THE IMPORTANCE OF IMAGING IN NONDESTRUCTIVE CHARACTERIZATION OF MATERIALS

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Abstract: There is an ancient saying that "A picture is worth a thousand words". Never is this more true than when applied to nondestructive characterization of materials. It is also true that it was the very first nondestructive test. After God created the universe, he stopped and "saw that it was good". Visual inspection is still the nondestructive testing technique most often used in practical applications today. In this paper examples will be given of the vast spectrum of applications where imaging dominates.

Discussion:

Visual: Visual inspection is the primary technique for inspection of materials used in civil structures including bridges, highway trusses and support columns, roadbeds, pipelines and commercial airplane fuselages. In April 2002 a most remarkable image appeared on the cover of the journal Physics Today. It was a composite space satellite image of the earth at night showing that the industrialized and urbanized regions of the world consume prodigious amounts of energy compared with less affluent regions.

Optical: A variety of optical techniques have found important applications in the nondestructive characterization field. One example is where double pulse holography was used to image the leakage rate of "sealed packages" including an electronic package which was designed to be hermitically sealed for insertion inside the human body to control a heart pacemaker. Double pulse holographic methods have also been used to monitor for leaks in food cans, drug vials, microelectronic packages and the anisotropic layup of graphite epoxy composites to detect the presence of internal delaminations.

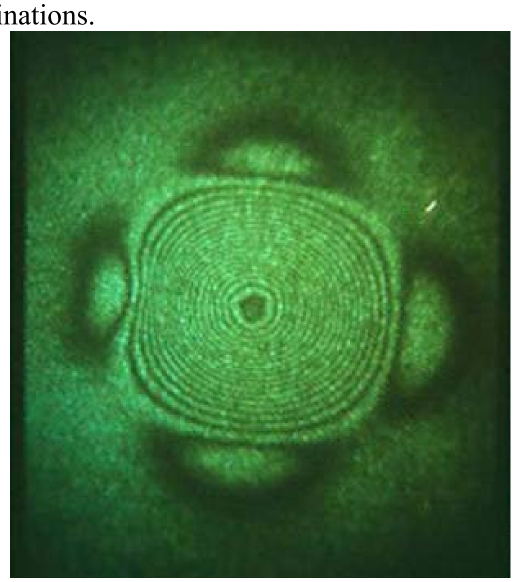

Figure 1. Double pulse optical holographic image of anisotropic layup of graphite epoxy composite showing delamination on left-hand side.

Thermographic and Vibrothermographic: Thermographic infrared images have been used to view heat patterns on the surface of objects ranging from cancerous human beings to heat profiles in industrial manufacturing applications. One of the early applications, which continues today, is vibrothermometry which typically uses an ultrasonic horn, operating in the 10-20 kHz range, to vibrate a test object in order to develop heat at defects in the structure which is detected with an infrared camera. An early example of the usefulness of vibrothermometry is the imaging of a delamination flaw in a full-scale production composite helicopter blade during fatigue testing. The delamination was so small that the blade lasted well beyond the expected service life and other existing nondestructive techniques failed to detect it. Since then, vibrothermography has been used by many investigators to look for heat generated at cracks, delamination in composites and metals and even grain boundaries in metals.

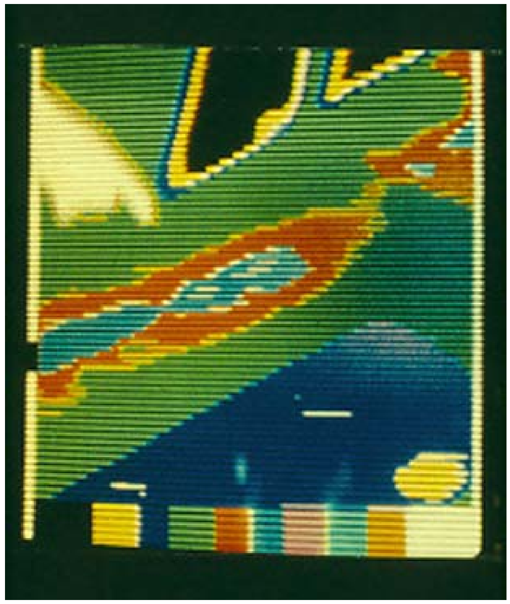

Figure 2. Vibrothermometry image of delamination flaw in a full-scale production composite heliocopter blade during fatigue testing.

