Non-Destructive Testing (NDT) – Guidance Document: An Introduction to NDT Common Methods

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Visual testing is the most widely used method of non-destructive testing (NDT). Even the more sophisticated methods require a visual test to be performed. In other methods, such as magnetic particle testing, after a component has been magnetised, the operator performs a visual inspection to look for indications. Large sections of industry tend to take visual testing for granted and pay little attention to training.

Ultrasonic testing is a versatile NDT method. Many techniques have been developed to allow full volumetric inspection of a large range of components made from a wide variety of materials. It is probably the most important method used in industry, certainly in the UK.

Radiography was one of the earliest NDT methods but, due in some way to health and safety implications, alternative methods are replacing it, for some applications, in industry. However, radiography remains one of the two main volumetric NDT methods.

Eddy current testing is a sophisticated method of NDT in which shallow swirling electric eddy currents are introduced into a component, allowing the detection of surface and slightly sub-surface discontinuities.

Magnetic particle testing is a relatively simple NDT technique that can be used in the detection of surface and slight sub-surface discontinuities in magnetic materials.

Penetrant testing is a simple NDT method used to locate surface-breaking discontinuities in metals and many non-metals using a penetrating liquid.

Thermal and infrared testing is a relative newcomer to the world of NDT. It involves monitoring the temperature variations of objects in the infrared portion of the electromagnetic spectrum.

There are other NDT methods and competencies listed in this section. Further details of these methods and competencies can be obtained from the British Institute of NDT.

Section 1 – Introduction

Non-destructive testing (NDT) is a mechanism used by engineers to detect defects in materials and structures, either during manufacturing or while in service. Typically, the methods used are ultrasonics, radiography, magnetic particle, eddy current, dye penetrant and visual methods. This important and growing industry is involved in applying these proven techniques and procedures to the full range of engineering structures.

When NDT is deployed to best effect as part of the complete engineering design process, it ensures the safe, reliable and long-lasting integrity of structures, such as power stations, aircraft, oil & gas installations and other safety-critical plant. Every day, more than 25,000 inspections are carried out in factories and on-site in the UK to detect defects and damage in a huge range of products, plant and structures; it is estimated that there are more than 120,000 inspectors operating worldwide.

The NDT community has formal mechanisms for skills development from Engineering Technicians through Chartered Engineer to Doctorate level. The global NDT industry had an estimated turnover in 2012 of about $5.6 bn (about £3.25 bn). This levers a much greater benefit to end-users through intelligent and reduced risk management.

Regulatory bodies demand that NDT is used to demonstrate compliance with safety and other legislation and, for unregulated industries, the commercial advantages of reduced warranty claims, improved plant reliability and higher customer satisfaction justify its use. NDT inspection personnel are required to be fully competent, trained and certificated in accordance with national and international standards.

This document has been provided as guidance for apprentices and other new entrants to our industry.

Robert Smith

Professor Robert A Smith

Professor Robert A Smith, President of the British Institute of Non-Destructive Testing 2015-2016

Section 2 – Visual and Optical Testing

Visual testing is the most widely used method of non-destructive testing (NDT). Even the more sophisticated methods require a visual test to be performed. In other methods, such as magnetic particle testing, after a component has been magnetised, the operator performs a visual inspection to look for indications. Large sections of industry tend to take visual testing for granted and pay little attention to training.

2.1 Description of the method

2.1.1 **Basic principles**

Visual and optical testing is a method of NDT used to examine the surface condition of a component. Visual testing is widely used by industry for just about every conceivable surface condition, from looking for processing or in-service discontinuities, to seeing if fruit is ripe and ready to eat. Without realising it, we will all do some sort of visual inspection every day.

By its very nature, visual and optical testing can be simple and straightforward. At its simplest, a clean component can be inspected by an operator in adequate light with no equipment – it can be that easy. Often, the operator will need to use optical equipment to aid the inspection, which can range from a hand-held magnifier to a flexible fibrescope or remote video systems.

You may think that an unaided visual test would not be able to find small discontinuities, but this is not necessarily true. An experienced operator, under optimum conditions, may be able to detect even small tight cracks. Repeatability is, however, a problem. If conditions are not optimised, the same operator may miss the same crack on the same component on a repeat inspection. This is why optical aids are often used to give the operator the best chance of finding the fault condition as often as possible.

We have mentioned *optimum conditions* for visual inspection but what are these optimum conditions?

2.1.2 **Environment**

Inspection must take place in a clean, comfortable environment with adequate lighting. Attention should be paid to safety, working position and atmospheric conditions. Inspection requires considerable concentration by the operator so, as an example, if the working environment is very hot and noisy, this will affect the operator's ability to concentrate on the job and discontinuities can easily be missed in this way.

Lighting is very important and can greatly affect the results. Natural daylight is the best type of light to perform visual inspection in because, as a biological system, we have evolved with the sun as a principal light source. A cloudy day is the optimum as this provides diffuse illumination. Bright sunlight can lead to glare from reflective surfaces and this, in turn, could lead to discontinuities being missed.

Artificial light can also be used for visual inspection; the operator must make sure that the correct light level stated in the specification or procedure is used. This light level is called *illuminance*, which is defined as the luminous flux per unit area falling on a surface. It is measured in lux, one lux being the illuminance of a surface one metre from a light source of one candela.

Luminous flux is the energy emitted per second from a light source. The unit of luminous flux is the *lumen* and the luminous flux emitted per unit solid angle is *luminous intensity*. A practical unit of luminous intensity is the candela. Most specifications will quote a minimum illuminance level that must be used, with figures between 500-1000 lux being common in many specifications. As a guide, to attain 500 lux at a test surface, a 100 W bulb at a distance of 460 mm, or a 75 W bulb at a distance of 380 mm, will be sufficient for this.

2.1.3 **Component preparation**

The component should be clean and free from protective coatings, for example dirt or paint, which can obscure the surface conditions being sought. Refer to the *Penetrant Testing* chapter for details of the methods of pre-cleaning.

2.1.4 Operator

It is of great importance that the operator has had sufficient training and experience before performing visual inspection. It is no good asking an operator to inspect a weld for undercut, for example, if the operator does not know what undercut is or what it looks like.

The brain builds up and stores images of specific conditions that it encounters and with experience a vast mental library is assembled. During a visual inspection, if an operator observes a condition of interest, the brain compares what is seen against the images in the mental library and recognises and identifies the condition. This is how a trainee operator can miss discontinuities that an experienced operator will easily find. The experienced operator has a large mental library to call upon. Once a trainee locates a condition and learns what to look for, it then becomes easier to find that type of condition.

The operator must also have good eyesight. No matter how good the lighting or how many years of experience the operator has, if the operator's eyesight is poor, an inadequate inspection will be performed.

It is common in many industries that visual inspectors undergo an annual eyesight test for visual acuity. As most visual inspection is performed close to a component, a near vision examination is carried out. This is usually at a distance of 300-400 mm using suitable reading charts, which have words printed with varying sizes of letters. A common type of chart is the *Jaeger* chart, with the small print size being J1, up to a large print size of J20. The operator must be able to read, with or without glasses, the specified print size. J1 is a common requirement for the aerospace industry. Distance visual acuity can also be checked if an operator will be visually inspecting components at a distance. Vision acuity can also be checked using various types of machine.

Another common vision test is for colour blindness – 10% of the male population has some sort of colour deficiency. As some visual inspection tasks require the operator to look for colours of certain conditions, an operator with a colour deficiency could miss such a condition.

At this point we should take a look at how the eye works. **Figure 2.1** below shows a cross-section of the eye.

The eye works like a camera. Light enters the eye through the transparent cornea. The quantity of light entering the eye is regulated by the iris. In bright sunlight the iris closes, which makes the pupil smaller and excess light is restricted. When light levels fall, the iris opens, making the pupil bigger, which allows more light to enter the eye.

