manually scanned and manually marked to identify the defect areas and that recorded information from this type of equipment is not easily obtained. Another modification of the ultrasonic technique is the eddy-sonic harmonic system. This system combines the principles of eddy current and ultrasonic testing. The eddy-sonic method does not require a liquid couplant and is generally limited to metallic structures. However, a modified probe, which mechanically excites the laminate over a bond failure or delamination, has been developed and will detect many such defects in a composite structure. Relatively little training is required to use this system. Further discussion on these modified systems is given in par. 2-2.7.2 and in Chapter 3.

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Other information on ultrasonic testing is given in Refs. 13, 14, and 15.

2-2.4 ACOUSTIC NDT

2-2.4.1 Acoustic Emission

Acoustic emission is a term used to describe elastic stress waves produced in solids as the result of the application of stress. The waves are produced by the rapid release of energy within the material. In fiber-reinforced composites the acoustic emission is generated by cracking of the matrix, debonding of the matrix from the fibers, lamination separation, fiber pullout, or breakage of the fibers (Ref. 16). The acoustic-emission technique listens to the different sounds made by a structure under stress. Silence is the indication of a good sound structure, i.e., the more pops and cracks detected, the more the structure has degraded (Ref. 17). This technique shows great promise as a technique for testing composite structures. both for new fabrication and for in-service use. The technique is used in field testing of composite pipes, tanks, bucket trucks, and in various aerospace applications.

The stress applied to the structure to cause the material to emit acoustic emissions (stress waves) is generally accomplished by applying a mechanical force such as bending, tension. or torsion to the item. A second method uses thermal stressing. The expansion of the composite structure caused by the application of heat is enough to induce the required stress. This often can be accomplished by use of a hot-air gun. Detailed discussions on acoustic-emission nondestructive testing can be found in Refs. 18 and 19.

2-2.4.2 Acousto-Ultrasonics

The technology of acousto-ultrasonics or ultrasonic-acoustics was developed by National Aeronautics and Space Administration (NASA)-Lewis Research Center to evaluate the subtle defects in composites (Refs. 20 through 24). Finding defects, delamination. and other discontinuities in fiber composites, although important, was not a problem since many techniques were available to address these areas. However, Vary of NASA-Lewis realized that it also was necessary to know how defects interact within the microstructural environment in the composite. If this were known, it would be possible to predict how serious or how critical a defect might be. The ability to evaluate strength loss after use was of particular importance. especially in composites where moisture absorption and fatigue can cause a loss in strength. Acousto-ultrasonics has opened the door to these and other new areas of nondestructive testing.

The principle behind acousto-ultrasonics, as described by Green, *et al.* (Ref. 19), is that "... a broadband pulser transducer imparts a repeating series of ultrasonic pulses to the material. Each of these pulses interacts within the material along its path. The modified stress waves then have superimposed the stress wave forms which would be produced by actual acoustic emission events as if the material were stressed and experienced local microcracking. The modified stress waves thus contain the energy and frequency content of stress wave emissions due to the actual microcracking in the material.". A receiving transducer from the acoustic emission equipment is coupled to the surface through a waveguide that transmits only longitudinal components of the wave and separates the received signal from the input pulse, which makes it possible to analyze the results.

Acousto-ultrasonics has been proposed as a means of indirectly measuring the interlaminar shear strength of fiber-reinforced composites (Ref. 25). The method has been used to inspect honeycomb panels and other complex laminated structures. Work is going on to study adhesive bond strength (Ref. 1) and bond degradation. This concept will be discussed further in Chapter 3.

2-2.5 RADIOGRAPHIC NDT

Radiographic nondestructive testing is the technique of producing a picture on a sensitive surface by a form of radiation other than light. The most widely known form of radiography is the X ray. Other forms of radiographic nondestructive testing are fluoroscopic radiography, neutron radiography, and gamma radiography. Each of these techniques is discussed in the paragraphs that follow.

2-2.5.1 X-Ray Radiography

X-ray radiography is effective for complex geometries that are difficult to inspect ultrasonically. However the method must be enhanced by the use of X-ray-opaque materials. The method can be used to detect water intrusion into honeycomb structures (Ref. 26), cracks, fiber orientation, porosity, inclusions, splice flaws, and crushed core (Refs. 12 and 27).

2-2.5.2 Fluoroscopic Radiography

Fluoroscopic radiography is real-time viewing of X-ray radiography. This technique has been reported useful for testing of composite materials, molded plastics, and bonded panels (Ref. 28). This technique has the same limitations as X-ray radiography but has the advantage of being in real-time, and it is a useful in-line inspection technique that will be discussed further in Chapter 3.

2-2.5.3 Neutron Radiography

Neutron radiography is particularly useful when components are not X-ray opaque. The hydrogen atoms in water and in organic materials are neutron opaque and

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hence can be imaged to detect defects or water intrusion. Metallic components are not neutron opaque, and for this reason, this technique is very useful for inspection of adhesive bonds or organic matrix materials which are hidden by large metallic components (Refs. 26, 28, and 29).

2-2.5.4 Gamma Radiography

Gamma radiography is similar to X-ray radiography. but at this time it has not been widely accepted. The gamma rays are obtained from radioactive isotopes such as cesium 139, cobalt 60, iridium 192, and thalium 70. Gamma radiography is generally used to measure properties such as fiber content and resin content (Refs. 30 and 31).

2-2.6 THERMAL NDT

Thermal nondestructive testing uses the patterns of surface temperature to detect nonuniformities below the surface. These patterns can be used to estimate the characteristics of the nonuniformities and to predict the resultant behavior or serviceability of the material. Cholesteric liquid crystals can be used for displaying variations in surface temperatures because these crystals will change color according to their temperature and formulation. Liquid crystals can be formulated so that the color change range can be regulated to the particular need. The color change can be regulated from –20 to 250°C (–4.0 to 482°F) with temperature resolutions of 0.1°C (0.05°F) within a given range. Furthermore, the color transition response time can be as low as 0.1 s. Ref. 32 describes the use of thermal nondestructive testing (liquid crystals) to evaluate a wood-stiffened composite for defects such as composite-to-wood debonding, laminate voids or inclusions, uncured matrix, composite-to-composite debonding, and cracks. Ref. 33 describes the use of liquid crystals to evaluate cracks of various types, early indication of damage, and inclusions. Other publications on thermal nondestructive testing are covered in Refs. 34, 35, and 36.

Vibrothermography involves the use of a low-amplitude mechanical vibration to induce localized heating in the composite and real-time thermography to record the resulting heat patterns. Heat generated by the vibrations is preferentially located around the damaged area and rises to the surface. The temperatures are measured with infrared computer-generated thermographs of the damaged areas (Refs. 37, 38, and 39).

2-2.7 MECHANICAL NDT

2-2.7.1 Tap Test (Coin Tap)

In the tap test the surface of the structure is tapped by hand, using a hard blunt object such as a tapping hammer or a coin. Voids and blisters sound hollow in comparison with a sound area. However, dents. crushed core, or an adhesive-filled area of core may be mistakenly identified as a good area when tapping inspection is used (Refs. 39 and 40). This method is very often used as the first inspection method, which is then followed by one of the other, more defining. techniques.

2-2.7.2 Mechanical Impedance

The mechanical impedance technique is based upon the excitation of the surface of the structure with a relatively low-frequency mechanical vibration and the measurement of the response. The excitation may be accomplished by a variety of means such as a vibrating pin or tapping probe, ultrasonically induced vibrations. or by piezoelectric excitation. The response to the vibration can be measured as either amplitude and phase shifts or as amplitude and frequency changes. Some mechanical impedance instruments require the use of a couplant, but the others do not and are described as dry coupling instruments. These techniques can detect skin-to-skin bond failures or voids. delamination, interlaminar porosity and crushed core. The theory behind this type of testing is given in Refs. 4 and 12, and the techniques are further discussed in Ref. 41.

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CHAPTER 3

APPLICATION OF NONDESTRUCTIVE TESTING

Quality control of advanced composite structures includes all stages from design to in-service inspection. A concept of quality control is presented and the methods and equipment available for the control of incoming materials during fabrication testing of prepregs, sandwich construction and adhesive bonding, end-item inspection, and final and in-sevice testing are discussed. New developments in nondestructive testing techniques for the various stages are also discussed.

3-1 INTRODUCTION

Quality control of advanced composite items must start early during the design phase. Many organizations form teams that consist of design engineers, engineers familiar with materials and production processes, and specialists in nondestructive testing (NDT) and destructive testing and failure analysis. This concept is shown graphically in Fig. 3-1. Only through close teamwork and exchange of data among disciplines can structural reliability be assured. The design engineers design the item to meet the user criteria. The materials and production process engineers are required to develop the specific data required to select the most appropriate materials and the best processes to do the job. The nondestructive test engineer sets up the NDT requirements to insure that the structural integrity that was designed into the part is actually there and that no defects that would affect the integrity of the part are present. The destructive test and failure analysis engineers work with the team to determine where the weak points in the structure are and where redesign is required.

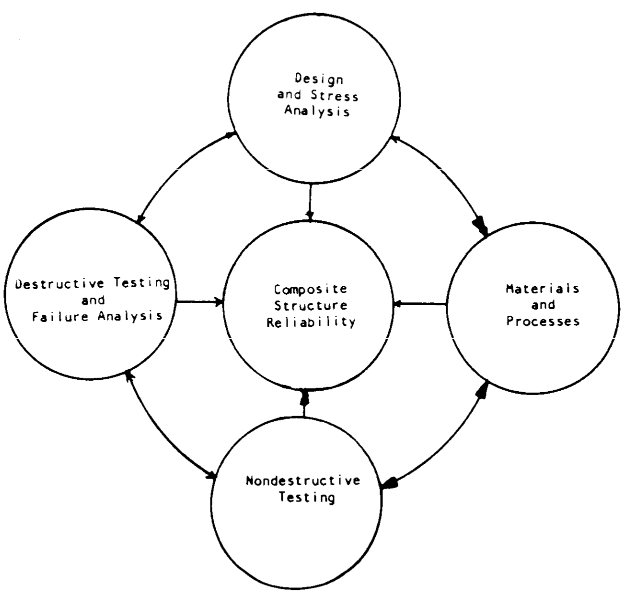

Figure 3-1. Design Team Concept for Structure Reliability

A nondestructive testing policy should be established for all advanced composite structures that are to be built. The intensity of the policy should be determined by the criticality of the item being built.

Collins (Ref. 1) outlines an NDT policy for the inspection of composite structures. The concept of the policy is

1. The purpose of NDT shall be to detect voids, delaminations, or major porosity.
2. Strict process controls supported by select in-process inspection are required.
3. The NDT engineering team shall coordinate its activities for specific development programs.
4. All structures shall be subjected to NDT.
5. Calibration standards with designed-in defects shall be provided for the nondestructive testing.
6. Defect allowable shall be determined.
7. The NDT engineer shall specify the design and fabrication of the defect standards.
8. Only proven NDT methods shall be used.
9. Written NDT procedures shall be required for all production programs.