Time Resolved Thermal Wave and Electron-Acoustic Wave Imaging: Initially thermal wave imaging used a laser beam to scan the surface of a test object placed in a closed gas-filled container. The amount of laser energy absorbed by the surface of the test object directly depends on he thermal properties of its surface. Variations in the amount of laser energy absorbed caused proportional variations in the gas pressure. Measurement of the gas pressure changes yielded information about the thermal properties of the test object as a function of the laser scan position. More recent developments have permitted elimination of the gas-filled container by use of a second probe laser beam which either detects surface displacements of the test object due to localized thermal expansion or changes in the refractive index of the air just above the test object surface. Thermal-acoustic imaging describes a further modification where the laser beam introduces heat locally and periodically onto the top surface of a test object and the elastic wave resulting from the local thermoelastic expansion is measured with a piezoelectric transducer coupled to the bottom surface of the test object. A further modification uses a chopped electron beam in a scanning electron microscope to excite thermal and elastic waves at the top surface of a test object. The elastic waves are detected either by a piezoelectric transducer coupled to the bottom surface or an optical interferometric displacement probe. By recording the output of the detector as a function of position of the scanning electron beam an electron-acoustic image of the test object is obtained.

Magnetic Imaging Methods: Magnetic resonance imaging techniques, which are well established in medicine, are also used successfully for creating visual images of defects in engineering materials. Magneto-optic eddy current imaging combines the principal of magneto-optical imaging and eddy current induction. By inducing eddy currents in an aluminum aircraft lap splice by using sheet currents in an induction coil, perturbations in the eddy current flow are communicated to the magneto-optic sensor. Magnetic fields normal to the test structure are created when the eddy current flow is disrupted by discontinuities. Any difference between the applied magnetic field and the magnetic fields generated by the eddy current flow are imaged by the magneto-optic sensor.

X-Radiography and Tomography: One of the nondestructive imaging techniques which has a most profound effect on both medicine and nondestructive testing is radiography. One of the largest x-ray radiographs ever taken was of the United States Liberty Bell when it was planned to move the bell from it's original location in Philadelphia, since there was concern about the famous crack growing larger and destroying the bell. The radiographic image was recorded on the largest sheet of x-ray film ever made at that time. However, in more recent years images of objects as large as cargo railway cars and tanker trucks have been made using a shuttered and collimated isotopic gamma-ray source or a pulsed-fast high energy neutron source coupled with a vertical array of large solid-state detectors. These detectors collect the gamma rays and measure the elemental contents (oxygen, nitrogen, etc.) of small volume elements inside the scanned container, analyze them with a computer, and display an image on a computer terminal screen. In addition to recording x-ray images on film, many modern images are obtained by using an electronic x-ray image intensifier and a television monitor and/or a computer. Such a system, operating in both the transmission and back-scattering mode is used to inspect baggage at airline terminals all over the world. Using a microfocus x-ray generator and an image intensifier detector, it is possible to obtain magnified images of objects such as composite honeycomb structures at increasingly higher magnifications. Most recently solid state imaging panel arrays are available, in a variety of sizes, which transfer images directly to computers. The most advanced x-radiographic imaging technique is x-ray computed assisted tomography (CAT) which permits imaging of detailed views of solid objects along any plane cutting through the object desired. One recent application has been to record images of slices through metal foam specimens in order to determine if the holes shown on the surface were due to a random distribution of spherical bubbles or tubular in shape passing through the body.