The light must next be focused and this is done by the ciliary muscles changing the thickness and curvature of the lens.

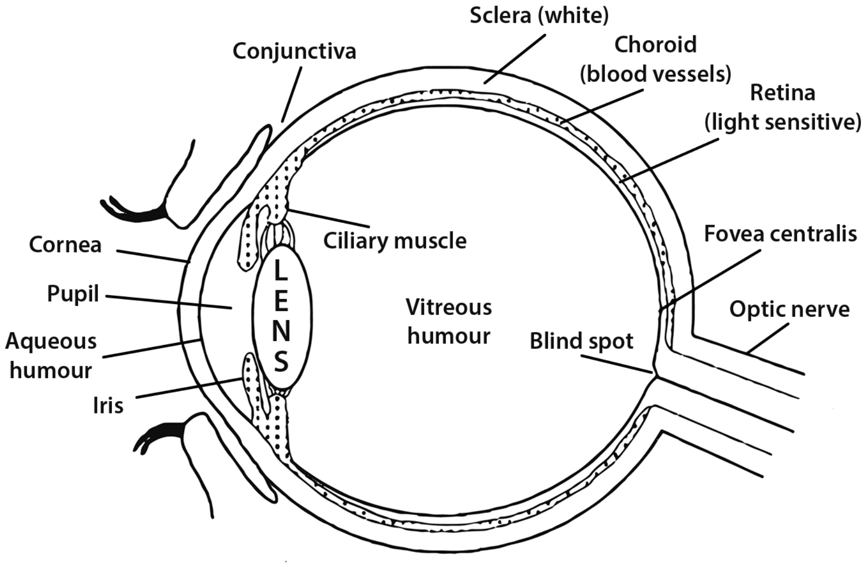


Figure 2.1 – Components of the human eye in cross-section

This process is called *accommodation* and gives us very fast continuous focusing adjustment. The lens focuses light onto the retina, which contains very many light-sensitive receptor cells called *rods* and *cones* that operate using a photochemical process to convert incident light into nerve impulses, which are sent via the optic nerve to the brain.

The receptor cells called cones are concentrated in a small area of the retina called the *fovea centralis*. The cones work in high light levels, such as daylight, and are very sensitive to colours but not to light intensities. When the eye is adapted to high light intensities, we call this *photopic vision* or *foveal vision*.

As light levels drop, the receptor cells called rods begin to work. They are sensitive to light intensity differences but colour vision is poor or absent. When the eye is adapted to low light intensities, we call this *scotopic vision* or *parafoveal vision*.

As we can see, the eye is a wonderfully sophisticated instrument but it does not *see* anything. It is designed to focus light onto the retina, convert the light to nerve impulses and send them to the brain. The brain then processes this information and forms the images we see. This leads us to perception, which is the difference between physical reality and the view we think we see. Different people interpret incoming information from the eye differently, so we all see the same physical scene slightly differently.

The Müller-Lyer illusion below in **Figure 2.2** demonstrates the difference between perception and reality. The shafts of the two arrows are the same length but appear to be different. The difference of perception between two people depends upon training and experience and the mental and physical state of the observers at the time the observation is made.

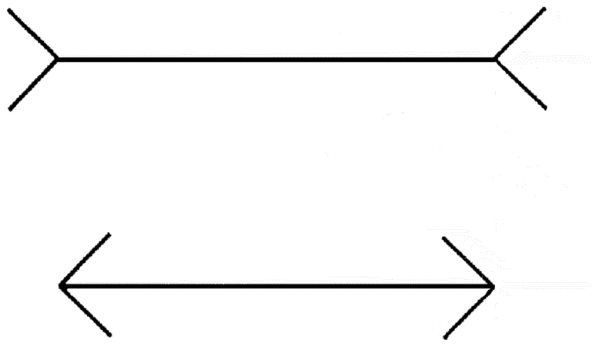


Figure 2.2 – The Müller-Lyer illusion

Perception can be effected by fatigue and health. Fatigue reduces an observer's efficiency and visual ability. There are also many diseases that will impair the sight and general ill health will reduce the brain's processing ability. These problems will all lead to inaccurate interpretation of physical data.

An ideal inspection will be one in which all of the above factors: training, experience, lighting and environmental conditions, are optimised.

2.1.5 Techniques

Broadly speaking, visual inspection is divided into several viewing techniques:

- Direct viewing – viewing of an object in the operator's immediate presence. This can be unaided or by using equipment, which we will look at in more detail later.
- Remote viewing – viewing of an object not in the operator's immediate presence. This can only be done using special equipment and, once again, we shall look at this equipment in detail later.

2.1.6 Components

Visual inspection can be applied successfully to virtually anything from man-made components and structures to organic matter. It can be used to locate many different types of surface condition, from discontinuities, such as corrosion or cracks, to the mottle effect of painted surfaces. An experienced heat treatment operator can even estimate the temperature of a component from its visual appearance once it has been heated to incandescence, *ie* dull cherry red steel at ~550°C.

2.1.7 Equipment

An operator will often be required to locate small discontinuities. This can be very difficult with the naked eye, so optical aids may be required. Here are some of the most common optical aids:

- Hand-held lenses are available from 1.5× up to 10× magnification. They are very useful for magnifying fine small detail to enable a better assessment to be made. The better quality, higher power lenses are of complex designs: doublet or triplet lens types are made from different types of optical glass cemented together, this type of design will remove chromatic aberration effects (colour fringing at the edges of the image).
- Measuring magnifiers incorporate a measuring scale to enable the surface condition to be measured. Some types of magnifier incorporate a small battery-powered bulb to provide illumination of the test-surface. Anglepoise magnifiers have up to 10× magnification and often have a circular fluorescent tube built in to provide uniform illumination.
- Microscopes come in a wide variety of magnification ranges. Low-powered microscopes often have one or two objectives, allowing magnification up to 40×. Medium-powered microscopes can have two or more objectives, giving magnification between 20× and 100× in a variety of designs. High-powered microscopes have a number of objectives, often up to six, which will provide a magnification range of 50× to 2000×. With microscopes of this type, specially prepared surfaces, sections or replicas are required. These high-powered microscopes often have the facility for polarisation, phase contrast and interference examinations.

  Polarisation is useful for studying most materials with directional optical properties, including fibres, crystals, sheet plastic and materials under strain.

  Phase contrast is used for inspecting transparent materials with refractive index discontinuities that can only be faintly seen in a normal microscope. Extensive work with living tissues and cells has been carried out with phase contrast microscopes.

  Interference microscopes use the wavelength of light to measure the surface contour and other characteristics and extremely precise measurements can be made with such equipment.
- Rigid borescopes are an excellent piece of equipment for inspecting the inside of tubes or pipes. They were originally used to inspect the bores of rifles and cannons. An example of a borescope can be seen in **Figure 2.3**.

  The image is transferred to the eyepiece via the objective lens and sets of relay lenses. The illumination is provided from a separate light box and utilises a fibre optic light guide system.

  Borescopes can have various angles of view: 0° direct, 45° fore-oblique, 90° lateral and 110° retro. Many will have magnification of up to 20× and a focus control. To allow access to very small openings, borescopes have been made down to 1.75 mm diameter. They have a single solid fibre to replace the lens, giving an infinite depth-of-field.