Vary (Ref. 2) graphically depicts the interplay of the principal activities that are related to structural reliability. He further points out that nondestructive testing is an important link in the design-production-inspection system. As pointed out by both Collins and Vary, nondestructive and destructive testing both play important roles in the overall plan for a well-designed, quality-controlled, reliable product.

Raw materials must be tested and standards established, cure cycles must be established and monitored, and resin and curing agent purity and specific requirements must be established. Refs. 3 through 6 describe testing of resin systems and prepregs for use in reinforced composite production. Kausen (Ref. 7) describes

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the concept of fiber areal weight as a practical manufacturing and quality control for composite laminates. The fiber areal weight is a function of the ply thickness, the resin weight fraction, and the laminate density. Ref. 8 describes overage indicators for prepreg materials, and Ref. 9 discusses the need for quality assurance material testing for glass-fiber-reinforced thermoplastic molding. The various test methods described in the papers in Ref. 8 are of value to determine and describe the properties of the resins, prepregs, and composite components, but they are not nondestructive.

Nondestructive test methods are generally used to detect defects in the structure. The defects must be defined and defect allowable must be evaluated and established. The major defects that might occur in a fiber-reinforced composite structure are

1. Contamination—the inclusion of foreign matter
2. Damaged fibers-broken filaments, knots, or splicings in the roving or fabric yarns
3. Delamination—the separation of the plies within a laminate
4. Density variations—variations associated with resin fraction variations, porosity, and voids
5. Fiber misalignment—the disorientation of the fabric or filaments, the deviation from a predetermined lay-up or filament-winding pattern, or washout of the fiber caused by excessive resin flow
6. Flow lines—local waviness of the surface due to fiber orientation or low mold temperature
7. Moisture pickup—excess moisture that is not normal within the resin or reinforcement
8. Porosity—accumulation of open or closed macroscopic or microscopic bubbles
9. Resin fraction variations—resin-rich and resin-starved areas over the surface of the laminate brought about by variations in the prepreg resin content, or by improper resin bleed out during vacuum-bag curing, or by variation due to flow conditions in short-fiber molding
10. Sink marks—caused by nonuniform shrinkage during molding due to uneven temperature in the mold halves or to insufficient pressure
11 Thickness variations—normally associated with variations in the resin content of the laminate and often inherent in open-mold processing
12. Unbends or disbonds (bond failures)—the separation of an adhesive bond or of the facing from the core in a sandwich structure
13. Voids—the entrapment of air or other volatiles that may be present in the resin system. These may be either macroscopic or microscopic and may be either localized or distributed through the laminate.
14. Warpage—the uneven shrinkage caused by uneven mold temperatures or by orientation caused by long flow paths in a mold
15. Washout—the abnormal fiber displacement during molding caused by excessive resin flow.

The design engineer and the NDT engineer must determine the importance of the defect based upon the frequency of occurrence, size and location, and effect on the properties of the laminate or structure. Only those defects that will adversely affect the performance should be considered nonacceptable. Therefore. the acceptance criteria will depend upon an analysis of the defects. It must be remembered that to insist upon the removal of all defects will result in excessive cost without necessarily increasing reliability, durability, or maintainability.

3-2 INCOMING MATERIALS

The incoming materials generally can be itemized to include reinforcements, matrix materials, prepreg materials, adhesives, core materials, laminates or moldings, and subassemblies. The basic raw materials such as reinforcements, matrix materials, and prepregs should be purchased in compliance with military or other specifications. There is an increasing tendency to move toward the consensus-type specifications, which are prepared by organizations such as the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE). SAE has prepared a group of specifications designated as Aerospace Materials Specifications (AMS). These consensus specifications cover a wide range of subjects and often replace the military specifications if both are considered to be equal. A list of specifications and standards covering nondestructive testing is given in Appendix A.

A list of some material specifications covering incoming raw materials is given in Table 3-1.

Components such as laminates, moldings, and subassemblies may be inspected by simple procedures consisting of dimensional and tolerance measurements, weight and density determinations, cure determinations by hardness measurements, visual examination for defects, and tapping for void determinations. If the integrity of the subassembly warrants a more complete inspection, this can be accomplished by using the various nondestructive testing techniques discussed in Chapter 2. However, nondestructive testing will, in general, add to the component cost and should be used only when warranted on critical applications. Some of the defects that can be detected by nondestructive testing are given in Table 3-2.

The adhesives used to assemble composite structures should be checked to determine that they are within the required shelf life for that particular adhesive. Adhesives stored for any period of time should be used on a first-

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TABLE 3-1
CONSENSUS SPECIFICATIONS FOR INCOMING MATERIALS

Specification No.	Topic
AMS 3616A	Resin, Polyimide, Laminating, and Molding
AMS 3671	Plastic Molding Compound, Novolac Epoxy, Short-Glass-Fiber Reinforced
AMS 3687A	Adhesive, Film, for Sandwich Panels
AMS 3823C	Fabric, Glass Cloth, Style 7781
AMS 3828A	Glass Roving, Epoxy-Resin-Preimpregnated
AMS 3832A	Glass Roving, Type-S Glass, Epoxy-Impregnated
AMS 3894C/1-9	Graphite Fiber, Tape and Sheet, Epoxy-Impregnated
AMS 3899	Graphite Fiber, Tape and Sheet, Polysulfone-lmpregnated
AMS 3906/1-7	Glass, Nonwoven Fiber, Tape and Sheet, Epoxy-Resin-Impregnated
ASTM E 865	Adhesive, Structural Film
ASTM E 990	Adhesive, Core Splice

TABLE 3-2
DEFECTS DETECTED BY VARIOUS NDT METHODS

Defect \ NDT Technique	X-Ray Radiography	Neutron Radiography	Gamma Radiation	Ultrasonic	Infrared Scanning	Heat-Sensitive Agents	Liquid Penetrants	Acoustic Emission
Unbond	X			X	X			X
Delamination	X[1]			X	X		X	X
Undercure				X		X		
Fiber Misalignment	X	X	X					
Damaged Filaments	X						X	X
Resin Variation		X						
Thickness Variation	X		X	X				
Density Variation	X		X	X				
Voids	X		X		X		X	X
Porosity	X		X	X			X	X
Fracture	X		X	X			X	X
Contamination	X		X	X				
Moisture	X	X						

[1]If oriented parallel to X-ray beam

in, first-out cycle. Adhesives that have exceeded the recommended storage life may, in some cases, be recertified by the quality control laboratory, but this recertification requires strict controls. These controls might include strength tests, gel and cure rate determinations, and flow characterization. Recertified adhesives must be used within a short time after recertification.

It is very important that frozen adhesives be allowed to stabilize at room temperature in the sealed wrappings to prevent moisture condensing on the surface of the adhesive. Rolls of adhesive generally should be removed from the cold storage and kept in their sealed wrappings at least 12 h prior to use. If samples have been cut and replaced in cold storage, shorter stabilization times may be used. The quality control laboratory should establish minimum stabilization times for these samples depending upon the size and volume of the sample package.

Core materials. especially the nonmetallic cores, such as the phenolic-impregnated kraft and Nomex paper honeycombs and the various polymeric foams, should be checked for moisture content and dried prior to use if their moisture contents are above the standards established in the processing specification.

Most new developments in the testing of incoming raw materials are in the area of chemical quality assurance testing, processability testing, and cure monitoring. The data obtained in these areas will be fed into computer-aided design and manufacturing programs, along with nondestructive inspection and in-service history data, to predict structural safety margins and composite durability and reliability.

3-3 DURING FABRICATION NONDESTRUCTIVE TESTING

3-3.1 SOLID LAMINATES

Once the raw materials have been certified as performing to the standards set forth, the next step is to require control and monitoring of the lay-up and curing of the composite. The control of the lay-up is generally done by use of well-trained and certified personnel. The monitoring of the cure may use various methods, which will be discussed in par. 3-3.1.2.

3-3.1.1 Control of Prepregs

In applications where the control of the thickness or weight per unit area is very critical and continuous control is required, gamma backscattering gages can be used for on-line inspection. Fig. 3-2 shows a gamma backscatter thickness gage.

The theory of operation of the gamma backscatter technique is based upon the Compton Photon Backscatter Principle. The system uses a small, radioactive isotope in the sensing probe, which emits low-energy gamma rays that are collimated and beamed at the

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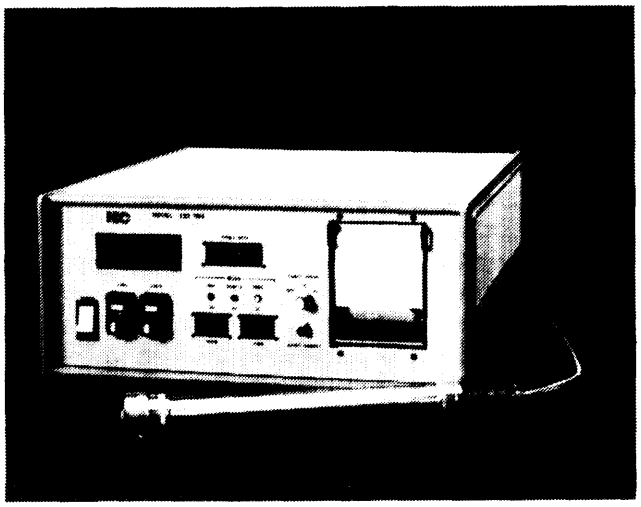


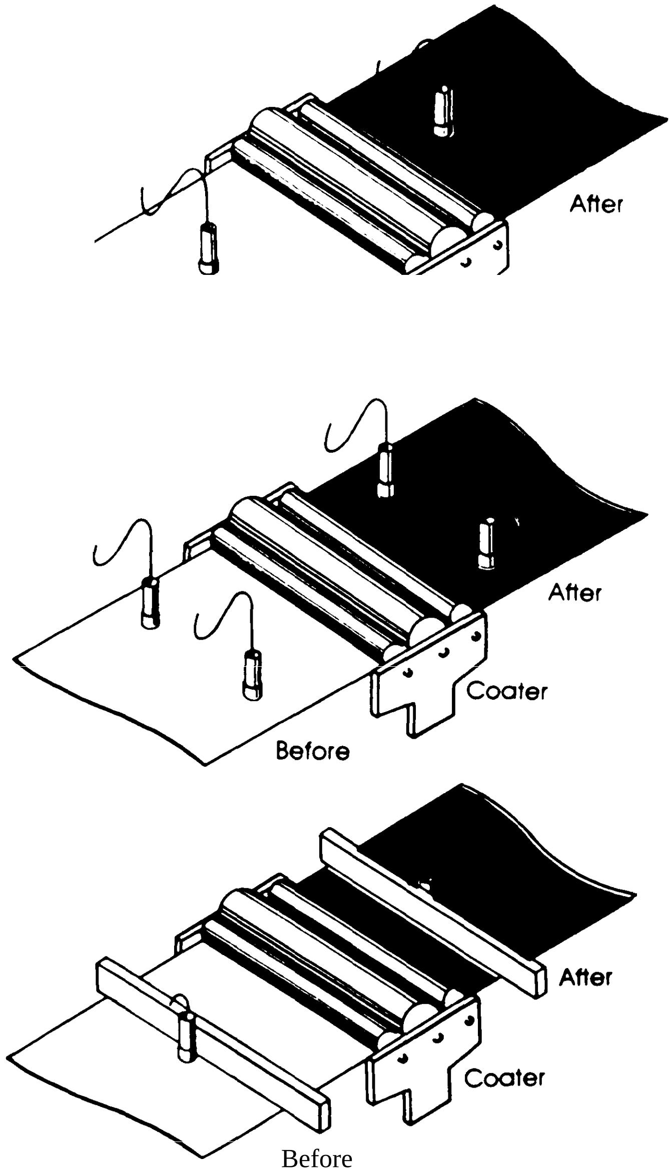
(Courtesy of NDC Systems)

