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MAE 589 **Prof. D.D.L. Chung**

Diffraction, Microscopy and Spectroscopy Techniques

1. Introduction

The most basic function of a smart structure is sensing. The sensing of damage is particularly important, since damage is a hazard. Damage sensing is akin to nondestructive evaluation (NDE) or nondestructive testing (NDT), which refers to the evaluation or testing of a component without harming the component, so as to assess the quality (during or after manufacture) or condition (during or after use) of the component [1-6]. Assessment during manufacture enables adjustment of the manufacturing conditions of either the particular component being manufactured or similar components to be manufactured, so as to improve the quality of the product; this assessment relates to smart manufacturing and quality control. Assessment during use enables the monitoring of damage induced by the use (whether damage due to fatigue, heat, corrosion, etc.), so as to mitigate hazards; this assessment relates to smart structures and structural health monitoring. These notes describe sensing methods that involve materials or instrumentation that are external to the structure. These methods are commonly used for inspection because they are non-intrusive and widely applicable, though they are limited to the sensing of damage such as cracks. Strain, residual stress and subtle damage cannot be sensed. Moreover, they may not be amenable to sensing in real time.

2. Liquid penetrant inspection

Liquid penetrant inspection is for detecting surface defects. It involves applying a penetrant (a liquid that wets) to the surface to be inspected by dipping, spraying or brushing. The penetrant is then pulled into the surface crack by capillary action (Fig. 1(b)). After allowing sufficient time for the penetrant to be drawn into the surface cracks, the excess penetrant is removed (Fig. 1(c)). After this, a developer (an absorbent material capable of drawing the penetrant from the cracks back to the surface) is applied, so that some penetrant is extracted to the surface (Fig. 1(d)) and visual inspection is possible. In order to make the penetrant more visible, brightly colored dyes or fluorescent materials are often added to the penetrant. Moreover, the developer is usually chosen to provide a contrasting background. After inspection, the developer and remaining penetrant are removed by cleaning.

3. Ultrasonic inspection

An ultrasonic wave has higher frequency than audible sound. The frequency typically ranges from 25 to 100,000 MHz. A higher frequency means a shorter wavelength, which allows smaller defects to be detected.

Ultrasonic inspection [7-15] involves sending an ultrasonic wave emitted by a pulsed oscillator and transducer (a piezoelectric actuator that changes electrical energy to mechanical vibration) through the material to be inspected and measuring the intensity of the reflected wave

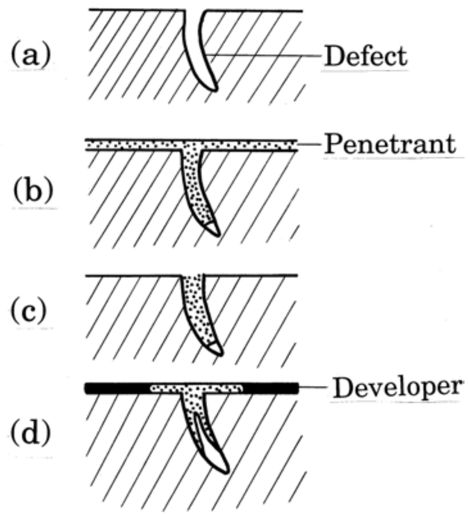

Fig. 1 Liquid penetrant inspection.

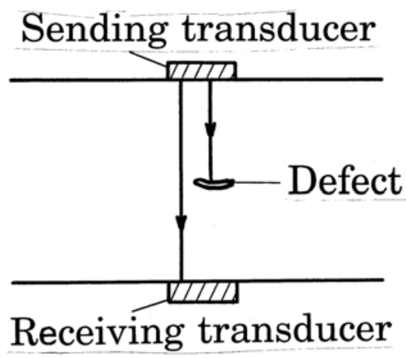

Fig. 2 Ultrasonic inspection involving two transducers in the through-transmission configuration.

or the transmitted wave, as well as the time it takes for the wave to be detected. A defect such as a crack acts as a barrier for the transmission of the wave, so that the intensity of the transmitted wave is decreased, as illustrated in Fig. 2, where two transducers (a sending transducer to send the wave and a receiving transducer to detect the transmitted wave) are used in the through-transmission configuration.

The through-thickness (in-line) configuration also allows measurement of the time it takes for the wave to go from the sending transducer to the receiving transducer. This time, together with the distance between the two transducers, gives the ultrasonic sound speed of the material under inspection. During the curing of a thermosetting resin, the ultrasonic sound speed of the resin changes. This makes sense since the viscosity increases greatly as curing takes place. Hence, measurement of the ultrasonic sound speed allows cure monitoring. Another method of cure monitoring is the dielectric method, in which the AC electrical conductivity is measured. This conductivity is the ionic conductivity, which changes during curing. Yet another method of cure monitoring uses an optical fiber.