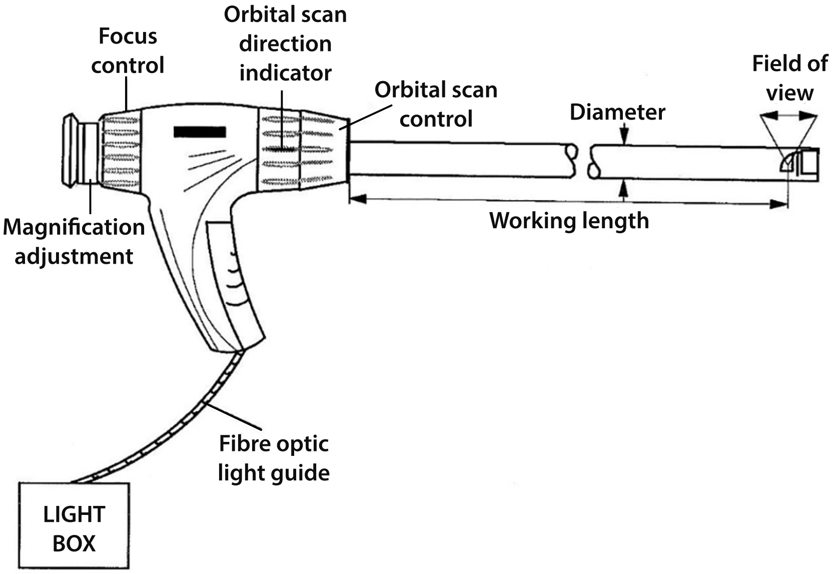


Figure 2.3 – A typical 0° direct view borescope

- A similar device to the rigid borescope is an endoscope. The difference between the two types of instrument is that the endoscope is flexible due to the use of fibre optics for both the light guide and the image guide. A typical example is shown below in **Figure 2.4**.

  The two guides (light and image) use thousands of very thin fibres of high-quality optical glass; each fibre has a coating of glass of a different refractive index. This coating acts like a mirror, allowing light to be passed down the fibre by the total internal reflection process. The more fibres there are in a bundle, the better the quality of the image. This is why image guide fibres are thinner than light guide fibres (9-17 µm for image guide fibres and 30 µm for light guide fibres).

  The image guide fibres must also be in a coherent bundle; every fibre must be aligned in an identical position at each end of the bundle. The internal reflection of light down each fibre works even if the fibre is bent, giving the endoscope its flexibility and allowing the internal inspection of complex pipes or machinery.

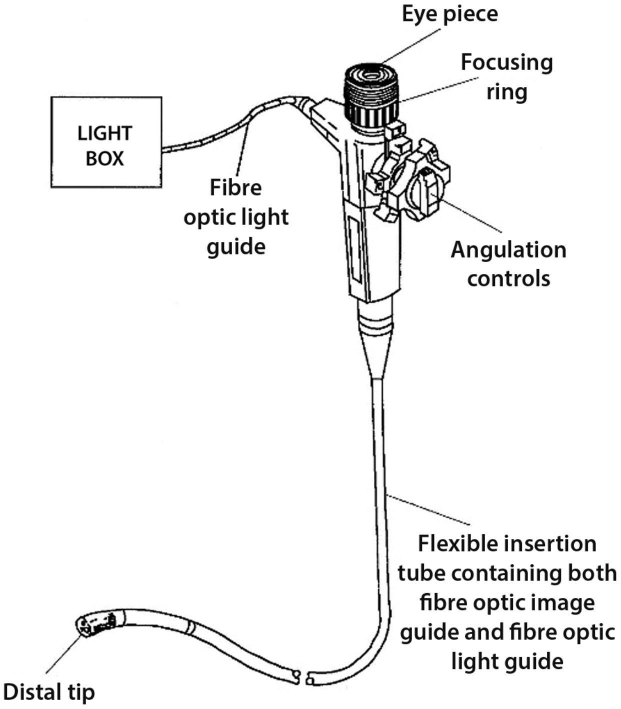


Figure 2.4 – A typical endoscope

- To improve image quality, the optical systems of borescopes can be replaced by a miniature video camera, which may contain an image tube such as a vidicon tube. A vidicon tube uses an electron beam to scan a photo-conductive target, known as the light sensor; alternatively, the camera may contain a solid-state imaging device, such as a *charge-coupled* device or a *charge-injected* device.

  The charge-coupled device works using the photoelectric effect, in which electrons are generated in a region of silicon by incident photons; the more photons incident on the silicon, the more electrons are generated. Each charge-coupled device has many silicon regions, each generating electrons under photon impingement. Each region is an individual picture element or pixel. These pixels are arranged in an array formation; the higher the number of pixels in the array, the better the image quality.

  The video image is created by reading the amount of charge caused by the electrons generated within each pixel. The video image can be recorded and evaluated at a later date.

  A video camera can also be used as part of a machine vision inspection system, which can acquire image data, process and analyse this data and make an evaluation automatically very quickly. Systems of this type are frequently used to inspect high-speed targets, such as metal in a rolling mill.

The system will typically consist of a light source, camera, digitiser, computer and display screen, as seen below in **Figure 2.5**.

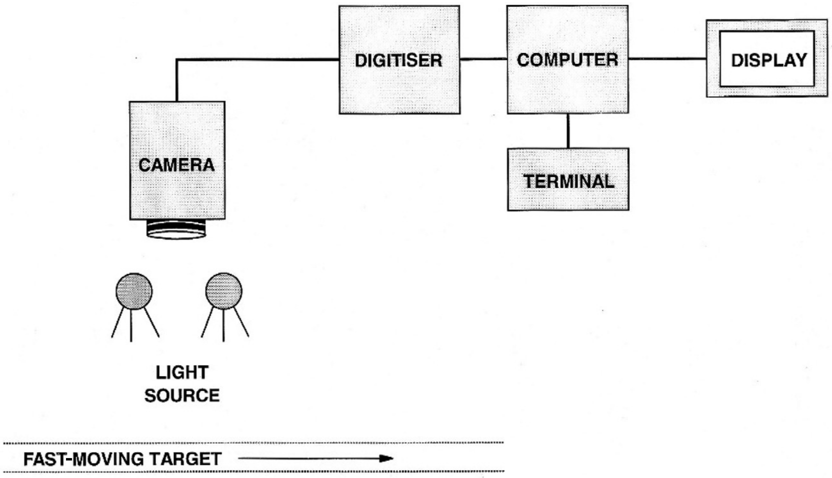


Figure 2.5 – Machine vision inspection set-up

Machine vision systems will typically process an image with a computer using four steps: image enhancement; image segmentation; feature extraction; and classification.

Video cameras can also be used on remotely-operated vehicles. This type of equipment can inspect pipes of 10 to 30 cm in diameter. A remote hand-held pendant is used by the operator to steer the crawler around bends or obstructions and can control the crawlers focus, lighting and speed.

2.1.8 Specific applications

Video borescopes can be used for many applications requiring remote visual testing, including the aerospace and power generation industries, engine manufacturing and marine inspections. Video borescope systems can be used to confirm questionable results of other NDT techniques, for example an indication can be located with ultrasonic inspection and then visualised with the video borescope.

A major use of video borescopes is to allow several operators or engineers to view a screen simultaneously. They are also very useful for applications requiring a critical assessment of detail or measurements, such as when checking coatings and seals, locating corrosion and pitting and burn-through of pipe weld roots. In boiler tubes, chemical deposits and oxygen pits can be located at an early stage and so help prevent tube failure.

Remote inspection can be performed in locations that would be hazardous to human operators, such as inside furnaces or high-radiation areas of nuclear power stations, where thorough use is made of visual testing during the plant shutdowns to test many critical components under high-stress, such as nozzle junctions with the vessel and cladding on nozzles.

Another important area of visual inspection is in the aerospace industry, where remote visual inspection is performed on otherwise inaccessible areas of the fuselage, where in-service problems such as fatigue cracks or corrosion can occur on aircraft integrity-critical components, such as pins joining the fuselage to the wings.