Figure 3-2. Gamma Backscatter Gage

material to be measured. These rays are scattered back toward the detector in direct proportion to the mass of the material in front of the probe. A scintillation crystal or photomultiplier detector is used to convert the back-scattered protons to an electrical signal, which, in turn, can be related to the weight per unit area or to thickness provided that the density is constant. Compared to other radiation-gaging methods, the gamma backscatter principle is insensitive to changes in color, opacity, and composition. This eliminates the need for complex calibration techniques. The gamma backscattering gages can be set up in various configurations, as shown in Fig. 3-3. In a dual scanning system, traversing frames and probes are mounted before and after the coater so that a complete profile of the sheet is generated and displayed on the recorder chart. The scanners are synchronized to make a same-spot measurement. The dual scanning system may consist of dual traversing frames, two gages, and complete color cathode-ray tube (CRT) display of product profiles and parameters, as shown in Fig. 3-4.

3-3.1.2 Cure Monitoring

Standard practices for monitoring the cure of a resin system involve control of the time, temperature, and pressure during cure. Autoclaves and presses are equipped with temperature- and pressure-recording devices and can be automatically controlled for time. However, these are often not enough. Other systems have been developed to help monitor the cure of the organic resins. These include dielectric analysis and ion graphing. Yolof (Ref. 10) points out that the theory covering the interrelationship between dielectric and mechanical relaxation properties, adhesion wetting, solubility, and molecular architecture has been known



(Courtesy of NDC Systems)

Figure 3-3. Various Configuration Set-Ups of Gamma Backscatter Gages

for some time. Further work on the application of this theory has progressed so that today dielectric cure monitoring is used not only in conjunction with the laboratory-controlled tests but also with large production equipment. Refs. 11 through 15 discuss dielectric-cure monitoring. The principle of dielectric measurement is quite simple. The resin matrix is the dielectric medium and a small condenser can be built into the fabrication part. In composite fabrication, thin metal foils or screening can be placed directly in the part; these metal parts act as the plates of the condenser. The mold, press platen, or caul sheet can also be used as one of the condenser plates. Most organic resins are polar because they contain dipoles, which will orient in

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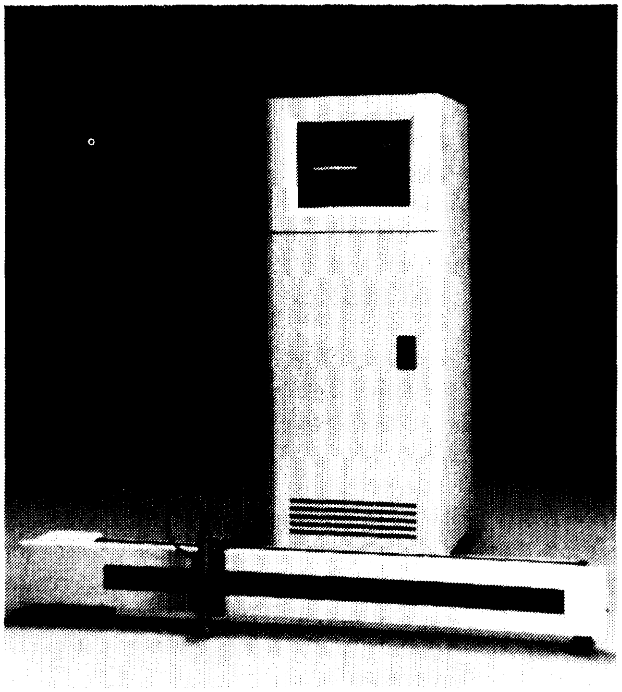

(Courtesy NDC Systems)

Figure 3-4. Dual Traversing Frames With Color CRT Display for Gamma Backscatter Gages

an electric field. These dipoles will change position in an alternating field. However, the movement of the dipoles is restricted by the physical state of the material. If the resin matrix is hard (unmelted or cured), the dipoles will not move because they are locked in place. If the resin matrix is very viscous or if gelation takes place, the dipoles will move only with great difficulty. When the resin matrix is fluid, the dipoles are free to move and will readily orientate. The ease or difficulty of orientation can be determined by measuring the dielectric constant or capacitance of the polymerizing resin. The dissipation factor, which is a measure of the energy lost due to dipole movement, also can be determined. This factor is related to the viscoelastic properties of the resin matrix, which are constantly changing as the cure proceeds. Changes in the resin caused by temperature and pressure variations can be defined and controlled accurately if the physical nature of the curing resin is known. Allen (Ref. 12) points out that the technique of automatic dielectrometry is reliable, but a background data base must be established for each resin system used. Yokota (Ref. 13) shows that, with the application of dielectric monitoring, it is possible to establish a temperature-time-pressure application diagram, which will define the optimum time to apply the pressure and what temperature range should be maintained. Ref. 14 discusses the use of dielectric monitoring in large autoclave operations. The dielectric system can be and has been used to determine at what stage of a cure the parts are in the event of a vacuum-bag failure. If the temperature-time-pressure window has not been reached at the time of bag failure, the parts often can be saved and rebagged; this decreases wasted time.

Ion graphing as an in-process, cure-monitoring procedure involves continuous measuring of DC resistance of the resin during cure. The resistance measurement changes with the fluidity of the resin. As the system goes from a viscous solid to a fluid to the cured solid, the resistance through the system drops and then increases again. In practice, aluminum foil electrodes are placed such that one is in contact with the laminate and the other is within the bleeder ply on the other side. In this way the cure through the thickness of the laminate is observed. The results of an ion-graphing analysis generally are plotted as voltage versus time. This system can also be used to monitor the recure of an aborted autoclave run. More details on ion graphing can be found in Refs. 16 and 17.

3-3.2 SANDWICH CONSTRUCTION

As mentioned in par. 1-3.2.2, sandwich construction consists of two or more laminates of dissimilar materials bonded together with an adhesive. Therefore, sandwich construction will be treated as an adhesive-bonded structure and, as such, will be discussed in par. 3-3.3. The testing of the structure itself will be covered in par. 3-4. To build a quality sandwich structure, it is necessary that the laminates be of sound structure. Their testing is covered in par. 3-3.1 and will be further covered in par. 3-4. The surfaces of the laminates should be clean and freshly prepared. The adhesive system should be selected based on its durability, bonding capability, and compatibility with the adherends (laminates and core). The core materials, especially if nonmetallic, should be dried to prevent blowing the panel during cure. Ref. 18 discusses some of the considerations that the designer should be aware of as far as acceptance test criteria for sandwich construction are concerned. The authors point out that there is a need for work and serious consideration of the problems involved with some types of sandwich structures.

3-3.3 ADHESIVE BONDING

The in-fabrication testing of adhesive bonding mainly involves the use of destructive coupon testing to insure that the proper controls of surface preparation, adhesive cure, and storage of the adhesive have been used. There are a few tests that can be used during fabrication. One of these is the use of cure monitoring, as described by Fritzen, *et al.*, in Ref. 19, which includes the use of ion

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graphing, dielectrics, and phase metrology. The phase metrology system uses a small, aluminum foil electrode placed in the adhesive "glue line". The system measures phase-angle shift and vector voltages. Basically, the three systems are similar in that they measure some form of electrical flow through the resin system and response to the changes as the resin cures. Ion graphing is also discussed in Ref. 20. Hart-Smith (Ref. 21) discusses the effects of flow and porosity on the strength of the adhesive joint. These defects are important to understand because they will dictate the inspection criteria for the nondestructive testing technique that will be used to inspect the final part and for subsequent in-service inspections.

There are some important but simple tests that the operator can use to inspect the parts being bonded. The first test, and a very important one, is a visual inspection for warpage, distortion, or misalignment. The edges of the joint should be checked for voids and flash (exuded adhesive), which will indicate whether too little or too much adhesive was applied. The flash should be checked to determine the degree of cure. If it is burnt, bubbly, or porous, it probably was cured at too high a temperature. If the adhesive system used was one that cures at room temperature, porosity may indicate that the use of a vacuum may have removed volatile constituents, such as amines, from the mix, which will result in adverse effects. Leaving a sample of the room-temperature-curing adhesive in the container overnight often will give a good indication of the cure in the parts that were bonded with that batch. Areas of uncured adhesive are also indicative of improper mixing of multicomponent adhesives. Elevated-temperature-curing adhesives can also be checked for cure by putting a small amount of the adhesive through the cure cycle and observing it.

3-3.4 NEW DEVELOPMENTS IN IN-PROCESS NDT

New developments in in-process testing will include the areas of design and manufacture. Boyce and Miller (Ref. 22), in a paper presented at the American Helicopter Society meeting, described the use of acoustic emission (AE) technology to evaluate the design of composite structures using static testing to locate those areas that needed to be reinforced without overdesign of the component. The authors pointed out that, if the advantages of composites are to be fully achieved, an economical method of detecting, locating, and assessing the severity of a defect was necessary. The development of a point-contact transducer and digital AE signal processing were the first steps toward developing AE as a quantitative NDT technique. Much work must be done in this area, and the design and NDT engineer should watch these developments as they progress.

Other work of interest involves the use of unmodified, general-purpose, ultrasonic equipment in conjunction with a digital-to-analog converter to help analyze the data by use of binary and colorgraphic displays. This work (Ref. 23) concludes that "the future application of color graphics to ultrasonic C-scan inspection, as well as more sophisticated image processing techniques promises to provide a more quantitative basis for material evaluation. and interpretation of ultrasonic composite material amplitude signatures will be facilitated."

A new optical method of NDT referred to as "Shearographic Nondestructive Testing" (SNDT) seems to be well suited for nondestructive inspection in production environments (Ref. 24). SNDT is an interferometric technique that allows surface strains to be measured. SNDT detects flaws in a manner similar to holography except that holography measures displacements and shearography measures strains. SNDT does not require special vibration isolation as is needed for holography. Thus SNDT should be more suited for inspection in the production plant environment.

