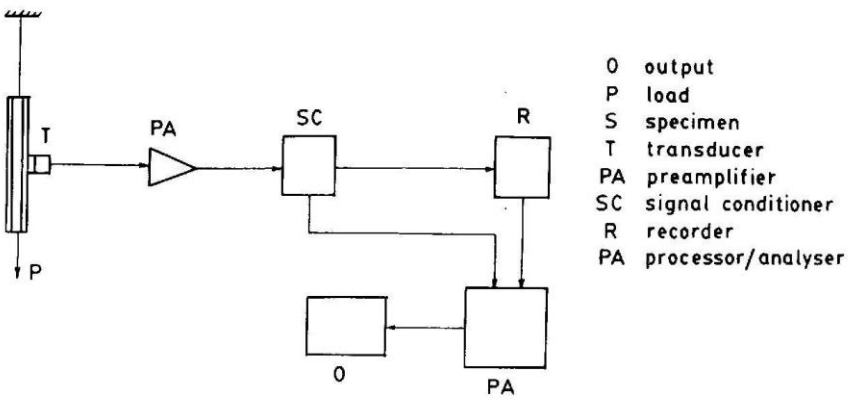
NDT METHODS

1. Acoustic Emission

Acoustic Emission (AE) is essentially a technique of listening to a material. Whenever there is a change of condition in the material during loading and other service conditions, e.g., the initiation and propagation of a crack, sound waves (transient elastic waves) are generated by the rapid release of energy and propagate through the medium which contains that crack. These sound waves can be detected using an AE sensor glued to the surface of the medium at a convenient location. In the early fifties Joseph Kaiser, a German scientist, conducted experiments with metals and wood using sensitive electronic instruments and listened to the sound emitted by these materials during the process of deformation. He noted a phenomenon, termed as 'Kaiser Effect', that a material that had emitted AE signals during earlier stressing, would exhibit AE signals again when the previous stress was exceeded. Since Kaiser's first experimentation, there has been an all-round growth in the use of AE techniques in materials and structures including composites. AE sensors (piezoelectric transducers) are in principle high frequency microphones which first receive the sound waves and then convert them to electrical signals. These signals are very weak and therefore are amplified before they are passed to the signal conditioner where other electrical noises are filtered out. The filtered AE signals are then processed and analysed. A simple AE measurement system is schematically illustrated in Fig.



The electrical signals received by an AE sensor are processed by a wide variety of parameters

(i) count rate and total count of the number of signals which exceed a reference threshold,

(ii) distribution of signal amplitude as a function of stress and time,

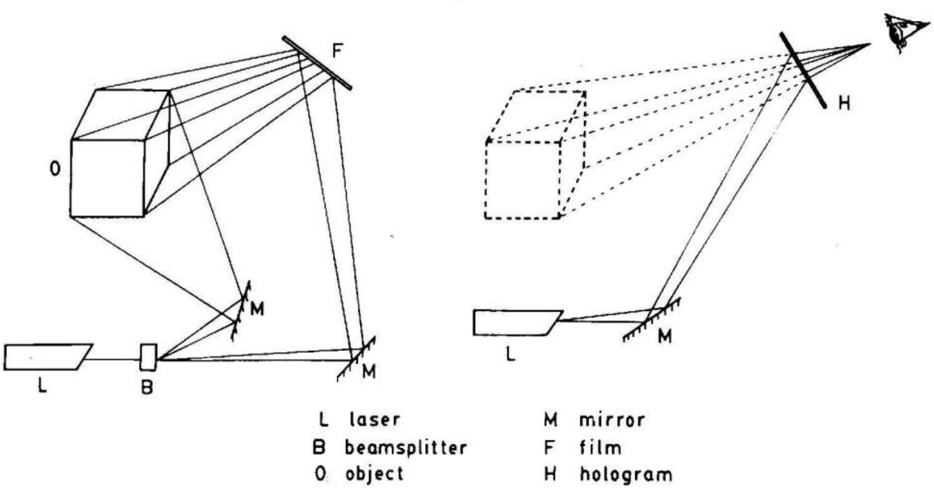
(iii) energy of the detected signals

(iv) frequency content of the signals.