Critical visual inspection of hollow helicopter blades is carried out using video borescopes, as well as the inner surfaces of jet engines and wings.

The chemical industry makes wide use of visual inspection to test furnaces, combustion chambers, heat exchangers, pressure vessels and numerous other areas within the plant.

In the automotive industry, the internal condition of engines can be assessed, such as carbon deposits on valves, broken transmission gear teeth and gear wear being very easy to find.

2.1.9 Advantages of visual inspection

- It can be a very simple but effective test to perform and often does not need expensive equipment.
- Experienced operators and advanced equipment make it possible for visual inspection to be very sensitive.
- It allows discontinuities to be seen and not be just a blip on the screen.
- Many different surface-breaking discontinuities can be found.
- Training and experience times can be short.
- Virtually any component can be examined anywhere on the surface.

2.1.10 Disadvantages of visual inspection

- Many variables can lead to discontinuities being missed.
- At its worst, it relies totally on the human factor.
- Many organisations pay little attention to the proper training of operators.
- Sub-surface discontinuities will not be seen.

2.2 Summary

Visual inspection can often be a cheap replacement for other more expensive exotic NDT methods, whilst still providing a good level of sensitivity. It may be the only method, when using remote viewing techniques, able to inspect internal component condition and it is probably the most widely used form of NDT, with other techniques still requiring an inspector to perform a visual inspection.

Section 3 – Ultrasonic Testing

Ultrasonic testing is a versatile non-destructive testing (NDT) method. Many techniques have been developed to allow full volumetric inspection of a large range of components made from a wide variety of materials. It is probably the most important method used in industry, certainly in the UK.

3.1 Description of the method

3.1.1 **Basic principles**

The sound frequencies used to perform ultrasonic testing are above the human audible range, which would normally be between 16 Hz and 20,000 Hz. The frequencies typically used for ultrasonic testing are between 500 kHz and 25 MHz.

The frequency of sound chosen to inspect a component is very important. High-frequency sound, for example 5 MHz for contact testing applications, would provide good *sensitivity*, which is a term referring to an ability to detect small material imperfections, called *discontinuities*.

This same sound frequency would also have good *resolution*, which is a term used to describe the ability of a testing system to display closely-spaced discontinuities separately on the instrument screen.

Some components, such as castings, can have a very large grain structure and as a consequence are difficult, if not impossible, to test with high-frequency sound. The sound at 5 MHz cannot penetrate through the coarse-grained material due to a scattering effect called *attenuation*, or loss of ultrasonic energy.

To test this coarse-grained material, low-frequency sound such as 1 MHz would be selected. Sound at 1 MHz would have good penetration but poor sensitivity and resolution.

As mentioned above, the objective of many NDT applications is to look for the presence of discontinuities. A discontinuity can be many different conditions: *cracks*, *slag*, *porosity* and *stringers* are the names of just a few.

It would be wrong to use ultrasonic inspection to locate, for example, a crack and then to refer to the crack as a defect. A discontinuity can only be called a defect it if exceeds specific acceptance standards. If we have two cracks of the same length but in different components, one may be acceptable but the other may not, therefore only one crack can be called a defect.

So, how can we use ultrasound to locate discontinuities? We will look at the specific equipment in more detail later in the chapter; however, in essence, we need an ultrasonic flaw detector, a connecting cable or lead, an ultrasonic probe and couplant.

The flaw detector is at the heart of the system. It has various controls and a screen to display the test information. The flaw detector fires a short duration voltage pulse, sometimes called the *initial pulse*, down the lead to the probe. The probe contains one or more special crystals that vibrate at a high frequency when hit with the voltage pulses.

The probe must be placed onto a component and the couplant ensures the efficient transfer of ultrasound into the component – an air gap would not allow sufficient transfer of ultrasound to occur.

The sound passes through the component as a series of short-duration waves. A typical pulse repetition frequency would be several hundred pulses every second. As the sound is a wave, it behaves in exactly the same manner as light waves, *ie* they are reflected when they encounter any surface in their path. The surfaces that a sound wave is likely to encounter are discontinuities in the component, or the backwall of the component. The reflected sound waves return to the probe, which converts them to an electrical signal. This passes back through the lead to the flaw detector, which displays them on the screen.

This is the basis of pulse-echo testing and a typical testing set-up, including the flaw detector screen display, is illustrated in **Figure 3.1**.

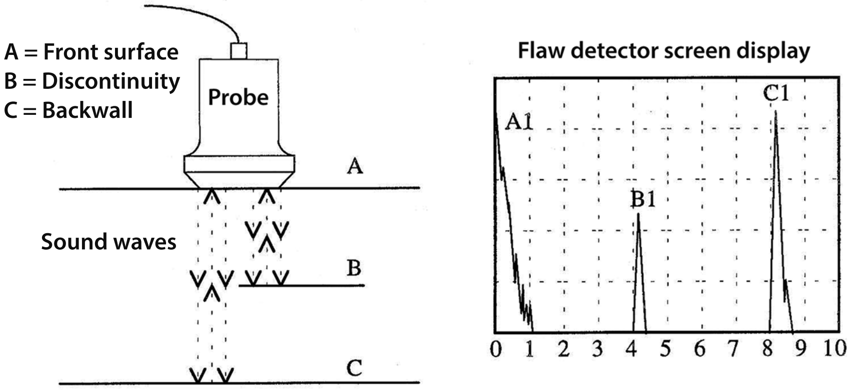


Figure 3.1 – The echo at A1 is the result of sound energy reflecting back off the front surface of the specimen, together with the ringing of the crystal and the initial pulse all merged into one signal. B1 is the discontinuity echo and C1 is the backwall echo

If the flaw detector is calibrated, then the depth of the discontinuity and the thickness of the component can be accurately determined from the time it takes for the sound to travel from the probe to the discontinuity or backwall and back again.

An estimation can be made regarding the relative size of a discontinuity by manipulating the probe on the surface above the discontinuity and by comparing the amount of sound returning to the probe from the discontinuity with the amount of sound returning from a reference target.

To test a whole component, the probe must be scanned fully over the component surface, ensuring that one pass of the probe overlaps the previous pass by a predetermined amount. The scanning can be done manually by hand or mechanically by automated systems.

3.1.2 Nature of sound

We have looked at the basic principles of the ultrasonic method: We now must look in more depth at the nature of ultrasound, which is at the heart of the method.

An ultrasonic wave in pulse-echo testing is a short-duration high-frequency mechanical vibration of the atoms or molecules that make up a material. These ultrasonic waves behave in the same manner as audible sound waves and, as such, will move through a medium that will support mechanical vibration – solids, liquids and gases. Ultrasonic waves will not move through a vacuum.

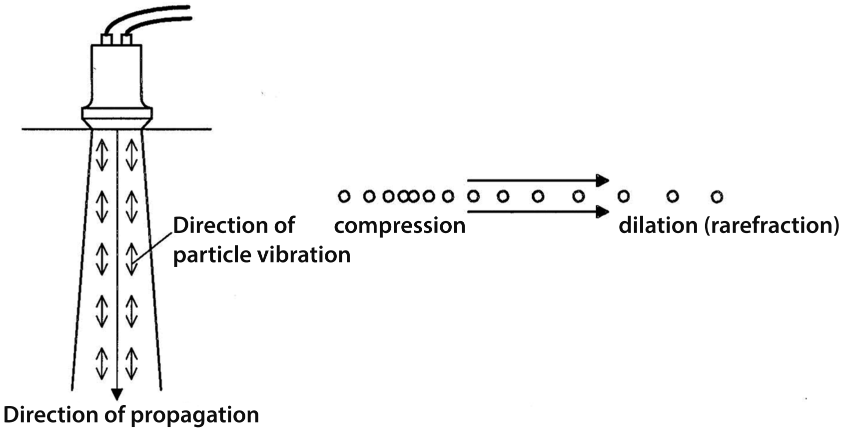


Figure 3.2 – With a compression probe, particle vibration and beam propagation are in the same direction

Ultrasonic waves pass through solid materials at a high velocity. The specific velocity of ultrasound will differ from material to material depending on its density and elastic properties. The velocity of ultrasound within a specific material will also differ depending on which *mode* of ultrasound is being generated, for example compression, shear, surface waves, etc.