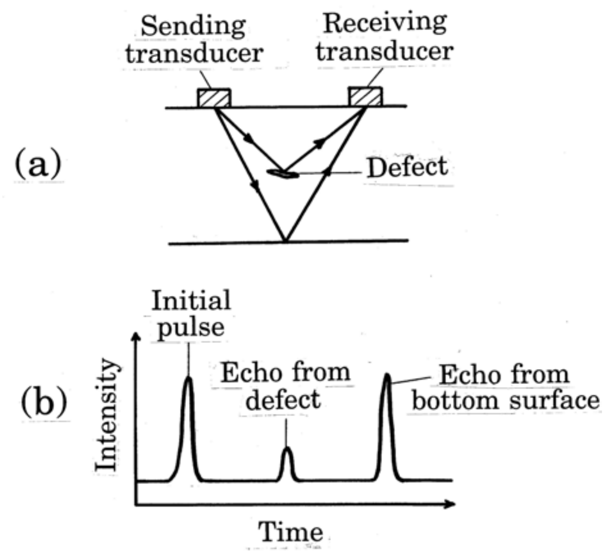

Fig. 3 (a) Ultrasonic inspection involving two transducers in the pulse-echo mode.
(b) Plot of intensity (transducer voltage) versus time showing the initial pulse and echoes from the bottom surface and the intervening defect.

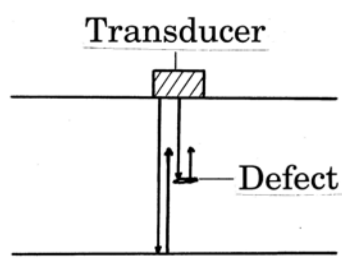

Fig. 4 Ultrasonic inspection involving a single transducer.

A defect provides an interface which reflects the wave, so that a reflected wave is detected at an earlier time compared to the time when the reflected wave from the bottom surface is detected, as illustrated in Fig. 3, where two transducers are used in the pulse-echo mode. An oscilloscope may be used to obtain the plot in Fig. 3(b). The time of the echo from the defect gives information on the depth of the defect. The intensity of the echo gives information on the size of the defect. It is possible for the receiving transducer and the sending transducer to be the same transducer, as shown in Fig. 4, but this is limited to the pulse-echo mode.

Since air is a poor transmitter of ultrasonic waves, an acoustic coupling medium (a liquid such as water, oil or grease) is needed to connect a transducer to the material to be inspected. Fig. 5 illustrates the use of water as a coupling medium in a pulse-echo configuration similar to Fig. 4. Note that Fig. 5(b) and 3(b) differ in that the echo from the front surface is present in Fig. 5(b) but absent in Fig. 3(b). The use of a coupling medium also means that the transducers do not have to make contact with the material under inspection. The non-contact configuration is particularly attractive when the material under inspection is hot.

An ultrasonic technique that is more sensitive for the detection of defects than the technique described in Fig. 2-5 involves measuring the attenuation of the intensity of the

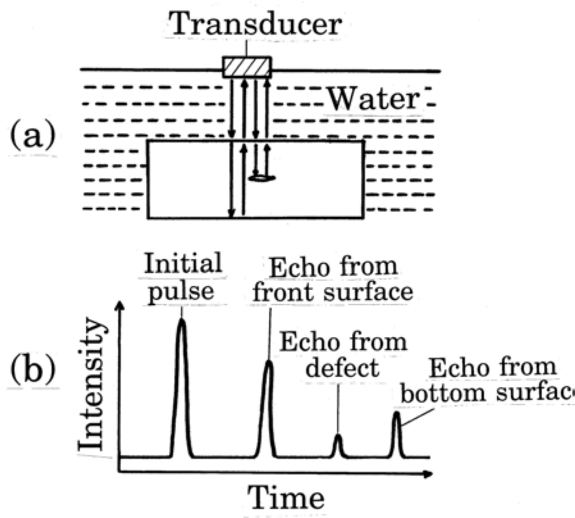

Fig. 5 (a) Ultrasonic inspection involving a single transducer connected to the material to be inspected by water, which serves as an acoustic coupling medium.
(b) Plot of intensity (transducer voltage) versus time showing the initial pulse and echoes from the front and bottom surfaces and the intervening defect.