AE can also be used to locate the crack or the signal source which emits AE signals. This requires the use of multiple transducers, and the source is located by the triangulation method, normally used to locate a seismic source. AE is an active NDT method and can be utilized for condition monitoring of composite parts and production control, as well as assessing severity of flaws and damages. It has been used extensively in composites not only to identify various failure modes, to define defects and to locate AE sources, but also to conduct real time monitoring during proof testing and in service. Each failure mode, namely, fibre breaking, matrix cracking, interfacial debond or delamination is found to exhibit distinct characteristic AE signals. But the identification of individual modes becomes extremely difficult when two or more failure modes occur simultaneously. The types of fibres and matrices, the anisotropy, the stacking sequence, structural boundaries, presence of micro-defects, etc. can considerably influence the AE signals and their propagation characteristics. All these problems need to be solved before AE can be routinely used as an NDT tool in development of composite materials and structures.

2. Holographic Interferometry

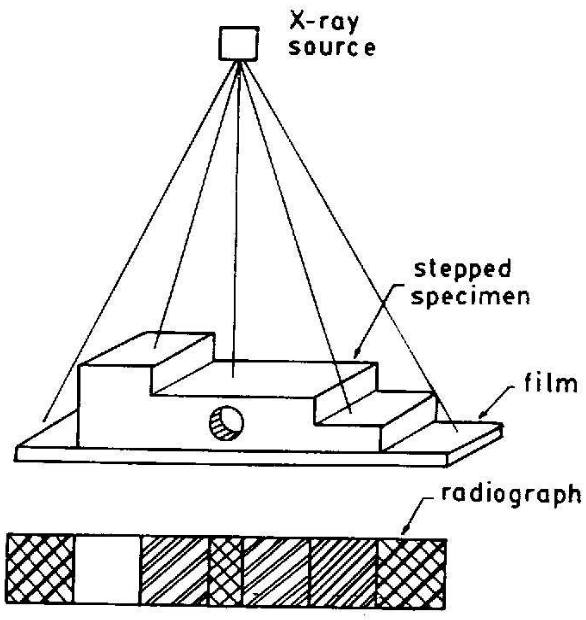
The holographic technique was discovered by Nobel Laureate Dennis Gabor in 1947, but it gained prominence after the discovery of the helium-neon laser in 1962. In holography, the entire optical wavefront both with respect to amplitude and phase is recorded in a film and phase is recorded in a film is called 'hologram' (after the Greek word holos meaning 'whole'). A hologram preserves the three-dimensional character of an object for which the hologram has been made. A simple holographic set-up (Fig) mounted on a vibration isolated table, uses a laser, the light from which is split into two waves by a beam splitter. One wavefront i.e., the reference wavefront after being reflected from a mirror system reaches directly a holographic film. The other wavefront, i.e., the object wavefront reaches the film after being reflected from the object. The two wavefronts create a complex interference pattern which is recorded on the holographic film. The interference lines represent points with the same displacement. The coherence of the laser light permits the interference of these two waves, although there exist relatively large differences in path length. The recorded holographic film, or the hologram when illuminated with the reference wave, the object wave is reconstructed and a three-dimensional view of the object can be observed behind the hologram (Fig). Several images which interfere with each other can be stored on the same film, which can be reconstructed when required. The holographic interferometry (HI) uses the technique of multiple exposure for application in NDT. The popular double exposure method, in which holograms of an object in two different states, e.g., stressed and unstressed, provide anomalies in the interference pattern which may in turn, reveal the existence of a flaw if any. The double exposure method is also known as frozen fringe HI. There are other HI methods which are used for specific purposes. The 'simultaneous method' or real time HI first creates a hologram of the object in a desired reference state, which is later used as a reference hologram with respect to which subsequent changes in the object position are recorded by filming the hologram image. The 'time averaging method' is used to record small amplitude oscillations of vibratory parts. The hologram of a vibrating body is first recorded on a film for a time interval longer than the period of oscillation and in the process a set of holograms are superimposed. The resulting hologram when reconstructed, reveals nodal lines as dark interference stripes. HI has a great potential for NDT applications. The capability of HI is enhanced considerably after the introduction of video and popular with the NDT personnel working in the field of composites and composite structures. The use of phase-locked holography may alleviate problems associated the low frequency environmental vibration. The phase-locked holography uses the diffuse reflection of an unexpanded beam shone on a small portion of the test object as the reference beam. Another important development in this area is the electronic shearography in which no separate reference beam is used. In this case, the returning object beam is doubly imaged with a video system. One image is then found to be slightly shifted or sheared relative to the original one.