If a probe is transmitting ultrasound into a material normal to the material surface (see **Figure 3.2**), *ie* with an incident angle of or close to 0°, the mode of propagation will produce compressional or longitudinal waves, which produce mechanical vibration of the atoms or molecules in the same direction as the overall direction of wave propagation; this will lead to alternate compression and dilation pressure areas. Compression waves can move through solids, liquids and gases and will have a velocity in mild steel of approximately 5960 m/s.

When an incident compression wave encounters a boundary between two materials with different sound velocities, for example at an angle other than normal (for steel the incident compression wave angle will be between 28° and 56°), mode conversion occurs from a compression wave in the first material to a shear wave in the second material. The direction of the wave will also change once the wave reaches the material boundary – this is called *refraction* (see **Figure 3.3**). Shear wave probes are very useful, particularly if discontinuities at various orientations are being sought.

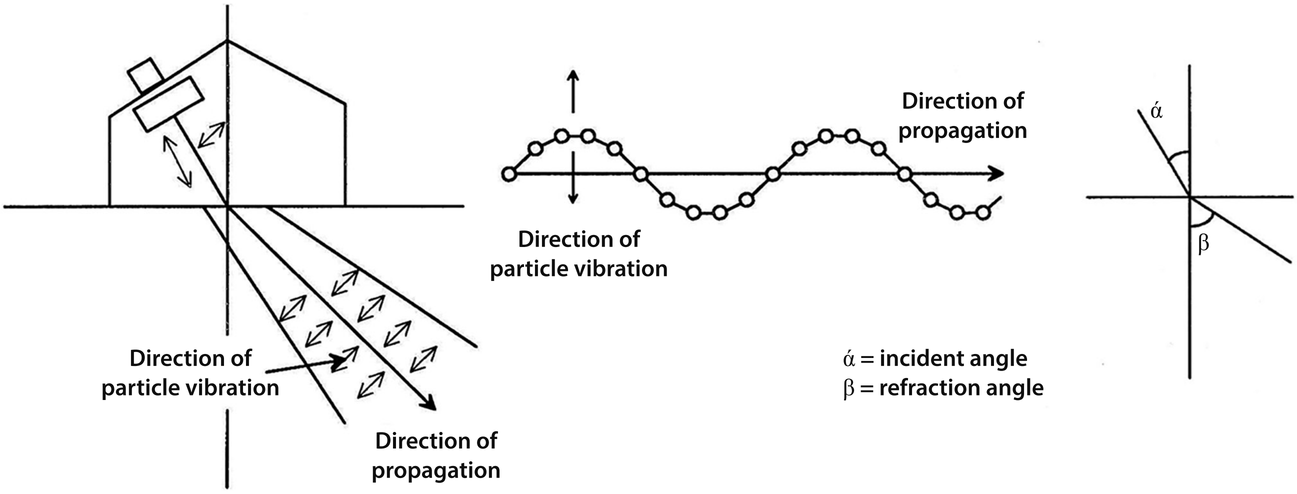


Figure 3.3 – A shear wave probe will have a set incident angle, which will produce a refracted angle in the component. The particle vibration and direction of propagation are shown

As stated above, a probe for use on steel will have an incident angle between 28° and 56°, producing a refracted shear wave between 34° and 80° in the steel. A shear wave will consist of mechanical vibrations of the atoms or molecules at 90° to the direction of wave propagation. The same effect can be seen if a cork is on the surface of the sea. The waves will move horizontally, whilst the cork moves up and down.

Shear waves can only move through solids, rigid particle bonding being a prerequisite, and will move through mild steel at approximately 3240 m/s.

Ultrasonic waves can also be created that pass along the surface of a component and will follow the surface contours. These are called *surface* or *Rayleigh waves*. They are quite shallow, only approximately one wavelength deep, and have a velocity of about 90% of the velocity of a shear wave in the same material. They are quite sensitive to surface cracks lying across their path, although a good component surface profile and cleanliness is essential if reproducible results are required.

The mechanical vibration of the atoms or molecules is in an elliptical direction, with the direction of the wave propagation parallel to the surface (see **Figure 3.4**).

If surface waves are introduced into thin material, they are called *plate* or *Lamb waves* and can be either symmetrical or asymmetrical. **Figure 3.5** shows symmetrical plate waves.

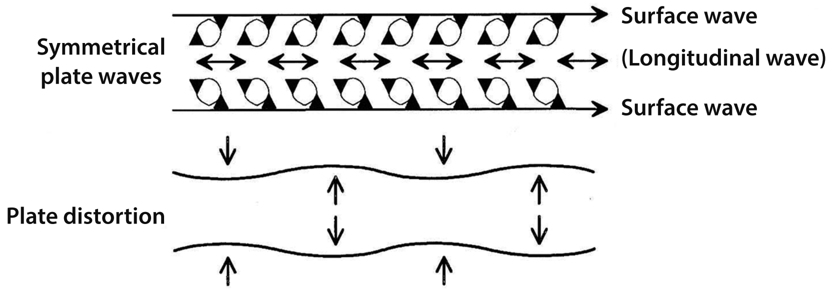


Figure 3.4 – The shallow depth of penetration of a surface wave can be seen

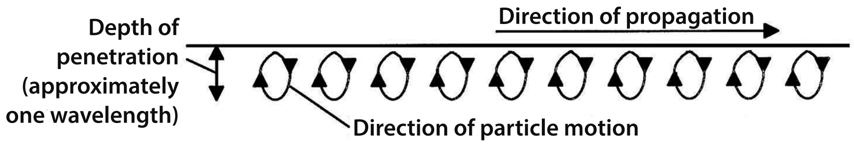


Figure 3.5 – Plate waves cause the thin plate to flex

3.1.3 Sound generation – the piezoelectric effect

We have looked at the nature of sound, now we will consider how sound is produced by the crystals contained within probes.

The piezoelectric effect is utilised, which is a property of certain crystals to convert electrical energy into mechanical energy and *vice versa* – this is shown in **Figure 3.6**.

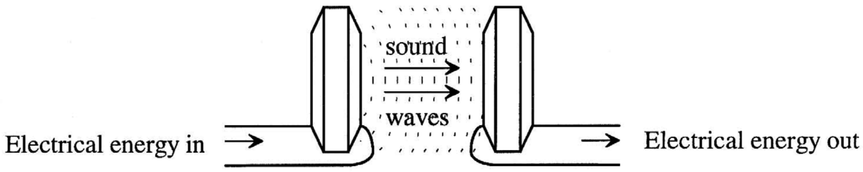


Figure 3.6 – Probes are often called transducers because they convert energy from one form to another, *ie* electrical energy to sound energy and sound energy to electrical energy

These crystals may be naturally occurring, artificially manufactured or grown in solution. Naturally occurring crystals, such as quartz, are rarely used these days because man-made ceramic materials tend to give much better properties in terms of sound generation, resolution, etc. A typical *ceramic* material is barium titanate.

A whole crystal is not used to manufacture a probe. A thin slice is cut from a crystal; the thinner the slice the higher the frequency of the ultrasound generated. The whole probe is then assembled, as shown in **Figure 3.7**.