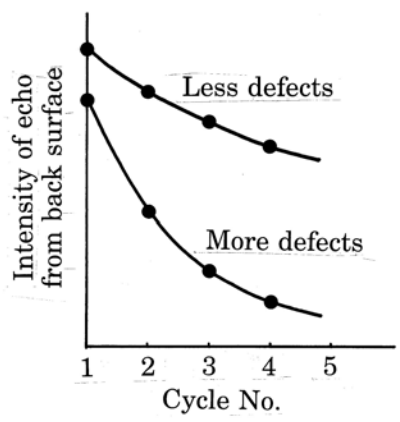

Fig. 6 Attenuation of ultrasonic wave upon travelling through the material. One cycle means traveling from front surface to back surface and then back to the front surface.

ultrasonic wave upon bouncing back and forth by the front and bottom surfaces of the material under inspection. The greater is the amount of defects in the material, the greater is the attenuation from cycle to cycle (one cycle meaning one travel of the wave from one surface to the other and then back to the first surface). For example, the echo from the back surface (Fig. 4) is recorded as a function of the cycle number, as shown in Fig. 6.

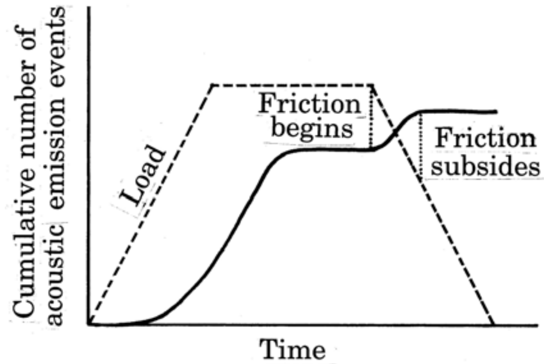

Fig. 7 Plot of the cumulative number of acoustic emission events vs. time (solid curve) and plot of load vs. time (dashed curve) during loading and subsequent unloading of a fiber composite experiencing delamination during loading and friction between delaminated surfaces during unloading.

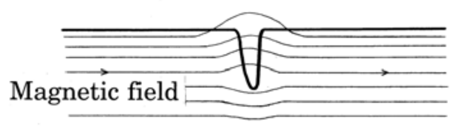

Fig. 8 Distortion of the magnetic flux lines due to a surface crack in a ferromagnetic or ferrimagnetic material.

4. Acoustic emission testing

In response to an applied stress, a material may develop defects such as cracks. The process is accompanied by the emission of ultrasonic waves. This is known as acoustic emission (AE) [16-19]. The detection of these waves emitted by a material provides a means of damage monitoring in real time. Detection is achieved using receiving transducers. By the use of two or more transducers in different locations of a test piece, the location of the damage can be determined. The energy of an acoustic emission event relates to the damage mechanism, e.g., fiber breakage vs. delamination in a fiber composite. Acoustic emission occurs during loading, as defects are generated during loading. However, some damage mechanisms, such as delamination, cause acoustic emission during unloading, in addition to more extensive acoustic emission during loading. In the case of delamination, this is due to frictional noise associated with the adjacent delaminated surfaces coming in contact as unloading occurs (Fig. 7).

5. Magnetic particle inspection

The magnetic flux lines in a ferromagnetic or ferrimagnetic material are distorted around a defect, since the defect (such as a crack) has a low magnetic permeability ($\mu_r = 1$ for air). This distortion is illustrated in Fig. 8 for a surface crack. As a result of the distortion, magnetic flux lines protrude from the surface at the location of the surface crack (Fig. 8). This is known as field leakage, which attracts magnetic particles that are applied to the surface of the material to be inspected. Hence, the location of the magnetic particles indicates the location of the defect.

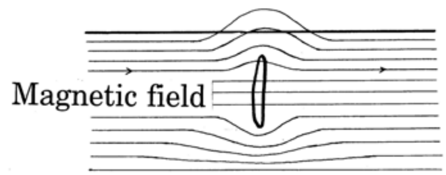

Fig. 9 Distortion of the magnetic flux lines due to a subsurface defect.

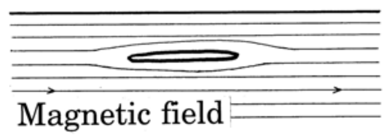

Fig. 10 Little distortion of the magnetic flux lines when the length of the defect is parallel to the applied magnetic field.