a) Making a hologram *b) Viewing through a hologram*

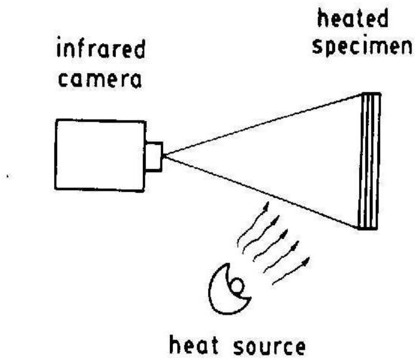
3. Radiography

X-ray radiography is the most commonly used NDT technique in industrial applications. X-rays are independent of the magnetic and electrical properties of a material and hence can be used with all materials. Two major characteristics of X-ray radiographic NDT method are that X-rays are absorbed differentially by different media and they produce photochemical effects in photographic emulsions. The intensity of a transmitted X-ray beam, when it passes through a medium, is given by $I = I0\ e^{-\alpha h}$ where I is the intensity of the transmitted beam, I_0 is the intensity of the incident beam, α is the absorption coefficient of the medium and h is the thickness through which the beam travels. The absorption coefficient (α) depends not only on the material, but also on the wavelength of X-rays. Thus it is observed from Eq 5.10 that the X-ray beam attenuates when it passes through a material. The attenuation depends on the absorption coefficient and the thickness of the material. If there exists any defect, say, a void, in the material, the void ($\alpha = 0$) does not absorb X-rays. So the intensities of the X-ray beams passing through the material thickness with and without a void will be different. When these transmitted beams are allowed to strike a photographic film, they create a contrast on the exposed film or radiograph (i.e., more the intensity, darker the film appears) from the knowledge of which the existence of a void can be predicted. It is also possible to determine the thickness and composition of a material by examining differences in the exposed film. The Fig. illustrates the principle how the radiograph is produced when a stepped specimen containing a hole is exposed to X-rays. Normally voids of small sizes (closer to fibre dimensions), and cracks and delaminations that exist normal to the X-ray beam are not easily detectable. However, inclusions, cracks, delaminations and other material defects and damages that are aligned parallel to the X-ray beam can be readily revealed. The X-ray radiography has also been applied to investigate the microstructural details of damages using low energy X-rays as well as using an X-ray opaque penetrant (e.g., tetrabomo-ethane or zinc iodide). The penetrant, however, should not react chemically with the constituents of the composite medium. The development of radiography with microfocus (in which electrons are focused on a small area by means of a magnetic field) opens up new vistas for locating smaller details closer to fibre dimensions (10μm). Microfocus radiography combined with real time image processing can be conveniently applied to investigate the nucleation and growth of cracks, delaminations and damages in composite and honeycomb structures. A large portion of the attenuation of the X-ray beam, especially with low X-ray photon energies is due to Compton scattering. The X-ray backscatter imaging uses the process of recording and investigating scattered radiation from the object. The backscatter radiation provides quantitative information about variations in density due to presence of flaws, delaminations, etc. as well as change in materials. The method is found to be very useful for the inspection of laminated composite pressure vessels and motor cases, and very tight delaminations can be easily detected. Computerized tomography (CT) provides a three-dimensional image of the desired section of an object and therefore all minute details of the variations in the image slice are recorded. The image is called a tomogram (after the Greek word tomos means 'to cut'). A point source of X-rays or gamma radiation is collimated to a flat, fan shaped beam which penetrates the slice of an object under inspection. The intensity of the transmitted beam is recorded by a detector. The movements of the beam and the recorder can be synchronized when the beam is rotated about the object along with the recorder and thereby a three-dimensional scanning of the whole slice is carried out. CT is now widely used in medical diagnostics and offers a great potential for uses in composite materials and structures. Neutron radiography is another NDT technique which is finding applications in polymer composite structures. However, the major limitation of this method is that a transportable neutron source should be available at the site of inspection.



4. Thermography

Thermography is also an effective NDT technique. It is basically a method of mapping and interpreting the contours of isotherms (equal temperature) over the surface of a body. A variation in the thermal field within the body occurs due to the presence of inhomogeneities, discontinuities and other defects which form hot or cold regions depending on their thermoelastic properties. These hot or cold regions exhibit sharp temperature gradients and can be located in the isothermal mapping. A thermal field within a body can be created externally by exposing it to a hot or cold source, or internally during the process of deformation when being loaded. A low level of mechanical vibration can raise the temperature in the regions containing discontinuities. A low temperature field may require spraying the body with liquid nitrogen. The thermal wave imaging technique employs a pulsed heat source to create pulsed thermal waves in the body. The thermal waves are then detected using acoustical or optical methods. Thermal patterns or isotherms are usually recorded employing an infrared electronic camera (Fig). These are then related to inhomogeneities or defects. Thermography has been successfully used to detect delaminations and other types of flaws in composites. The final image was acquired by heating the rear side of the panel using a hot air gun and focusing the infrared camera on the front side. Thermography finds extensive uses in metal-matrix composites, as metals are, in general, good thermal conductors. The real time thermography permits scanning and imaging a large surface area in a shorter period of time. The vibro-thermography, in which mechanical vibrations are employed to induce thermal gradients near the damage regions, combined with the real time recording using an infrared video camera has been used to investigate damages in composites.