Another new NDT tool has been introduced which is reported to be able to inspect the quality of surfaces to be coated or bonded. This tool is described as Surface Quality Unit for Inspection by Nondestructive Testing (SQUINT) with photoelectron emission (Ref. 25). The tool measures current due to optically stimulated electron emission and relates these measurements to peel strengths of bonds to graphite-epoxy composite laminates. This new tool or method, when perfected, will lend itself to the inspection of composite surfaces prior to bonding, an area in which there is currently no acceptable inspection tool.

Flash X ray and cineradiography (X-ray movie pictures) are coming and will provide new insights into composite performance (Ref. 26). These techniques are being applied to study deformations and strains in fiber-reinforced composites. They are expected to be useful in the study of composites under ballistic impact. However, this information will indicate whether the adhesive will cure at the cure temperature but will not account for the possibility that the bond line may not have reached the required temperature. Ref. 27 is a good introduction to nondestructive testing of adhesive-bonded structures and describes some of the test techniques that will be discussed in par. 3-4.

3-4 END-ITEM NONDESTRUCTIVE TESTING

The inspection of end-items, either as the final production inspection of subassemblies or complete products, is the area where nondestructive testing is used the most. Another area in which nondestructive testing is being rapidly adopted is in the in-service inspection of

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composite structures and adhesive-bonded structures. These two areas, final inspection and in-service inspection, will be discussed in the paragraphs that follow.

3-4.1 FINAL INSPECTION

Final inspection of the finished item must consist of a number of tests. These tests include visual inspection for dimensional tolerances, flatness or contour, and nondestructive testing for structural integrity. Table 3-3 lists some of the common defects that would affect the structural integrity of the composite structure and the nondestructive test technique that may be used to inspect for these defects. Ref. 28 describes a product inspection development program for the inspection of a carbon-fiber-reinforced composite-honeycomb panel that was part of a commercial aircraft rudder.

3-4.1.1 Radiographic Inspection

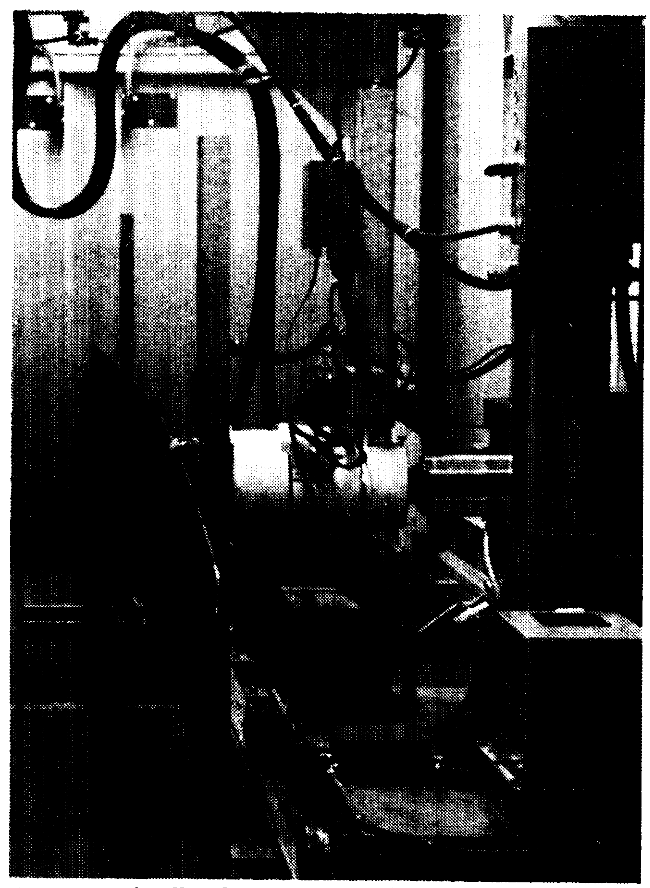
Radiographic inspection techniques are widely used for the detection of discrepancies in the internal details of the structure which will show up as cross-sectional density variations. These discrepancies include excess or missing material, porosity, inclusions, and damaged or distorted honeycomb core in a sandwich structure. X-ray radiographs are a permanent record that the engineer can use to evaluate problems that may occur later during service. However, radiographs are expensive in terms of time and materials. Recent advances in improving equipment have made real-time viewing radiographic (fluoroscopic) techniques very appealing for inspection of composite structures. Fluoroscopic evaluation has been reported to be particularly applicable to composite materials to detect exaggerated resin-rich/resin-starved areas, to determine ply orientation (if indicators are included), and to detect cracks that are oriented parallel to the X-ray beam and have a depth greater than approximately 3% of the total part thickness (Ref. 29). The fluoroscopic system is particular) applicable to bonded honeycomb structures such as helicopter main rotor blades, tail rotor blades, and panels to detect hidden foreign materials, mismatch or misalignment of detail parts, lack of potting material around inserts, and a wide variety of core defects including entrapped matter. Fig. 3-5 shows a helicopter main rotor blade being inspected by fluoroscopic radiography, Fig. 3-6 shows the control room of the Fluoroscopic Radiography Laboratory at Bell Helicopter Textron, and Fig. 3-7 shows a variety of parts awaiting fluoroscopic radiographic inspection. Other discussions of radiographic inspection of composite structure can be found in Refs. 30 and 31.

TABLE 3-3
FINAL INSPECTION TECHNIQUES
FOR SPECIFIC DEFECTS

Technique	Delamination	Disbonds	Cracks	Foreign Matter	Condition of Internal Parts
Radiographic			X	X	X
Ultrasonic	X	X			X
Acoustic Emission	X	X	X		
Mechanical Impedance	X	X		X	X
Thermal	X	X	X		

3-4.1.2 Ultrasonic Inspection

The ultrasonic inspection system has found wide acceptance in the inspection of composite structures. There are two different approaches to ultrasonic in-



(Courtesy of Bell Helicopter/ Textron)

Figure 3-5. Composite Main Rotor Blade Inspection by Fluoroscopic Radiography

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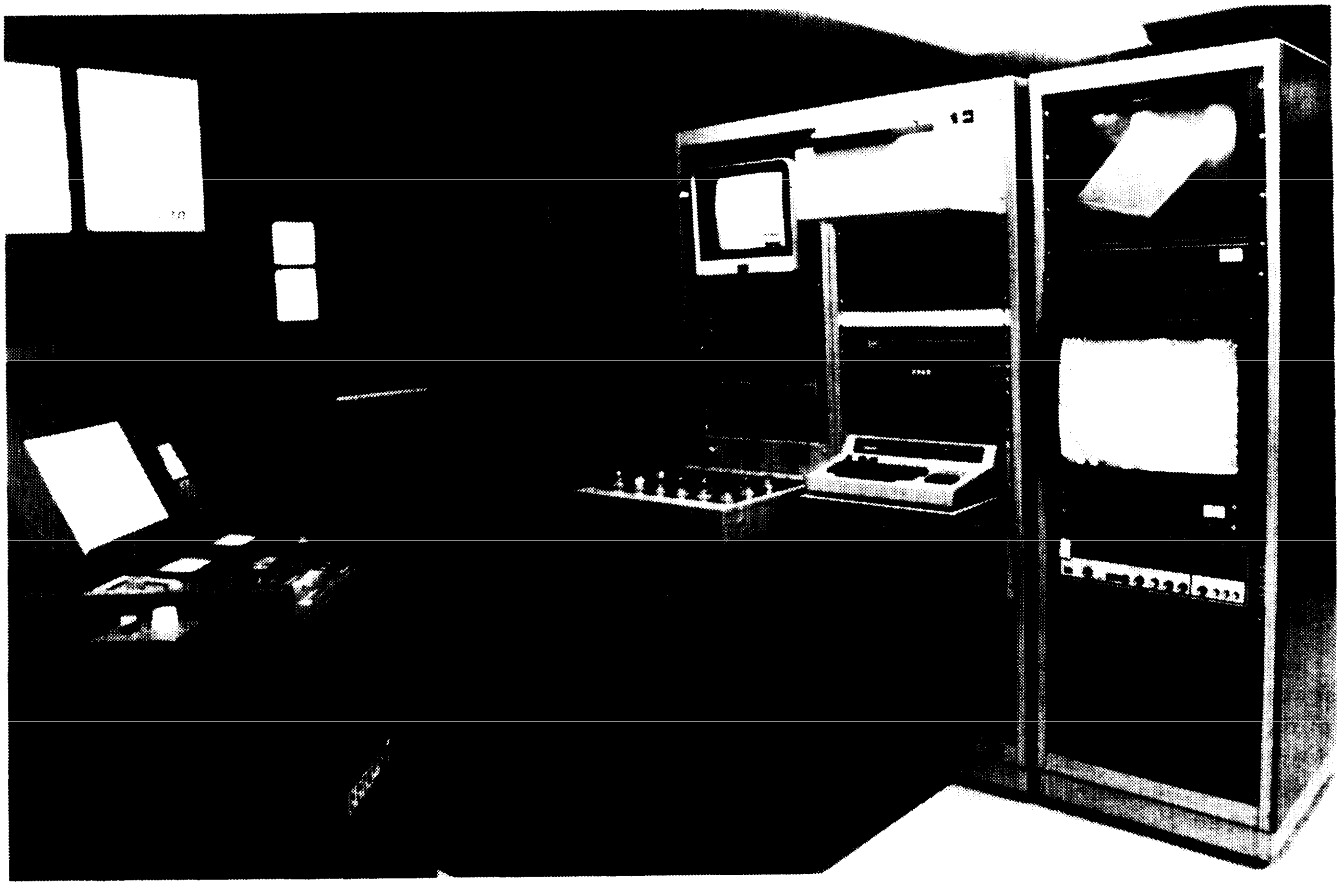
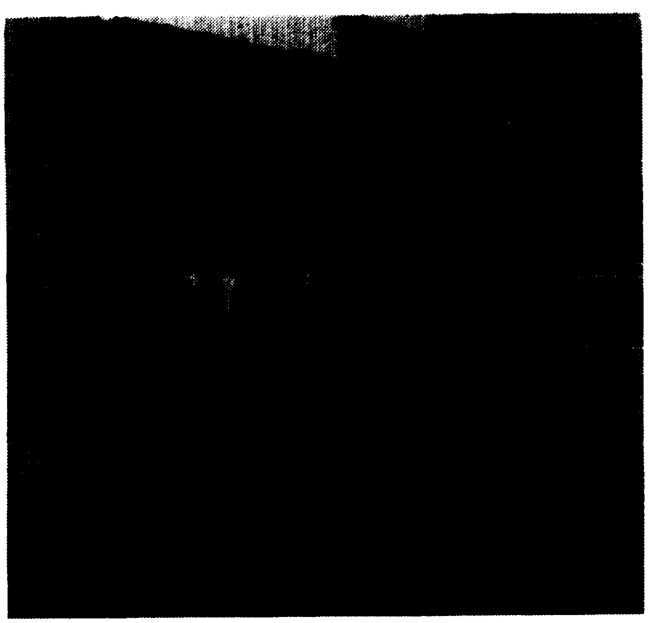


(Courtesy of Bell Helicopter/Textron)

Figure 3-6. Control Laboratory for Fluoroscopic Radiography Showing Real-Time Imspection of Honeycomb Panel



(Courtesy of Bell Helicopter) Textron)

Figure 3-7. Variety of Parts Awaiting Fluoroscopic Radiographic Inspection

spection of a laminate. One is pulsed wave and the other is standing wave. The pulsed wave approach includes the pulse-echo and through-transmission techniques. In ultrasonic pulse echo the pulses are generated and detected by a single transducer in contact with the surface through a couplant. The pulse travels internally through the part and ethos. or reflects, from each material change, for example, the interface of a laminate bonded to a different substructure. The reflected pulses or echos are detected by the transducer and the resultant signals are monitored on a CRT for changes caused by the defects. Fig. 3-8 depicts a bonded laminate structure with no defect, a delamination, and a void. The sound path for each type of defect is also shown. The signal on the CRT would vary in shape and duration for each of these three locations. The time interval from pulse initiation to its return to the transducer can be electronically presented as a depth reading. For this method to detect bond failures, the skin-to-substructure bond must permit the pulse to pass into the substructure. Also this method requires a reference standard of the same material with and without the defect; this standard is used to set up the instrument.