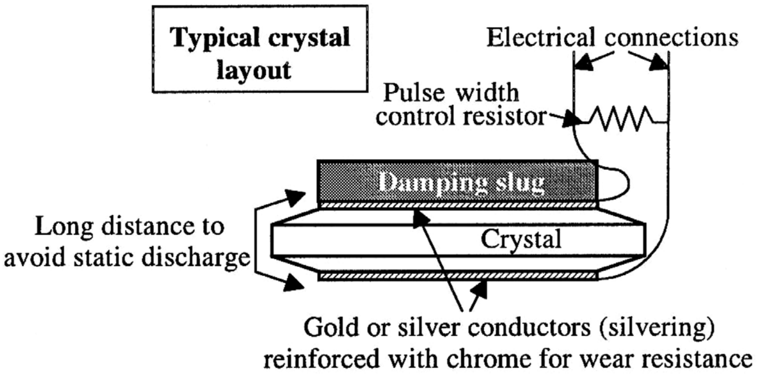


Figure 3.7 – A crystal has an axis and once cut, is assembled with electrical connections and damping material to control the pulse length

3.1.4 Flaw detector data presentation

There are three main types of display for flaw detectors: the A-scan, the B-scan and the C-scan presentation.

An A-scan presentation is the most common display used in ultrasonic testing. It shows returning signal amplitudes vertically and the elapsed time or distance horizontally. An experienced operator may be able to determine the nature of a discontinuity from the shape of the signal on the screen, as well as determine the component thickness and an approximation of the discontinuity size. **Figure 3.8** shows a typical A-scan display.

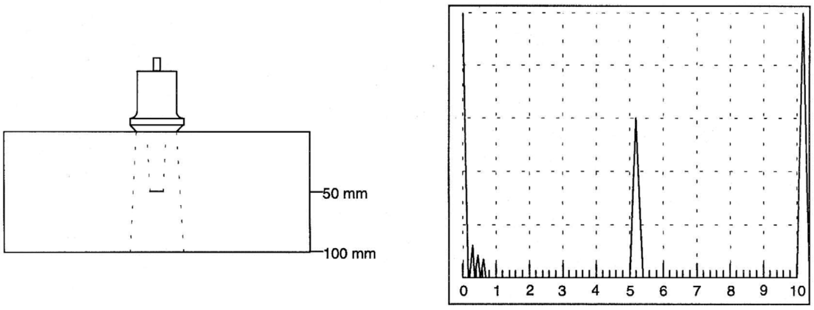


Figure 3.8 – The greater the amount of energy returning to the probe, the higher the signal on the screen. The depth of a reflector can be accurately determined: the discontinuity at 50 mm depth is shown as an echo on the screen at 5, and the backwall at 100 mm depth is shown as an echo on the screen at 10

With B-scan displays, a cross-sectional view of the component under test is seen. The display shows the depth of reflectors and is used to determine the cross-sectional size, location (both position and depth) and, with large discontinuities, can show the shape and orientation to a certain degree.

With a B-scan system, it is the time of arrival of a pulse (vertical direction) plotted as a function of the probe position (horizontal direction) that is displayed (this is shown in **Figure 3.9**).

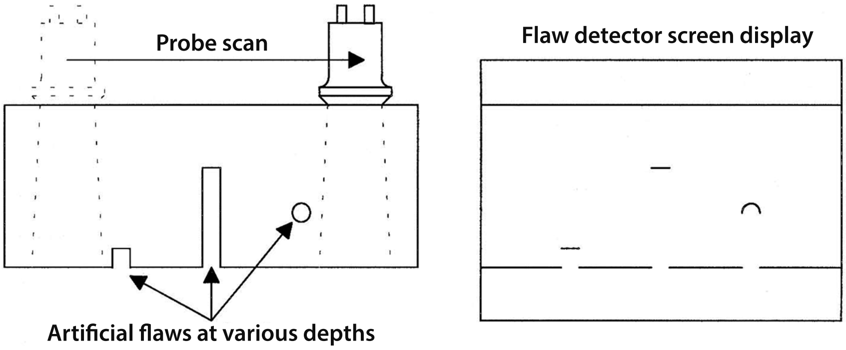


Figure 3.9 – A typical B-scan display with different-sized artificial flaws at different depths

If a plan view of a component is needed, a C-scan display system is used and is particularly effective for flat materials, including honeycomb panels, rolled products and adhesively-bonded or laminated composites.

A C-scan display is built up using raster scanning (X *versus* Y) over the component surface. It is mainly used with automated immersion equipment and is well suited for use with through-transmission systems.

The defect size in terms of area and the position within the plan view are recorded either as a computer file or printed as a hard copy (see **Figure 3.10**).

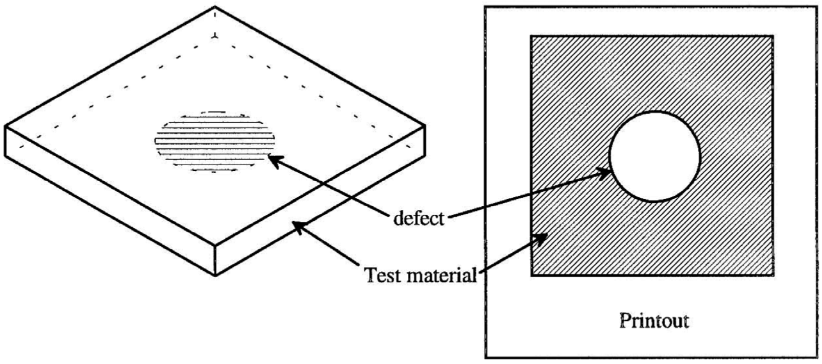


Figure 3.10 – An advantage of the C-scan system is the permanent record of the scan results

3.1.5 Basic equipment

We will now take an in-depth look at the equipment an operator may use for a typical ultrasonic inspection.

3.1.5.1 Ultrasonic flaw detector

Flaw detectors have changed a great deal and modern digital flaw detectors are much more sophisticated than earlier analogue sets. Flaw detectors are often used in conjunction with computers for data interpretation and storage.

A basic flaw detector will produce a high repetition of voltage spikes to produce the vibration of the crystal within the probe. These voltage spikes can be up to 1000 V. Returning signals are filtered and amplified and displayed on the screen.

Flaw detector controls allow accurate calibration of the screen time base, which is very useful for the determination of discontinuity depth or material thickness.

Electronic gates are common, which trigger alarms if signals within a predetermined position on the screen rise or fall to selected levels. This function allows automation of ultrasonic systems, which can scan much faster than a human operator.

3.1.5.2 Probes

Probes come in a wide variety of sizes, frequencies and angles. The choice of probe will depend on the material being examined and the type of defect being sought.

Single crystal 0° compression probes, such as the example shown in **Figure 3.11**, have the advantage of good penetrating power; fine-grained forgings up to 6 m thick may be tested. Volumetric discontinuities and planar discontinuities parallel to the component surface can be detected; however, defects not perpendicular to the ultrasonic beam may not be detected on the screen but a loss of backwall signal may be observed.

With coarse-grained material, a lower-frequency probe will be selected. The disadvantage of single-crystal probes is the presence of the dead-zone, which exists at the surface and is caused by the probe still emitting ultrasound as the returning pulse tries to enter the probe, thus preventing near-surface discontinuities from being detected. This can be seen contained within echo A1 in **Figure 3.1**.