5. **Ultrasonics**

Ultrasonics is also a popular NDT technique for composites. The ultrasonic inspection in composites employs high frequency sound pulses usually in the megahertz range. Piezoelectric transducers are normally used to produce sound pulses. These sound pulses (ultrasonic signals) are allowed to propagate as a narrow beam through a material under examination. The sound waves attenuate based on the characteristics of the material (even if it is homogeneous) as given by the relation $I = I_o e^{-\alpha h}$ where I is the intensity of the transmitted sound wave, I_0 is the original intensity of the sound wave, α is the attenuation constant and h is the distance travelled by the sound wave. The intensity of propagating signals attenuates further due to the presence of inhomogeneities (e.g., different materials, poor adhesive bonding, etc.) and discontinuities (e.g., delamination, cracks, voids, etc.) in the material. The sound signals are scattered and /or reflected at the interfaces of these defects. The characteristics of these defects are predicted by investigating the reflected and / or transmitted signals. In fact, more than 99% of an ultrasonic signal is reflected from a crack surface which is a material-air interface. This method of monitoring the reflected sound signal is called the 'pulse-echo' ultrasonic test. A piezoelectric transducer (probe) located at the top surface of a test specimen transmits a very short, high frequency pulse. The pulse is reflected from the crack top as well as from the bottom surface and is received by the same transducer (receiver). The variations in the amplitudes of reflected pulses when compared with that of the start pulse give the measure of attenuation. The depth at which the crack is located can be determined monitoring the time of arrival i.e., by relating the time axis with the sound path length. By mapping the surface and using angle probes the size and orientation of a crack can also be determined. The main advantage of the pulse-echo method is that it requires access only from one side of a structure. The portable pulse-echo systems are very common in in-situ inspection. The pulse-echo system helps locating flaws at different depths. The pulse echo C-scan can provide a map of all flaws located at different depths. The method is also very sensitive to foreign body inclusions. Even the existence of a piece of paper or a similar material contained within a laminate can be easily identified from the reflected signal strength. The transmitted ultrasonic signals can also be monitored by placing a probe (receiver) on the bottom surface of the specimen. This is called the 'through-transmission' ultrasonic test. The presence of a flaw will reduce the intensity of transmitted signals. The through transmission ultrasonic technique is relatively more popular in composite applications. There are several other ultrasonic test techniques that are receiving sufficient attention in recent years. The 'ultrasonic polar backscatter' technique employs slightly angled beams. This helps detection of matrix cracking in oriented plies. The 'ultrasonic resonance' method makes use of the fact that the existence of a delamination reduces the normal surface stiffness of the material. A continuous ultrasonic wave is transmitted through the material, and the mechanical stiffness or impedance of the material is monitored. The reduced surface stiffness due to presence of a delamination decreases the surface loading on the ultrasonic probe and a shift in the phase, amplitude or resonant frequency is observed. The 'ultrasonic correlation' method enhances the sensitivity of ultrasonic signals (higher signal to noise ratio) by making use of a continuous wave cross-correlation technique. The method is very useful for highly attenuative composite materials. The 'acousto-ultrasonic or stress wave factor' test technique employs an ultrasonic transducer to send a simulated acoustic emission pulse through the test object. A defect or damage can modify the waveform which is monitored at a distance away from the source and is analysed. The 'ultrasonic microscopy' can image microstructural differences on the surface of a material. The reflection scanning acoustic microscope uses a very narrow high frequency (100 MHz to 1GHz) ultrasonic beam to scan the object line by line. Its limit of resolution is that of an optical microscope but the acoustic imaging, in some cases, provides additional information. One of the major disadvantages of the ultrasonic NDT method is that a coupling agent is needed between the probe and the specimen to transmit and receive ultrasound signals. Normally either the specimen is immersed in a water bath or a water jet is directed to the specimen. Other coupling agents are also used. The coupling agents may have a deleterious effect on the specimen material. Further, this also poses special problems, when the size of a part to be inspected becomes large. The other alternative in such situations is to make use of transducers with dry coupling. The transducer is coupled acoustically to the specimen via a plastic material which is attached to the tip of the transducer.