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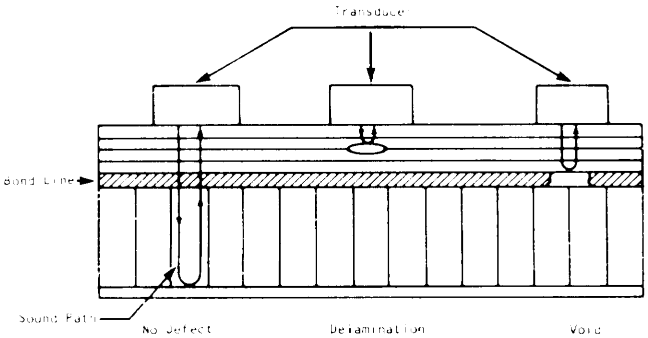
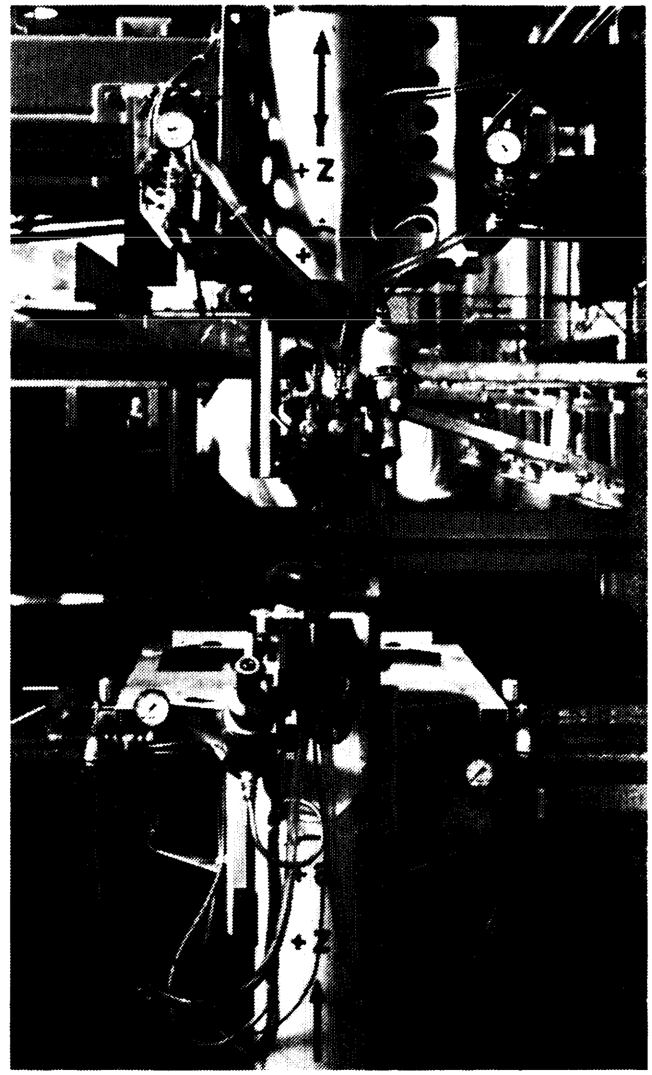


Figure 3-8. Pulsed Echo Ultrasonic Inspection

Pulse-echo ultrasonic inspection can be used while the section to be inspected is a part of the whole or in in-place inspection. The part need not be removed for inspection

In through-transmission ultrasonic inspection the pulses are generated by the "transmit" transducer, which is coupled to the surface of the part by a water bath, water column, or by direct contact through a couplant. The pulse enters the part and travels through to the other side and is detected by the "receive" transducer. which is coupled to the other side in the same manner as the "transmit" transducer. Detectable defects will block or reduce the sound transmission; this causes a loss or reduction in signal amplitude. This system will only distinguish between a good and a defective part. the through-transmission system and the use of a water bath or column can be used with C-scan recording. The transducers can be moved over the part to be inspected in pairs, and the signal recorded as a C-scan that will locate the areas of lost or reduced signal. Through-transmission ultrasonics generally is used with the part removed from the whole assembly, and it cannot be used to measure depth of the defects. Fig. 3-9 shows a water squirter or water column for use with through-transmission ultrasonics. The squirter nozzles can be used in-plane or offset in either the *x*- or *y-axis*. An adapter can be used to mount the squirter nozzles so that their centerline is horizontal instead of vertical. It is also possible to have the squirters mounted on an auxiliary manipulator, which will rotate the transducers 360 deg around the vertical axis. The system can be controlled by a programmable controller. Multiple squirter assemblies can be placed in "gangs" to decrease inspection time. This is depicted in Fig. 3-10.

Standing wave ultrasonics, or impedance plane ultrasonics, relies on the generation of a standing wave pattern throughout the laminate thickness and on measuring its collective effects on the acoustic impedance at the surface. The system uses a small probe (typically resonant) to generate the standing wave across the laminate thickness. The theory of standing wave ultrasonics is explained in Refs. 32 and 33. Standing wave



(Courtesy of Custom Machine, Inc., Cleveland, OH)

Figure 3-9. Water Squirter Used to Couple the Ultrasonic Signal to the Part in Through-Transmission Ultrasonics

ultrasonics has specific areas of application for the inspection of fiber-reinforced polymeric composites. The major applications include the detection of bond failures between bonded laminates or composite-to-metal bonds, delamination between layers of the composite laminate, and detecting internal-impact damage, especially in graphite-reinforced composites. Fig. 3-11 shows a portable standing wave ultrasonic instrument. In Fig. 3-11 the dot display represents various defects; the center dot is a bonded or structurally sound laminate. The dot in the lower, fourth quadrant is a measure of the probe in air, The dots, starting with the one on the *x-axis* (first quadrant) and proceeding counterclockwise, would indicate a defect (void or delamination) at a progressively deeper depth. Other papers on ultrasonic nondestructive testing are cited in Refs. 34 through 37.

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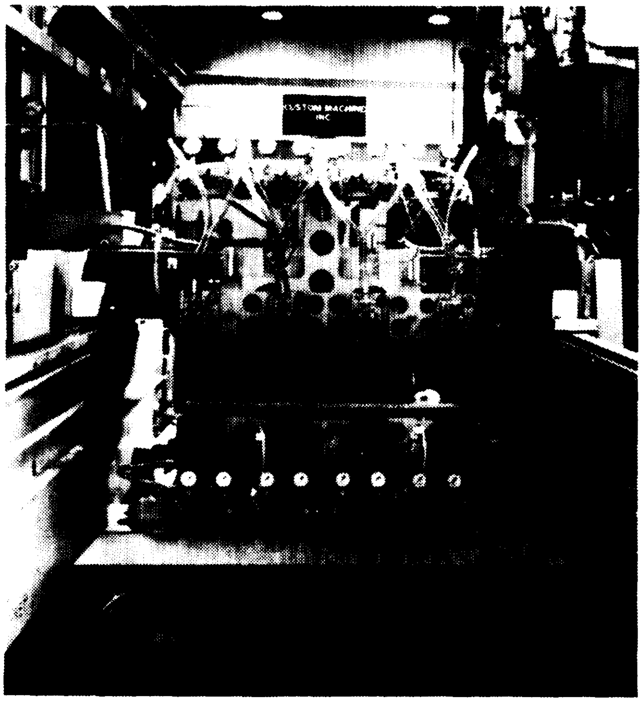
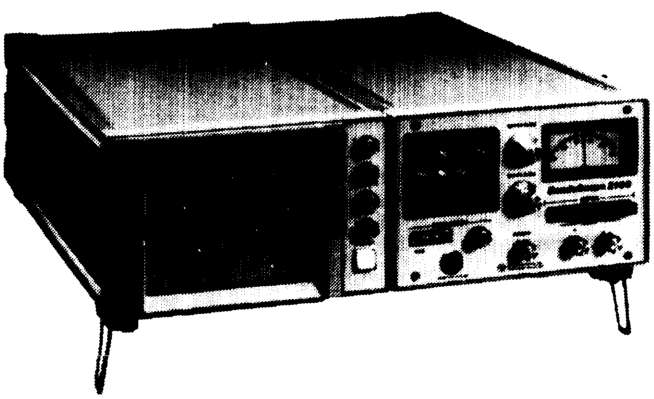


(Courtesy of Custom Machine, Inc., Cleveland, OH)

Figure 3-10. Multiple Squirters for the Inspection of Large Parts



(Courtesy of NDT Instruments, Inc.)

Figure 3-11. BondaScope 2100 Standing Wave Ultrasonic Inspection Instrument

3-4.1.3 Acoustic Emission Inspection

Of the various types of defects one might inspect for, there are three primary failure modes in composite structures. These include matrix cracking, delamination, and fiber breakage. The three modes can occur during the pressurization of a fiber-reinforced pressure vessel. Delamination is critical to the buckling strength of the vessel, and the fibers are the primary load-bearing constituent of the structure. However, the matrix cracking is important only if it leads to fiber damage. AE can inspect for all three modes of failure. AE testing involves the placing of AE transducers at various locations on the structure and then applying a load or stress. As the load increases and any microfailures start to occur, the transducers will pick up the signal. The time for the signal to reach the different transducers can be used to locate the source of the signal and hence the location of the defect. By use of standard specimens representing a structure, AE counts versus load traces can be prepared and then compared to the counts obtained during pressure testing to help to predict the strength or weakness of a structure. AE tests have been used to inspect pressure vessels such as rocket motor cases. Refs. 38 through 40 discuss the use of AE testing to evaluate the structural integrity of fiber-reinforced composite pressure vessels. AE requires some sort of proof testing, i.e., a load must be applied to the structure. The load may be applied by mechanical, thermal, or sonic means. These methods are generally used to check on the structure once it is in service and will be discussed further in par. 3-4.2.