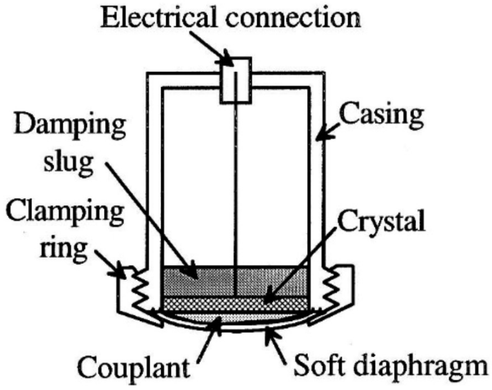


Figure 3.11 – Section through a single-crystal compression probe

To eliminate the dead-zone and allow near-surface defects to be detected, a 0° combined double-crystal probe can be used (see **Figure 3.12**). Two crystals are built into the probe, separated by a cork separator; one is the transmitter, the other the receiver. Probes of this configuration may be used to test thin sections for discontinuities and/or thickness measurements.

Once again, the ultrasound is introduced perpendicular to the component's surface, allowing the detection of volumetric discontinuities and planar discontinuities parallel to the component's surface.

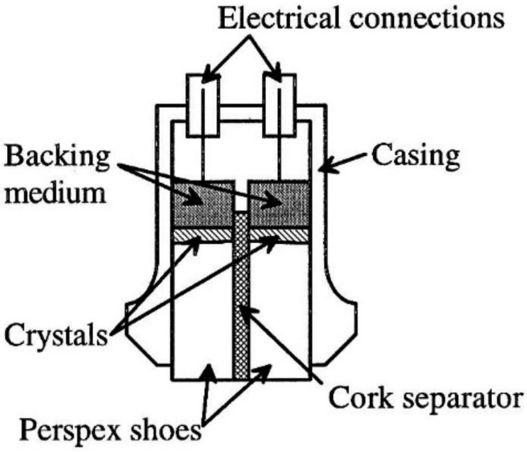


Figure 3.12 – Section through a twin- or dual-crystal compression probe

Flaws may be orientated in a direction not favourable for detection with a 0° compression probe, so probes are also manufactured to introduce ultrasound into the component at a variety of angles, 38°, 45°, 60° and 70° being common.

In **Figure 3.13**, probe A is a 0° compression probe and is unlikely to detect the crack because very little, if any, energy will be reflected back to the probe from the crack. Probe B is a 45° angle-beam shear wave probe and will easily detect the crack.

Angle beam probes can contain either single or double-crystals and at various frequencies.

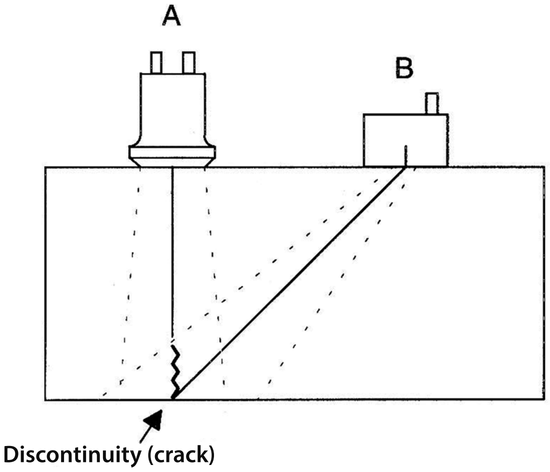


Figure 3.13 – Probe A is unlikely to detect the crack as little or no energy will be reflected back. Probe B will detect the crack

3.1.5.3 Probe lead

A probe lead is required to connect the flaw detector to the probe. It is a length of coaxial cable with a specific connector on each end.

3.1.5.4 Couplant

Couplant is used to allow the efficient transfer of ultrasonic energy between the probe and the component. If the probe was placed on a dry component, then there would be an air-gap, which would stop the transfer of ultrasonic energy.

Couplant could be oil, cellulose paste or a more specialised halogen and sulphur-free type, depending on the specific application.

3.1.6 Reference standards

Reference standards are used to allow the standardisation of ultrasonic inspection, so the same sensitivity levels are used whenever the component is tested and by whoever tests it. The aim is for a reasonable assurance that consistent results will be obtained.

Standardisation will also allow ultrasonic operators to estimate the equivalent size of any discontinuities found.

Reference standards can be test-blocks that contain natural flaws, test-blocks that contain artificial flaws, or a technique can be used to determine the percentage of back reflection.

Test-blocks containing natural flaws will be similar in configuration to the part that is to be inspected and will contain defects of the same type likely to occur.

Test-blocks containing artificial flaws will consist of metal sections containing reference targets, which may be notches, slots or drilled holes. It is important to note that if a discontinuity echo reaches the same height on the screen at the same depth as a reference target echo, the discontinuity is not the same size as the reference target. The reflection characteristics, orientation, etc of the discontinuity may be quite different from that of the reference target, so all we can say is that the discontinuity is equivalent in size to the reference target. This is illustrated in **Figure 3.14**.

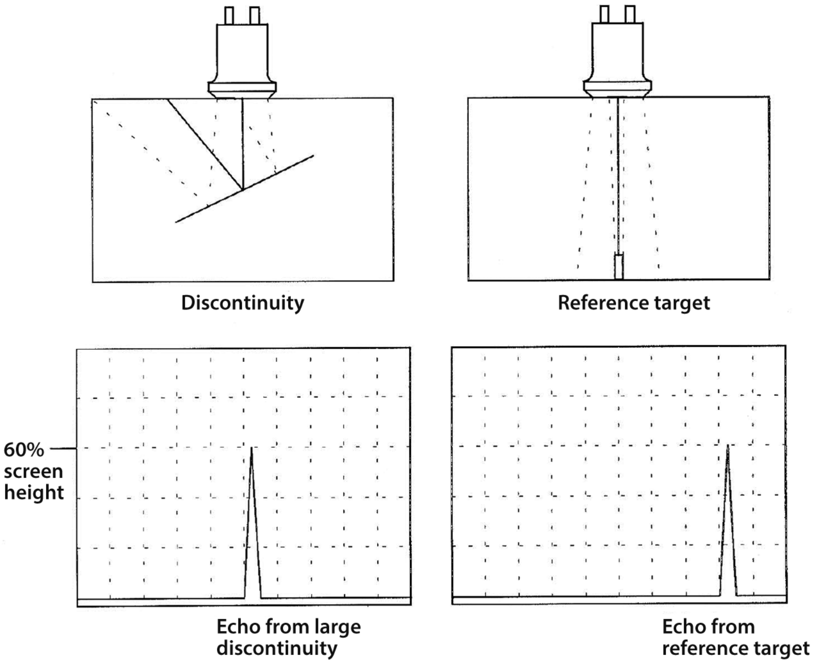


Figure 3.14 – The echoes on the screens above are the same height but, as you can see, the sound has been reflected by very different-sized reflectors

An alternative to using reference blocks is to use the percentage of back reflection technique, in which the probe is placed on a defect-free area of the part, the controls of the flaw detector are adjusted to obtain a predetermined echo height from the backwall of the component and any defect echoes or loss of backwall echo can be evaluated against this predetermined backwall level; however, this technique is only applicable to 0° probes.

3.1.7 Test procedure

An inspection procedure and technique sheets should be available to the operator for every component to be tested. A procedure contains information on a specific NDT method covering the general requirements of inspections, such as equipment type, equipment calibration, reference standards and operator qualification, whereas a technique sheet contains specific information about the component to be inspected, such as scanning patterns, defects sort and reporting criteria.

3.1.8 Components

Ultrasonic techniques can be used to test a wide spectrum of components. The following product types are some of the most common encountered:

Castings come in many shapes and sizes. They can be coarse-grained and may therefore require testing with low-frequency probes. Ultrasonic testing is able to detect surface and sub-surface defects and is well suited to locate typical casting defects, such as porosity, tears and cracks, shrinkage, voids and inclusions.

Wrought products cover forgings, rolled and extruded components, blooms, billets, slabs and bars. Wrought products will usually have a fine-grain structure and so testing can be carried out at higher frequencies to give better sensitivity and resolution.