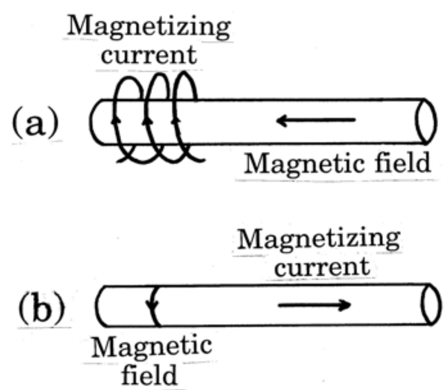

Fig. 11 (a) An axial magnetic field generated by a circumferential electric current.
(b) A circumferential magnetic field generated by an axial electric current.

A subsurface defect that is sufficiently close to the surface can also be detected, as shown in Fig. 9.

This method [20,21] requires applying a magnetic field in a suitable direction, which is preferably perpendicular to the length of the defect in order to maximize the distortion of the magnetic flux lines. As shown in Fig. 10, a defect that has its length parallel to the applied magnetic field does not cause much distortion of the magnetic flux lines. A magnetic field along the axis of a cylindrical sample may be applied by passing an electric current circumferentially, as shown in Fig. 11(a). A circumferential magnetic field may be applied by passing a current in the axial direction, as shown in Fig. 11(b). Depending on the direction of the magnetic field, defects of various orientations are detected.

This method is restricted to ferromagnetic and ferrimagnetic materials.

6. Eddy current testing

An eddy current is an electric current induced in an electrically conducting material due to an applied time-varying magnetic field. The phenomenon is due to Faraday's law, which says that a voltage (and hence a current) is generated in a conductor loop when the magnetic flux

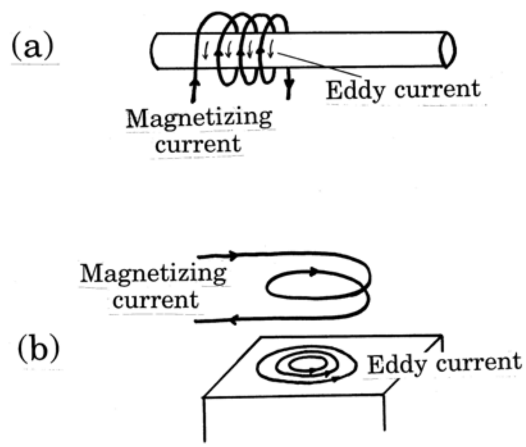

Fig. 12 The generation of an eddy current by an applied magnetic field. (a) A cylindrical sample. (b) A flat sample.

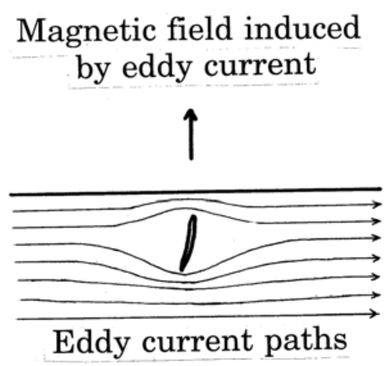

Fig. 13 Distortion of eddy current paths around a defect.

through the loop is changed. The eddy current is in a direction such that the magnetic field that it generates opposes the applied magnetic field. If a circumferential current is used to generate the applied electric field, the resulting eddy current is in the opposite direction from the magnetizing current, as shown in Fig. 12 for a cylindrical sample and a flat sample.

The eddy current paths are distorted around a defect, which is a region of higher electrical resistivity, as shown in Fig. 13. Hence, the magnitude of the eddy current is diminished. As a result, the magnetic field induced by the eddy current is decreased. Thus, this magnetic field, as sensed by a sensor coil, indicated the severity of the defect. By moving the sensor coil to different locations on the sample surface, the location of the defect is detected.

This method [22] is limited to electrically conducting materials.

7. X-radiography

Internal defects are usually best detected by x-radiography [23-26], which involves sending x-ray through the material to be inspected and detecting the transmitted x-ray image using a photographic film (as in chest x-ray), as shown in Fig. 14. A pore in the material to be

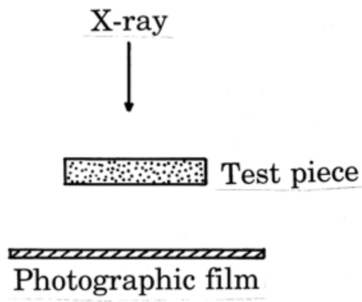

Fig. 14 X-radiography set-up involving an x-ray source and a photographic film, with the material to be inspected in between them.

inspected is low in density, so it gives more transmitted intensity and hence greater film darkening. On the other hand, an inclusion of high density in the material gives less transmitted intensity and hence less film darkening.

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