3-4.1.4 Mechanical Impedance Inspection

Mechanical impedance testing techniques use bond test equipment that excites the structure with relatively low-frequency mechanical vibrations and then measures the response to these vibrations. This type of equipment includes such instruments as the Uniwest-Shurtronics Composite Tester and Harmonic Bond Tester (Fig. 3-12), the Fokker Bond Tester, and Inspection Instrument's Acoustic Flaw Detector. The two Uniwest-Shurtronic units use a probe with a vibrating pin, which excites the composite structure. The amplitude and phase shifts of the returned signal are measured and processed to detect the defect. The Fokker Bond Tester and the Acoustic Flaw Detector use a piezoelectric transducer to excite the surface. The Fokker instrument requires a liquid couplant and the transducer must be repositioned for each reading. The other instruments are dry-coupling and rapid-scanning. Refs. 28 and 41 discuss mechanical impedance techniques.

3-4.1.5 Thermal Inspection

Large structures such as large nose radomes and some communication satellites are made from composite materials that present some different and unique problems in nondestructive testing. Often the skin ply thickness is very thin and the use of couplants could result in couplant penetration of the laminate surface. Couplant penetration may affect the adhesion of rain-erosion-resistant coatings. Photochromic coatings that will change color with changes in surface temperature have been found useful in these applications. For further details on the use of the thermal-sensitive photochromic systems, see par. 2-2.6 and Refs. 42 through 44.

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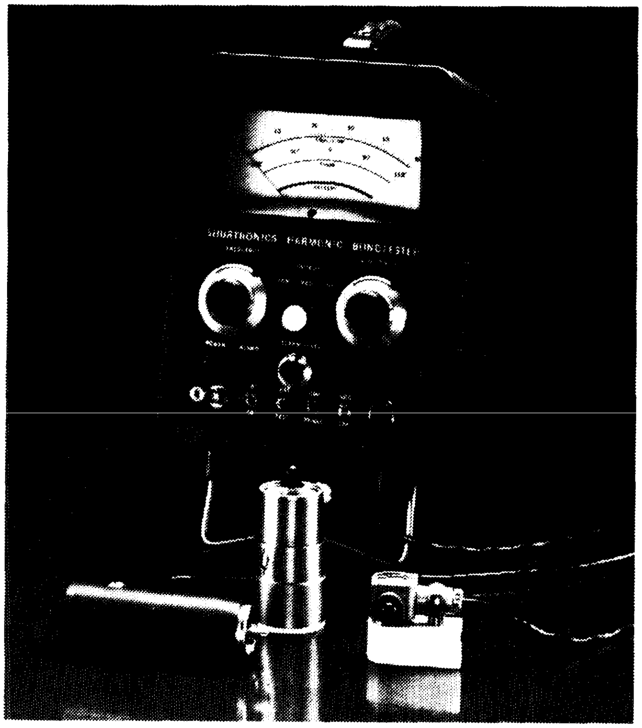


(Courtesy of Uniwest-Shurtronics)

Figure 3-12. Harmonic Bond Tester With the Vibrating Pin Probe- Left Front

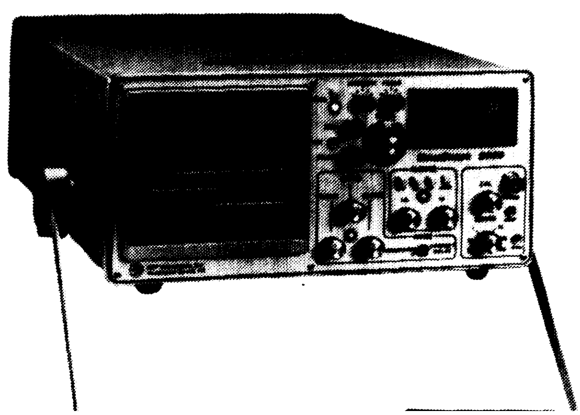
3-4.2 IN-SERVICE NONDESTRUCTIVE TESTING

The testing of items in service for defect development, defect growth, or degradation is one of the most important uses of nondestructive testing.

In 1977, Wadin and Pollock (Ref. 45) reported that "Acoustic emission can conveniently be implemented into a periodic overload proof test to detect the existence of material cracks and other discontinuities or to predict impending material failure.". This work was done to establish a nondestructive test procedure for testing the safe service life of fiberglass nonconductive aerial booms. In 1979, under a contract to NASA, the Boeing Commercial Airplane Company conducted an assessment of the state of the art of in-service inspection of graphite-epoxy composite structures on commercial transport aircraft (Ref. 46). Appendix B to Ref. 46 lists seven areas of nondestructive testing that had been or were being used to inspect advanced composite structures on in-service aircraft at that time. These tests included

1. Visual and visual optical
2. Tap testing
3. Ultrasonic pulse-echo
4. Ultrasonic through-transmission
5. Ultrasonic digital thickness gage
6. Radiography
7. Bond test equipment.

Some of these methods could be used while the part is on the aircraft, but other methods require that the part be removed. Many of these methods are still in use. In 1980 Botsco (Ref. 47) described new methods for nondestructively evaluating airframes and jet engines. What Botsco described was the ultrasonic impedance display concept for testing a variety of laminated and honeycomb-core, adhesive-bonded structures that were discussed in par. 3-4.1.2, and the use of high-resolution ultrasonic techniques for inspecting graphite composites and bond line thickness. This high-resolution ultrasonic equipment includes the NovaScope 2000 shown in Fig. 3-13. Botsco reported that the high-resolution ultrasonic technique is particularly useful for inspecting graphite-reinforced composites for delamination. Delamination are not only readily detectable, but their depths can be precisely measured with a digital readout of thickness. Since 1982, there has been an increasing number of papers presented on the use of AE as an in-service test method for fiber-reinforced composite structures. Refs. 48 through 52 describe the use of AE field testing of aerial lift trucks shown in Figs. 3-14 and 3-15. Fowler (Ref. 53) states that "Compared to many other nondestructive test methods acoustic emission has predetermined, objective evaluation criteria and is not open to the subjectivity of operator interpretation.". The author further points out that the test method provides information about the entire item of equipment, rather than about small, localized areas. Furthermore, in-service equipment can be tested while in use, and in most cases it is not necessary to shut the equipment down. The paper shows that since acoustic emission testing of all fiber-reinforced plastic chemical processing vessels has been used at Monsanto, there has been a dramatic decrease in the number and frequency



(Courtesy of NDT Instruments, Inc.)

Figure 3-13. The NovaScope 2000 Ultrasonic Inspection Equipment

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(Courtesy of Physical Acoustics Corp.)

Figure 3-14. Acoustic Emission Testing of Aerial Lift Trucks Showing the Use of a Tie-Down to Stress the Boom

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(Courtesy of Physical Acoustics Corp.)

Figure 3-15. Acoustic Emission Sensors Located on the Boom of an Aerial Lift Truck During Test

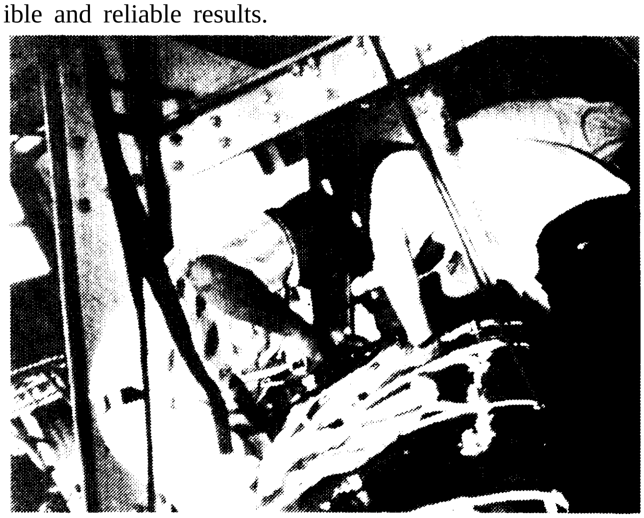
of catastrophic failures of the tanks, Only one tank failed before it was removed from service, and that failure had been predicted as a result of the testing. This work is also described in Ref. 54. Gillette (Ref. 55) discusses the use of AE to predict long-term performance of reinforced thermosetting resin pipe and concludes that acoustic emission has proven to be a valuable tool in determining the structural integrity of reinforced thermosetting pipe at the time of the test. However, much more work is required if the method is to be used to predict long-term strength under cyclic loading conditions. In 1985, Vargas reported (Ref. 56) that AE techniques were being applied to the quality control problem in many areas such as fiber-reinforced tanks and vessels, rocket motor cases, composite aircraft structures (Fig. 3-16), and pipes. The author points out "A limitation of acoustic emission as a quality control method is that it can only detect flaws that are growing. Either an external force, or some force within the composite must be acting on the flaw in such a way as to cause it to grow in order for it to release energy.". The author also discusses the "uses of ultrasonic AE. Ultrasonic-acoustic, or acousto-ultrasonic, emission is a method of testing composite components and bonded structures without physically loading them. This method has been used to detect the difference between a good and a poor adhesive-bonded joint.

The progress made in the area of in-service inspection since 1977 has been impressive. but much more work is required.

3-5 NEW DEVELOPMENTS IN END-ITEM NDT

The inspection of the finished item, whether final production or in-service inspection, is the area in which advances must be made. Work is underway in the area of detecting degradation in composite structures and in adhesive bonds during acousto-ultrasonics. The combination of highly pulsed ultrasonic transducers with AE systems shows promise in the ability to detect differences in structures that appear to be sound but in fact have advanced in degradation due to environmental and chronological aging (Ref. 57). Acousto-ultrasonic techniques can be used to determine the relative adhesive bond strength of composite assemblies (Ref. 56). Ref. 58 also discusses acousto-ultrasonics and its potential to detect dispersed microstructural anomalies in composites and differences in the bond strength or interlaminar strength of the composites. The paper also describes a dry-coupled, two-wheeled sensor that contains the pulser in one wheel and the receiver in the other. Further information on acousto-ultrasonics is included in Ref. 59.

It is possible to detect differences in strength, absorption of moisture or other liquids, and changes in moduli of materials by NDT techniques. Therefore, it is conceivable that the nondestructive testing industry will be able to produce and market instruments that will be capable of reading the strength of an adhesive joint or the interlaminar strength of a composite with reproducible and reliable results.



(Courtesy of Physical Acoustics Corp.)

Figure 3-16. Acoustic Emission Testing of a Composite Helicopter Rotor Blade

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APPENDIX A

NONDESTRUCTIVE TESTING EQUIPMENT SUPPLIERS

ACOUSTIC EMISSION TECHNOLOGY CORPORATION
Division of Krautkramer-Branson International
1812J Tribute Road, Sacramento, CA 95815; (916) 927-3861

The Acoustic Emission Technology Corporation designs, manufactures, sells, and services acoustic emission instruments, systems, and accessories. Special instrumentation systems for structural testing, nondestructive inspection and testing, and destructive testing are supplied.

