Nondestructive Testing: A Developing Tool in Science and Engineering

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Nondestructive testing (NDT), also known as nondestructive inspection (NDI) and nondestructive examination (NDE), is used to solve a wide range of problems in science and industry. Without any permanent changes or alterations to objects being examined, NDT methods provide advantages including increased testing reliability, efficiency, and safety, as well as reduced inspection time and cost. Since the second half of the 20th century, NDT technology has advanced significantly. NDT techniques are classified into several branches depending on the physical properties being measured. This article provides a brief overview of commonly used NDT methods and their technological advancements including optical examination, radiography, acoustic emission, and ultrasonic testing. Extended reviews on many currently used NDT methods are given in Ref. 1 and 2.

Optical examination

Probably the most widely used among all NDT methods is optical examination, especially in checking surface flaws and defects. Without any optical aids, examination with human eyes is a convenient, valuable NDT method, and is usually low in cost [3]. With the aid of optical tools like microscopes, borescopes, endoscopes, telescopes, and holography, the capabilities of visual examination are significantly extended. One of the most frequently used devices for visually magnifying defects is the microscope. However, its depth of field is normally shallow, providing a limited area of sharp surface image around the region of interest. The depth-from-defocus (DFD) method introduced in the 1990s [4] helps to solve this problem, enabling visual examination of very rough surfaces using new digital microscopes.

Other optical methods developed after the 1980s also advanced NDT technology. Digital image correlation (DIC), comparing images of the same specimen before and after deformation, allows measuring displacement and strain fields without contacting the specimen surface and provides high resolution results continuously and instantaneously [5]. Normally, the region of interest (ROI) on the sample is divided into a certain number of subsets. The deformation of each subset can be calculated by individual correlation analysis, rendering a full-field measurement thereafter. Synchronously, a series of photos of the sample are taken and stored while applying the load, making continuous measurement a reality.

To track local displacement with good accuracy, a random speckle pattern on the sample surface is required for DIC analysis. Therefore, the sample surface is painted with fine black and white dots if it is optically homogeneous. Figure 1 shows an example of displacement and strain fields of a plane sample subjected to a tensile load measured using a DIC system [6]. Displacement measurement accuracy is within 0.05% and strain measurement accuracy could be as high as 0.5%. Currently, commercial DIC products are widely applied in both fluid-mechanics and material-mechanics research.

A recent advancement in optical technology is electronic speckle pattern interferometry (ESPI), which uses short-wavelength lasers to obtain interferometry images of specimens. By calculating speckle patterns before and after deformation, this technology can achieve a much higher accuracy in deformation measurement (as high as 20 nm) than DIC technology [7]. Application of DIC and ESPI technologies in NDT can be further extended when they are combined with other optical devices, such as microscopes.

Radiography and tomography

Radiography (two dimensional, or 2D) and tomography (three dimensional, or 3D) can detect internal defects within bulk samples. The principle of radiographic examination is based on the different degree of radiation absorption...
due to differences in material properties and variations in component thickness. Various radiation sources can be used including x-rays, gamma (γ)-rays, and other penetrating radiations[^9]. X-ray is the most used source among all radiation sources. The wavelengths of x-rays are in the range of 0.01 to 10 nm, corresponding to energies in the range of 100 eV to 100 keV. In 1967, the idea of a computed tomography (CT) scanner was conceived by Godfrey Newbold Hounsfield[^11], enabling the 3-D x-ray measurement method.

Recently, synchrotron x-ray CT was used in in-situ ultra-high temperature tensile tests at Lawrence Berkeley National Laboratory’s Advanced Light Source in Calif. Three-dimensional CT scans were taken to show the formation of microcracks in ceramic composites under applied tensile loads at 1750°C, obtained using a unique mechanical testing rig (Fig. 2)[^8].

The x-ray CT scanning method guarantees not only detection, but also accurate measurement of flaws, defects, and cavities in the object. Some commercially available CT products (e.g., SkyScan 1173 Micro-CT, Micro Photonics Inc., Allentown, Pa.) can acquire images with a 4-micron/pixel resolution. These units can even be made small enough to be stored in an on-board luggage cage for great portability.

However, there are several limitations of x-ray CT techniques. The principle of x-ray inspection requires placing the test sample between the x-ray source and the radiation-sensitive film or detector screen, which limits sample size. The method also requires use of an x-ray shield, or personnel must evacuate the working area. In addition, x-ray penetration depth is limited even with higher radiation energy.

Gamma (γ) rays with frequencies above 10¹⁹ Hz and energies above 100 keV are more powerful than x-rays[^10]. A mobile γ-ray system (e.g., VACIS imaging system, SAIC Inc., McLean, Va.) can penetrate steel 6.25 in. thick, and components tested typically are huge containers or vehicles up to 13 ft high × 8 ft wide × 100 ft long.

Neutrons, which can be absorbed by hydrogen with a specific high ratio, complement the application of x-rays[^11]. Neutron radiography provides more contrast for organic materials than x-ray radiography does. The proton can also provide beams with energies of several hundred MeV to penetrate thick, dense objects, with a possible 0.05% density discrimination[^11]. However, application of both neutron and proton radiography is very limited due to the availability of stable sources generated by atomic reactors, spallation sources, and radioactive isotopes. Laboratories like Spallation Neutron Source at Oak Ridge National Laboratory achieved remarkable research in these rare facilities.