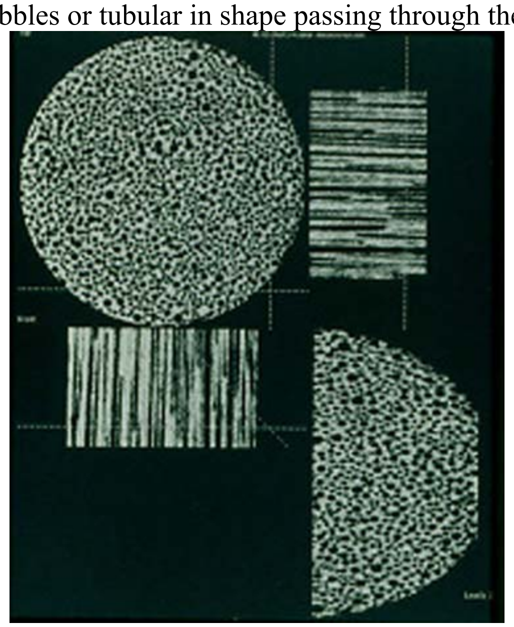

Figure 3. Slices of x-ray tomographic images through a metal foam specimen in order to determine if the holes shown on the surface were due to a random distribution of spherical bubbles or tubular in shape passing through the body.

X-ray Diffraction and Topography: Electro-optical systems optimized for rapid x-ray diffraction imaging have been used to rapidly determine the crystallographic orientation of single crystals, crystal lattice rotation accompanying plastic deformation, rate of grain boundary migration during recrystallization annealing of cold-worked metals, physical state of exploding metals, amorphous to crystalline phase transformation of rapidly solidified metals and the dynamics of structural phase transitions in ferroelectric crystals. X-ray topography permits recording an image of a single Laue spot over a large area of a single crystal. With synchrotron x-radiation images can be obtained through relatively thick crystals, i.e. several centimeters. Laue transmission topographic images have been obtained from a large portion of a gallium arsenide wafer by moving the x-ray detector a greater distance behind the wafer and recording the image of a single Laue line along the entire diameter of the specimen. Similar x-ray transmission topographic images have been obtained from vibrating quartz crystals without scanning to reveal their vibrational modes and from nickel single crystal turbine blades by scanning the blades and detector along their length in a back-reflection mode and thinner blades in a transmission more.

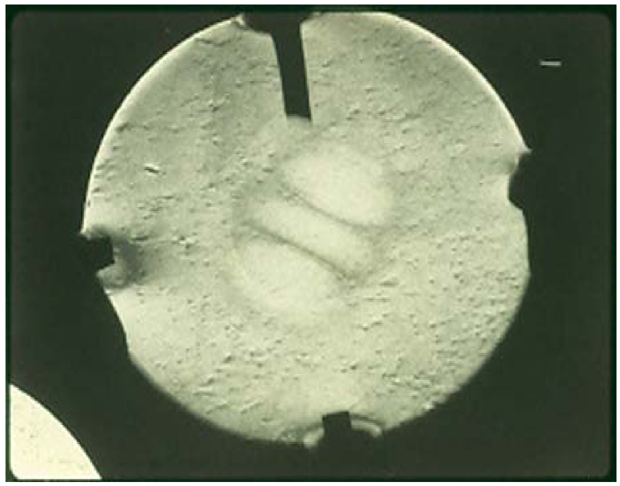

Figure 4. X-ray transmission topographic image of vibrating quartz crystal revealing vibrational modes.

Flash/Pulsed X-ray Imaging: Flash, or pulsed, x-ray generators, normally used for radiographic applications such as ballistic studies and baggage inspection, have also been used for rapid x-ray diffraction imaging. These devices produce x-ray tube currents of the order of thousands of amperes as opposed to the tens of milliamperes in conventional x-ray tubes. However, the burst of emitted x-radiation only lasts a few tens to perhaps a hundred nanoseconds. The result is an extremely high x-ray photo flux over a very short time span. Pulsed x-ray diffraction systems have been used to record x-ray diffraction patterns of exploding metal foils, shock-wave compression of pyrolytic boron nitride, phase transformations in ferroelectric crystals caused by polarity switching and electrically initiated temperature jumps, and to characterize shaped-charge metal jets. One most recent application is to use a small portable rechargable battery pack pulsed x-ray source and a portable CCD sensing array connected to a laptop computer to image defects in aircraft wiring.