BALTEAU ELECTRIC CORPORATION
Box 385, 63 Jefferson Street, Stamford, CT 06902; (203) 324-6118

Balteau Electric Corporation is involved solely in nondestructive testing equipment sales and service. The products encompass X-ray, ultrasonic, eddy current, acoustic emission, magnetic particle, and crack depth measuring inspection equipment. Training courses are also available in ultrasonic inspection,

BIG THREE INDUSTRIES, INC.
Tempil Division
2901 Hamilton Blvd., South Plainfield, NJ 07080; (201) 757-8300

The Tempil Division is a manufacturer of temperature-indicating crayons, liquids, paints, and labels. These products are used in determining preheat temperatures and the calibration of commercial ovens and equipment.

CUSTOM MACHINE, INC.
9200 George Avenue, Cleveland, OH 44105; (216) 341-3994

Custom Machine Corporation designs and builds special machinery for various industries. Transport mechanisms and systems have been designed and built for ultrasonic inspection. Equipment ranges from simple manual operation to fully automated inspection lines using computer controls.

CUSTOM SCIENTIFIC INSTRUMENTS, INC.
P.O. Box A, Whippany, NJ 07981; (201) 538-8500

Custom Scientific Instruments (CSI) is a manufacturer of instruments for nondestructive and physical testing of materials. The standard line of instruments is designed to ASTM. International Organization for Standardization (IS0). and Federal specifications. CSI also designs and manufactures special equipment such as test jigs and fixtures that can be used with existing test equipment.

DOSIMETER CORPORATION OF AMERICA
Nuclear Accessories Division
6106 Interstate Circle, Cincinnati, OH 45242: (513) 793-6051

The Dosimeter Corporation of America (DCA) provides radiation detection auxiliary equipment and supplies for measuring gamma rays, X rays, and neutrons during radiography. DCA was previously known as the Bendix Dosimeter Product Line and the Landverk Electrometer Corporation.

DUNEGAN
Rancho Viejo Road, San Juan Capistrano, CA 92675; (714)831-9131

Dunegan, previously Dunegan Endevco, manufactures acoustic emission instrumentation for flaw detection and location. Applications include detection and location of discontinuities, delamination, voids, porosity, inclusions, cracks, etc., in a wide variety of engineering materials and structures. Instrumentation ranges from low-cost, single-channel systems to complex, multichannel, computerized flaw-location systems.

ECHO LABORATORIES
P.O. Box 552, RD No. 4, Box 76, Lewistown, PA 17044; (717) 248-4993

Echo Laboratories is a manufacturer of ultrasonic couplants and ultrasonic transducers used in nondestructive testing.

HOLOSONICS, INC., INDUSTRIAL PRODUCTS
4340 Redwood Highway, Suite 150, San Rafael, CA 94903; (415) 479-5880

Holosonics provides acoustic imaging systems and services. Equipment capabilities range from simple hand-scanning applications to fully configured systems for a broad range of metallic and nonmetallic structures, such as composites and multilayered structures.

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INSTRUMENT TECHNOLOGY, INC.
P.O. Box 381, Main Line Drive, Westfield, MA 01085; (413) 562-5132

Instrument Technology, inc., (ITI) specializes in the design, development, and manufacture of remote viewing systems. ITI products include borescopes, binoculars, and optical devices for inspection. ITI systems are used visually but are also available with photographic and TV cameras.

J. B. ENGINEERING AND SALES CO., INC.
207 Greenwich Avenue, Stamford, CT 06902; (203) 348-6753

J. B. Engineering is a provider of complete ultrasonic immersion test systems that provide accuracy, repeatability, and reliability. Immersion test systems are built to meet specifications defined by customer needs. Customer personnel are trained on customer parts.

JODON, INC.
Laser Products Division
145 Enterprise Drive, Ann Arbor, MI 48103; (313) 761-4044

Laser Products Division provides holographic NDT systems for performing utility and specialized continuous wave services, real-time, time-average, and double-exposure holography. Systems include complete turnkey setups with on-site indoctrination.

KAMAN SCIENCES CORPORATION
Products Division
P.O. Box 7463, Colorado Springs, CO 80933; (303) 599-1500

Kaman Sciences manufactures a complete line of 14 MeV neutron generators and transfer systems for neutron radiography.

KRAUTKRAMER-BRANSON, INC.
P.O. Box 408, Stratford, CT 06497; (203) 377-3900

Krautkramer-Branson, Inc., a subsidiary of Smith Kline Corp., is a manufacturer of ultrasonic nondestructive testing equipment, which may be made compatible with computers.

KRAUTKRAMER-BRANSON, INC., KB-AEROTECH
P.O. Box 350, Lewistown, PA 17044; (717) 242-0327

KB-Aerotech designs and builds transducers for use in nondestructive testing applications. The product line includes transducers for contact testing, shear wave inspection, immersion testing, and applications involving dual-element probes, delay, and thickness gaging.

METROTEK, INC.
800 Wellsian Way, Richard, WA 99352; (509) 9464684

Metrotek manufactures and supplies ultrasonic nondestructive testing equipment, including ultrasonic imaging systems, module pulsers, receiver amplifiers, gates. immersion tanks, XY bridge assemblies, scan controllers, and transducers.

MIKRON INSTRUMENT CO., INC.
P.O. Box 211, Ridgewood, NJ 07481; (201) 891-7330

Mikron Instrument Co. manufactures noncontact infrared-temperature-measuring instruments (both AC and battery-powered) for use between the limits of −75°to 2200°C (–100° to 4000°F) and surface emissivity limits of targets from 0.2 to 1.0. Many ranges, spectral responses, and physical configurations are available.

NDC SYSTEMS
1859 Business Center Drive, Duarte, CA 91010; (818) 358-1871

NDC Systems is a supplier of gaging for on-line, continuous measurement of the weight of prepregs, composites, sheet molding compounds (SMC), and reinforced plastics (RP).

NDT INSTRUMENTS, INC.
15622 Graham Street, Huntington Beach, CA 91649; (714) 893-2438

NDT Instruments designs, manufactures, and sells ultrasonic, sonic, and eddy current instrumentation. In the ultrasonic realm are ultrasonic thickness gages, bond testers, and an extensometer for gaging bolt tightness. In the eddy current realm is a coating thickness gage.

NUCLEAR EQUIPMENT CORPORATION
963 Industrial Road, San Carlos, CA 94070; (415) 591-8203

Nuclear Equipment Corporation manufactures energy-dispersive X-ray fluorescence spectrometers, energy-dispersive X-ray diffraction spectrometers, and X-ray spectrometers for use with electron microprobe, and scanning electron microscopes. X-ray fluorescence systems range from small, portable units using radioisotopic sources to large, computer-based systems using X-ray tubes. Systems have been adapted for on-stream and in-stream use.

OLYMPUS CORPORATION OF AMERICA
Industrial Fiberoptics
4 Nevada Drive, New Hyde Park, NY 11042; (516) 488-3880

Olympus fabricates an industrial fiberscope, which is a flexible fiberoptic borescope permitting internal inspection without disassembly. Brilliant, cold lighting is supplied from a 150-watt external source.

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PHILLIPS ELECTRONIC INSTRUMENTS, INC.
85 McKee Drive, Mahwah, NJ 07430; (201) 529-3800

Phillips Electronic Instruments, Inc., (EPI) is part of North American Phillips Corporation and manufactures X-ray and X-ray fluorescence systems for industrial inspection.

PHYSICAL ACOUSTICS CORPORATION
P.O. Box 3135, 819 Alexander Road, Princeton, NJ 08540; (609) 451-2510

Physical Acoustics Corporation (PAC) designs. manufactures, sells, and services acoustic emission equipment for in-service inspection of a wide variety of materials and structures.

SONIC INSTRUMENTS, INC.
1014 Whitehead Road Extension, Trenton, NJ 08638; (609)883-5030

Sonic Instruments is a manufacturer of ultrasonic instrumentation and transducers used in the field for NDT and applied to materials testing.

SONOSCAN, INC.
530 East Green Street, Bensenville, IL 60106; (312) 766-7088

Sonoscan is engaged in the development, manufacture, and sale of very high-resolution ultrasonic test equipment and acoustic microscopes.

SOUTHWEST RESEARCH INSTITUTE
P.O. Drawer 28510, San Antonio, TX 78284; (512) 684-5111

Southwest Research Institute is a not-for-profit corporation having activities in a wide range of nondestructive testing disciplines. Located at the Institute is the Nondestructive Testing Information Analysis Center (NTIAC), which is operated under contract to the Defense Logistics Agency. This Center collects and maintains a computerized information bank in the field of nondestructive testing for dissemination to both Government and private requesters.

TETRAHEDRON ASSOCIATES, INC.
5060A Convoy Street, San Diego, CA 92111; (619) 277-2820

Tetrahedron Associates designs, manufactures, sells, and services the Audrey dielectric cure analysis system for the dielectric analysis cure monitoring of most polar materials.

TFl CORPORATION
NDT Products Divion
P.O. Box 1611. West Haven. CT 06516; (203) 934-5211

TF1 manufactures X-ray equipment and systems used in nondestructive testing. TFl will design and fabricate special purpose X-ray generators as well as incorporate standard or custom products into complete systems, consisting of material handling and radiation-protective components.

TORR X-RAY CORPORATION
4031 Via Oro Avenue. Long Beach, CA 90810-1495; (213)513-1411

Torr X-Ray Corporation manufactures cabinet-type X-ray units. These systems are offered in standard 0.61-m (24-in.) cabinets with or without fluoroscopic capabilities. Special electronic fluoroscope), complete systems with image intensifiers, image enhancers, and TV readout are also available.

UNITRON INSTRUMENTS. INC.
Ehrenreich Photo-Optical Industries, inc.
101 Crossways Park West, Woodbury, NY 11797; (516) 364-8046

Unitron Instruments manufactures and markets a line of microscopes, metallographs, telescopes, and related optical products.

UNIWEST-SHURTRONICS
United Western Technologies Corp.
1029 North Kellogg, Kennewick, WA 99336; (509) 783-0680

Uniwest-Shurtronics designs, manufactures, sells, and services nondestructive equipment for testing adhesive bonds, coatings, composites, and laminates.

X-RAY INDUSTRIAL DISTRIBUTORS
P.O. Box 1015, Clifton, NJ 07014; (201) 773-9400

X-Ray Industrial Distributors distributes industrial radiographic equipment and supplies as well as designs and manufactures radiographic systems.

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APPENDIX B

SPECIFICATIONS AND STANDARDS ON NONDESTRUCTIVE TESTING

A partial list of specifications, standards, and handbooks pertaining to nondestructive testing of materials follows. Par. B-1 contains the Department of Defense documents, and Par. B-2 contains the various society-sponsored documents, (See Table 3-1 for specifications covering incoming raw materials.) Par. B-3 contains a list of societies and their abbreviations.