These radiography methods, integrated with 3-D geometry-reconstructing technology, expand the use of NDT into wider applications. In many industries, computer aided design (CAD) and computer aided manufacturing (CAM) are replacing traditional blueprints. Coupling radiography methods with CAD and CAM to provide an accurate measurement of a device, object, or system without disassembling or damaging it created a novel process called reverse engineering. Geometry data from radiography is imported into CAD software directly rendering a virtual 3-D model without any drawings. The software gives users more flexibility to review, modify, update, and store object details. Furthermore, the 3-D model can be input into CAM software for direct manufacturing, such as 3-D printing. This emerging technology can benefit from the radiography-reconstructing process. In addition, 3-D models generated from radiography can be imported into finite element analysis (FEA) software or computational fluid dynamics (CFD) software for numerical simulation, which enables virtual testing to save time and expense.

**Acoustic emission**

Any local plastic deformation or fracture event inside a solid material releases energy. Part of the released energy is converted into elastic waves that propagate through the material and can be detected at the material surface using high-sensitivity sensors. This phenomenon is called acoustic emission (AE). The AE source can be identified and located using a sufficient number of sensors with appropriate configuration. A diagram of the AE method is shown in Fig. 3.
The AE method emerged in the middle of the 20th century. Manson, et al. in the U.S. and Kaiser in Germany studied the phenomenon of acoustic emission independently. In 1964, a practical application of the AE method was applied to detect flaw growth during hydrostatic testing of Polaris missile chambers. In most applications, the AE frequency range is between 1 kHz and 1 MHz.

AE has been successfully applied to field tests such as leak detection of pipelines, surveillance of known flaws in pressure vessels, and monitoring suspected slow fatigue crack growth in reactor process piping. In laboratories, AE was successfully used to detect and monitor the degradation of silicon electrodes for lithium-ion batteries. When silicon is lithiated at room temperature, it undergoes a volume expansion in excess of 280%, which leads to an extensive fracturing that could cause a rapid decay in cell capacity. Distinct emission bursts were measured on charge and discharge steps, which were identified as the brittle fracture of silicon particles. In addition, the method was applied to detect flaw formation in welds, stress corrosion cracking, and fatigue failures.

The AE method has drawbacks due to the high resolution necessary to locate the moment and position of crack sources. Existing cavities and cracks cannot be detected by AE sensors directly without applying a load. Electromagnetically induced acoustic emission (EMAE) partially addressed the problem, but is unable to detect the size or shape of the flaw. Furthermore, it is difficult to distinguish AE signals from other background noise.

### Ultrasonic techniques

Instead of passively listening to elastic waves emitted from plastic deformation or a crack developing (such as with AE methods), short ultrasonic pulses can be sent into a structure being tested, and echoes through the structure can be detected to locate internal flaws. Unlike the AE method, the test structure does not need to be loaded in ultrasonic testing (UT). Figure 4 shows a simple illustration of pulse-echo style ultrasonic testing. The transducer serves as the echo receiver as well. Generally, sound waves with frequency above 20 kHz are categorized as ultrasonic. The range of frequencies used in UT is > 0.1 to <15 MHz, and wavelengths range from 1 to 10 mm.

UT was developed around the same time as acoustic emission. Inspired by sonar technology before World War II, early ultrasound investigators migrated the echo concept to ultrasonic medical diagnosis. In the 1930s, UT theory and application were discussed and developed by Sokolov and Mulhauser individually. In the next decade, Firestone (1940) and Simons (1945) developed pulse ultrasonic testing using a pulse-echo technique, which required only one transducer and has become the most generally used method. Besides detecting defects, ultrasonic methods are often used to measure sound velocities in solid materials, which, in turn, are used to determine the material's elastic properties, such as Young's modulus, shear modulus, etc.

An advantage of many ultrasonic tests is portability. Benefiting from the developing of computer and automation technologies after the 1980s, automatic ultrasonic testing scanning systems like Raptor - Imaging Flaw Detector (Advanced NDT Ltd., Worcester, UK) are available. Smaller handheld portable devices like TI-25M (Electromatic Equipment Co. Inc., Cedarhurst, N.Y.) make the method suitable for inspecting complex uneven surfaces. Also, immersion inspection (immersing the object into water for ultrasound scanning) is helpful in examining samples with complicated geometries. However, very coarse castings are not suitable for ultrasonic testing because the coarse grain structure gives high sound scattering and low signal-to-noise ratio.

Another closely related technique measures the response of solid materials subject to ultrasonic excitation, which can determine the natural vibrational frequencies (eigen values) of the materials. These eigen frequencies can be used to inversely calculate material stiffness. One example is resonant ultrasound spectroscopy (RUS). In a typical RUS test, cylindrical or rectangular parallelepiped samples are used without special sample installation, and measurement can be completed in a few minutes. RUS can be easily integrated with various testing environments (e.g., high temperature, vacuum, inert atmospheres, etc.), making it a versatile NDT technique.

### Summary

In addition to the techniques discussed above, other NDT methods, such as liquid penetrant testing, magnetic particle testing, eddy current testing, thermography, in-situ metallographic examination, and liquid/gas leak testing, are also used in different kinds of applications. With the rapid growth of computational technology, traditional NDT methods are being updated, providing new benefits.
and added value to research and industry. Among the new applications of NDT methods is quantitative nondestructive evaluation. It extracts more useful information from a specimen, and could be the future direction of NDT.

References

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