Scanning Acoustic Microscopy: Scanning acoustic microscopy has developed to the extent that it possesses spatial resolutions comparable to optical microscopes. Since the contrast mechanisms depend on the elastic properties of the materials under examination, these instruments provide a valuable tool for materials characterization not obtainable in any other manner.

Contact Ultrasound: Piezoelectric transducers coupled to test objects either using water, oil, grease or polymer gels are among the most useful nondestructive techniques for looking for flaws and overall characterization of materials. Ultrasonic C-scans are routinely used in nondestructive testing applications. Ultrasonic tomographic imaging is used much less frequently, although much more information can be obtained by this method. Like x-ray tomography, ultrasonic tomography can provide images of any desired slice through a solid object, but since the ultrasound field is different from the x-ray field, information can be obtained using ultrasound that is not obtained by x-rays and vice-versa.

Non-Contact Ultrasound: A variety of non-contact ultrasound techniques are currently available including pulsed laser generators, optical interferometric detectors, electromagnetic acoustic transducers (generators and detectors), and air(gas)-coupled (generators and detectors).
Pulsed laser generators appear to be the most efficient and with a single pulse they can generate a longitudinal wave, a shear wave, and a surface Rayleigh wave. Also the frequency of the waves optically generated can be controlled by placing a shadow-mask consisting of a series of parallel alternating optically opaque and transparent lines between the laser pulse and the test object. Moreover, the laser pulse may be easily delivered to the test object by means of an optical fiber, or fiber bundle, to remote or difficult to reach locations. Recently laser generation/air-coupled detection systems have been optimized to monitor the mechanical tape laying process for manufacture of graphite/epoxy composites and for rapid inspection of railway rails and wheels.

Non-Contact Wire Insulation Inspection: Spacecraft and especially aircraft often fly well past their original design lives. A major problem that ensues is the aging of the wiring and associated electrical components, which are vital for control and operation. The most common aircraft wire insulation flaws are chafes, cracks, cuts, delaminations and embrittlement. The factors contributing to the insulation deterioration are mechanical vibratons, mechanical stress, moisture, elevated temperatures, repeated temperature fluctuations and exposure to chemicals.

Destructive testing of the wiring systems is both labor intensive and expensive since it involves removing the wiring from the craft, determining the serviceability, and then either reinstallation or replacement with new wiring. Currently, there are significant electrical originated fire hazards associated with aging and deteriorating wire insulation. Moreover, there are approximately 200 miles of electrical wiring on typical commercial jet aircraft. These wires have historically been inspected visually and a large number have never been inspected. Thus, it is essential that a method be developed to evaluate the status of the wiring bundles and individual wires in situ. Recently two noncontact imaging methods have been applied to solve this problem, namely infrared thermographic imaging and pulsed x-radiography.

Countering Terrorism: Unfortunately the people in our world find themselves continuously in conflict. One of the most insidious and difficult to control types of conflict is terrorism. Nondestructive imaging techniques play a very important role in countering terrorism. Nondestructive systems currently exist for imaging inspection of baggage, sealed containers and people for weapons, explosives, contraband and other hidden objects. Among the nondestructive techniques used are x-ray and neutron imaging, radar, microwave, ultrasonics and, infrared thermography, spectroscopy, holography and the synergism when using more than one technique.

Conclusions: The importance of imaging to nondestructive characterization of materials is self evident. Let this paper stand as a challenge to researchers to portray more results in an easily understood visual format, since it will enable less well trained nondestructive inspectors and those scientists and engineers not trained in nondestructive testing, to do a better job and make the world safer.

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