B-1 DEPARTMENT OF DEFENSE DOCUMENTS

Document No.	Title	Year
MIL-HDBK-204	Inspection Equipment Design	62
MIL-HDBK-333	Handbook for Standardization of NDT Methods	
VOL 1		74
VOL 2		74
MIL-HDBK-732	NDT Methods of Composite Materials—Acoustic Emission	84
MIL-STD-410D	NDT Personnel Qualification and Certification	79
MIL-STD-453C	Inspection, Radiographic	84
MIL-STD-1875	Ultrasonic Inspection, Requirements for	83
MIL-I-6870E	Inspection Program Requirements, Nondestructive for Aircraft and Missile Materials and Parts	79
MIL-M-38780A	Manual, Technical, Nondestructive Inspection	73

B-2 SOCIETY-SPONSORED DOCUMENTS

Society Document	Title
ANSI PH 1.28	Specification for Photographic Film for Archival Records, Silver-Gelatin Type, on Cellulose Ester Base
ANSI PH 1.41	Specification for Photographic Film for Archival Records, Silver-Gelatin Type, on Polyester Base
ANSI PH 2.22	Methods for Determining Safety Times of Photographic Darkroom Illumination
ANSI PH 4.32	Method for Evaluating the Processing of Black-and-White Photographic Papers With Respect to the Stability of the Resultant Image
API Bull 5T1-85	Imperfection Technology, Bulletin on, With Suppl. 1-1986
ASNT 005-82	Film and Paper Radiography—Section Five: The NDT Handbook on Radiography and Radiation Testing
ASNT 007-82	Radiographic Latent Image Processing—Section Seven: The NDT Handbook on Radiography and Radiation Testing
ASNT 014-83	Real-Time Radiography—Section Fourteen: The NDT Handbook on Radiography and Radiation Testing
ASNT 015-82	Image Data Analysis—Section Fifteen: The NDT Handbook on Radiography and Radiation Testing
ASNT 020-83	Attenuation Coefficient Tables—Section Twenty: The NDT Handbook on Radiography and Radiation Testing
ASNT 101-59	NDT Handbook (Vols. I and II)
ASNT 127-85	Nondestructive Testing Handbook, 2nd Ed., Vol. 3, Radiography and Radiation Testing

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ASNT 127A-85	Introduction to Radiography and Radiation Testing (NDT Handbook, 2nd Ed., 1985—Radiography and Radiation Testing)
ASNT 2021-82	Recommended Practice for a Demonstration of NDE Reliability on Aircraft Production Parts
ASNT 2028-80	Ultrasonic Test Method Question and Answer Book C
ASNT 2250-81	Materials and Processes for NDT Technology
ASQC E2-84	Inspection Planning, Guide to (ANSI-Approved Standard)
ASTM D883-83A	Definitions of Terms Relating to Plastics—DoD Adopted
ASTM E41 -79	Conditioning, Definitions of Terms Relating to
ASTM E94-84A	Radiographic Testing, Standard Guide for—DoD Adopted
ASTM El14-85	Ultrasonic Pulse-Echo Straight-Beam Testing by the Contact Method—DoD Adopted
ASTM E142-85	Controlling Quality of Radiographic Testing—DoD Adopted
ASTM E214-68	Immersed Ultrasonic Testing by the Reflection Method Using Pulsed Longitudinal Wave (R 1985)
ASTM E242-68	Appearances of Radiographic Images as Certain Parameters are Changed, Reference Radiographs for (R 1985)
ASTM E253-85	Sensory Evaluation of Materials and Products, Definitions of Terms Relating to
ASTM E284-81A	Appearance of Materials, Definitions of Terms Relating to
ASTM E317-85	Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Systems Without the Use of Electronic Measurement Instruments—DoD Adopted
ASTM E428-71	Fabrication and Control of Steel Reference Blocks Used in Ultrasonic Inspection (R 1985)
ASTM E494-75	Measuring Ultrasonic Velocity in Materials (R 1985)
ASTM E500-86	Ultrasonic Examination, Terminology Relating to—DoD Adopted
ASTM E545-81	Determining Image Quality in Thermal Neutron Radiographic Testing
ASTM E569-85	Acoustic Emission Monitoring of Structures During Controlled Stimulation
ASTM E586-84A	Definitions of Terms Relating to Gamma and X-Radiography
ASTM E587-82	Ultrasonic Angle-Beam Examination by the Contact Method
ASTM E610-82	Definitions of Terms Relating to Acoustic Emission
ASTM E650-85	Mounting Piezoelectric Acoustic Emission Contact Sensors, Guide for
ASTM E664-78	Measurement of the Apparent Attenuation of Longitudinal Ultrasonic Waves by Immersion Method (R 1983)
ASTM E748-85	Thermal Neutron Radiography of Materials
ASTM E750-80	Measuring the Operating Characteristics of Acoustic Emission Instrumentation

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ASTM E763-85		Calculation for Absorbed Dose From Neutron Irradiation by Application of Threshold-Foil Measurement Data
ASTM E797-81		Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method
ASTM E801-85		Controlling Quality of Radiographic Testing of Electronic Devices—DoD Adopted
ASTM E803-81		Determining the L/D Ratio of Neutron Radiography Beams
ASTM E804-81		Calibration of an Ultrasonic Test System by Extrapolation Between Flat Bottom Hole Sizes
ASTM E 1000-84		Radiologic Real-Time Imaging, Guide for
ASTM E1001-84		Detection and Evaluation of Discontinuities by the Immersed Pulsed-Echo Ultrasonic Method Using Longitudinal Waves
ASTM E1065-85		Evaluating Characteristics of Ultrasonic Search Units, Guide for
ASTM E1067-85		Acoustic Emission Examination of Fiberglass-Reinforced Plastic Resin (FRP) Tanks and Vessels
ASTM F526-81		Dose Measurement for Use in Linear Accelerator Pulsed Radiation Effects Tests—DoD Adopted
BSI	BS3683-65	Glossary of Terms Used in Nondestructive Testing—Part 4: Ultrasonic Flaw Detection (1985)
BSI	BS4331-72	Methods for Assessing the Ultrasonic Flaw Detection Equipment—Part 2: Electrical Performance
BSI	BS4331-74	Methods for Assessing the Ultrasonic Flaw Detection Equipment—Part 3: Guidance on the In-Service Monitoring of Probes (Excluding Immersion Probes)
BSI	BS5650-78	Apparatus for Gamma Radiography
BSI	M 34-70	Method of Preparation and Use of Radiographic Techniques
ISO	R1027-69	Radiographic Image Quality Indicators, Principles and identification—First Edition
ISO	3999-77	Apparatus for Gamma Radiography—Specification— First Edition
ISO	5580-85	Nondestructive Testing—Industrial Radiographic Illuminators—Minimum Requirements—First Edition
SAA	1929-81	Nondestructive Testing Glossary of Terms
SAE	AMS 2630A-80	Ultrasonic Inspection Product Over 0.5 in. (13 mm) Thick (ANSI-Approved Standard)
SAE	AMS 2632-74	Ultrasonic Inspection of Thin Materials 0.5 in. (13 mm) and Thinner (ANSI-Approved Standard)
SAE	AMS 2635C-81	Radiographic Inspection
SAE	AMS 265045	Fluoroscopic X-Ray Inspection (Noncurrent)
SAE	ARP 1611-80	Quality Inspection Procedure, Composites Tracer Fluoroscope
SAE	AS 1613-79	Image Quality Indicator Radiographic
SAE	J 358-80	Nondestructive Tests, Information Report (SAE Handbook, 1984)

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SAE J 427-83 Penetrating Radiation Inspection, Information Report (SAE Handbook, 1984)

SAE J 428-83 Ultrasonic Inspection, Information Report (SAE Handbook, 1984) (ANSI-Approved Standard)

B-3 SOCIETY ABBREVIATIONS

ANSI	American National Standards Institute
ASNT	American Society for Nondestructive Testing
ASQC	American Society for Quality Control
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
ISO	International Organization for Standardization
SAA	Standards Association of Australia
SAE	Society of Automotive Engineers

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G L O S S A R Y

A

Acoustic Emission (AE). The class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material or from the transient elastic waves so generated. (Acoustic emission is the recommended term for general use. Other terms that have been used in AE literature include (1) stress wave emission, (2) microseismic activity, and (3) emission or acoustic emission with other qualifying modifiers.) (From ASTM E610)

Acousto-Ultrasonic. A technique that combines highly pulsed ultrasonic transducers with an acoustic emission system to detect subtle defects in composites and bonded joints.

A-Scan. A method of data presentation on a cathode-ray tube (CRT) using a horizontal baseline that indicates distance, or time, and a vertical deflection from the baseline, which indicates amplitude. (From ASTM E500)

B

Bubbler. A device using a liquid stream to couple an ultrasonic beam to the test piece.

C

Caul. A sheet of material employed singly or in pairs in hot or cold pressing of assemblies being bonded. (Note: A caul is used to protect the faces of the assembly or the press platens, or both, and it may be made of any suitable material.) (From ASTM D907)

Couplant. A material used at the structure-to-sensor interface to improve the transmission of acoustic energy across the interface during acoustic emission monitoring. (From ASTM E610)

C-Scan. A means of data presentation that provides a plane view of the material and discontinuities therein. (From ASTM E500)

D

Dual Search Unit (Twin Probe). A probe or search unit containing two elements—one a transmitter, the other a receiver. (From ASTM E500)

F

Fluoroscope. Real-time viewing of X-ray radiography.

H

Holography (Acoustic). A data presentation system using acoustic waves; analogous to optical holography. (From ASTM E500)

Holography (Optical). A data presentation system using light waves to form an image.

Holography (Thermal). A data presentation system using temperature gradients; analogous to optical holography.

I

Immersion Testing. An examination method during which the search unit and the material are submerged in water. (From ASTM E500)

Impedance (Acoustic). A mathematical quantity used in commutation of reflection characteristics at boundaries, i.e., product of wave velocity and material density. (From ASTM E500)

Interface. The boundary between two materials. (From ASTM E500)

M

Mechanical Impedance. A technique that uses low-frequency mechanical vibrations to locate defects.

N

Neutron Radiography. A process of making an image of the internal details of an object by the selective attenuation of a neutron beam by the object. (From ASTM E500)

P

Probe. See Search Unit.

S

Search Unit. **A** device incorporating one or more transducers. (From ASTM E500)

Squirter. *See* Bubbler.

T

Through Transmission. A test procedure during which ultrasonic vibrations are emitted by one search unit and received by another at the opposite surface of the material examined. (From ASTM E500)

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Transducer. An electro-acoustical device for converting electrical energy to acoustical energy and vice versa. (From ASTM E500)

U

Ultrasonic. Pertaining to mechanical vibrations having frequency greater than approximately 20,000 Hz. (From ASTM E500)

V

Vibrothermography. A system that uses the heat developed by a defect under vibration to locate the defect.

Other sources of definitions of terms relating to NDT are ASTM E41 , E94, E253, E284, E500, E586, E610, E748, E1065, E1067, and D883; BSI BS 3683-PT4; DIN 50035-SH 1, and SH 2; and SAA AS 1929.

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