The working process will usually flatten and elongate defects in the direction of working so usually 0° compression wave probes will locate the expected defects, such as porosity, pipe, internal ruptures, laminations, flakes and inclusions. Cold extruded products may have internal bursts called *chevrons*.

Welds are tested with both straight-beam and angle-beam probes to cover all possible defect orientations. Defects that may be located in welds with ultrasonic inspection are porosity, slag entrapment, incomplete fusion, incomplete penetration and various types of cracks and in-service induced defects.

3.1.9 Specific applications

3.1.9.1 Through-transmission testing

So far, we have looked at pulse-echo ultrasonic testing, where one probe is used to scan a component. An alternative technique that could be applied is called *through-transmission testing*. With this technique there are two probes, one on each side of the component under test. One probe is used to transmit pulses of ultrasonic energy; the other probe is used to receive the ultrasonic energy. The received ultrasonic signal is displayed on a screen and is set at a predetermined level. A typical set-up is shown in **Figure 3.15**.

When the probes are scanned over a defective area, the defect will intercept some or all of the ultrasonic energy and, as a consequence, the displayed signal level will drop, *ie* attenuate.

Because only one pass through the material by the ultrasonic energy is needed, materials with higher attenuation can be tested; however, access to both sides of the material is needed and the defect depth is not displayed.

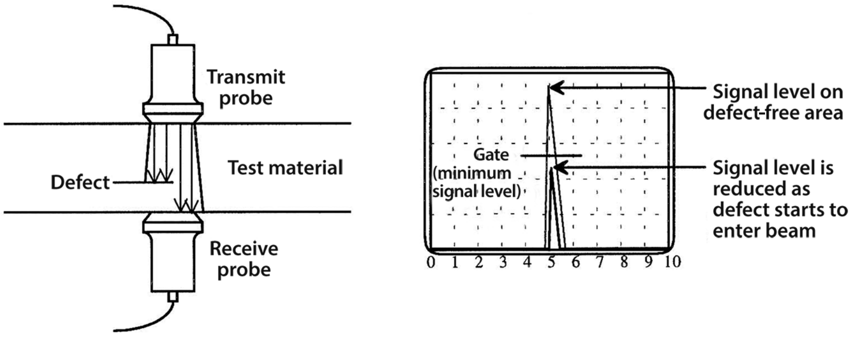


Figure 3.15 – The basic set-up of through-transmission testing and screen display

Through-transmission testing is mainly used on automatic systems and is useful for assessing bonds in composite materials and brazed joints. It has been successfully used in the power generation industry for assessing the quality of braze between thin metallic erosion shields and turbine blades that have had a history of failure during operation, leading to significant and expensive damage to the turbines.

3.1.9.2 Immersion ultrasonic testing

Not all ultrasonic testing involves an operator manually contact scanning a component. Automated testing systems have been built, that scan components in a water-filled tank and are called *immersion ultrasonic testing systems*. **Figure 3.16** shows a typical immersion tank that could be used to test new manufactured components.

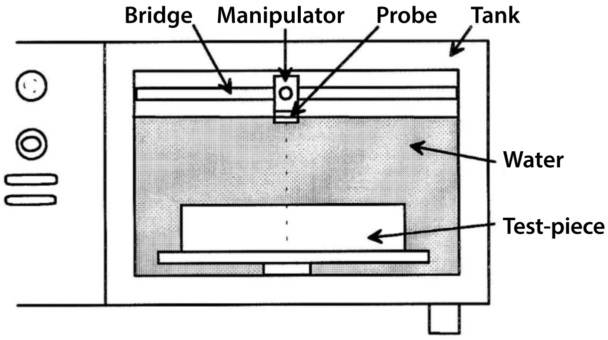


Figure 3.16 – A typical immersion test system

Many systems allow the component to be rotated on a turntable. The probe can be moved over the component via the bridge. The probe can be angled, allowing any beam angle desired to be produced in the component.

Probes are often focused to allow ultrasonic energy to be concentrated at a specific depth. The probe does not touch the component and a constant water gap is kept between the probe and component.

Other immersion systems are in use that do not use a tank but instead use columns of water, either *squirter* or *bubbler* systems, or a rubber wheel filled with water containing the probe.

Immersion testing has little utilisation in most industries, other than in manufacturers' works where the inspection of items such as high-quality forgings and other individual components are inspected prior to installation. These can be of certain sizes and geometries that would make it difficult to inspect them to a critical enough level using contact techniques.

3.1.10 Thickness measurement and condition monitoring

Thickness measurement can be carried out accurately with ultrasonic techniques (accuracies of ±0.1 mm are possible using the appropriate technique). Dedicated digital-readout ultrasonic thickness gauges utilise the pulse-echo method and do not require the same level of skill as a flaw detector to use. If the velocity of sound in a material is known and the time of the ultrasonic pulse is measured, the thickness can be determined. This is the basis of ultrasonic thickness gauges. These should be used with caution, however, as the numeric information displayed does not allow a detailed interpretation of features such as laminations or inclusions, which could in turn lead to incorrect decisions being made. Using an ultrasonic flaw detector does not present us with these problems.

Large-scale thickness surveys can be assisted by the use of data-loggers, whereby digital thickness data can be downloaded straight into PC applications and displayed graphically with different colours representing different thicknesses, etc.

The ultrasonic measurement of metal thickness can be used as a condition monitoring tool to check for corrosion or erosion, with the advantage that internal corrosion, *ie* wall thinning, of pipes and vessels can be determined without internal access being necessary. Boiler tubes in fossil-fuel power stations suffer from degradation by these mechanisms due the high-temperatures, impurities in the fuel, gases, particulates, etc. Repeat surveys are carried out over time to allow wall-thinning rates to be estimated and to therefore decide when tubes need replacing before they fail.

Another application for ultrasonic condition monitoring is in-service inspection for cracks and crack propagation, such as stress rupture cracks, thermal or mechanical fatigue cracks, stress corrosion and creep cracks. High-energy steam pipework and components such as steam valves are critical items in power stations and are subject to regular in-service inspection using ultrasonic techniques. The failure of such components presents a significant safety risk, notwithstanding the commercial effect due to the loss of generation. It is, however, common to find that plant is allowed to operate with cracks following an assessment, taking material properties, stresses and exact flaw mechanisms into account. With older plant in some industries, such as offshore rigs, nuclear sites and power stations, when components come to the end of their design life it is often more effective to carry out extensive NDT including ultrasonic inspection in order to extend plant life at significant reduced cost.

3.1.11 Material condition and properties

Ultrasonic techniques are also used to assess microstructural differences in metals. For this, attenuation, velocity and backscatter measurement can be employed. For example, as ultrasound makes multiple journeys through a piece of metal, some energy is lost each time, so the display of multiple backwall echoes will show a decay pattern. A reference standard can be used and the decay pattern of production parts compared to the decay pattern of the standard. This means if the decay pattern of production parts is lower on the screen than the decay pattern of the standard, the microstructure of the production parts is coarser, *ie* of a larger grain size than the standard.

Micro-structural anomalies, such as cavitation due to hydrogen damage or creep in carbon steels, can be assessed using the same measurement techniques. These are particularly useful when combined with computer-based ultrasonic imaging systems, which may also utilise digital signal processing (DSP) technology.

Stress measurement is another application of ultrasonic inspection. The technique is used to measure all velocity changes in the metal, which are caused by the presence of stress. Example applications of this technique are tensile loading of steel bolts and measuring residual stress in metal components.

Ultrasonics has been used to measure hardness and hardness can be used to determine the strength of a material. The hardness and therefore strength of aluminium copper alloys has been determined by measurement of pulse-echo velocity and attenuation.

The depth of case hardening in steel can also be estimated using either a pulse-echo backscatter or Rayleigh (surface) wave dispersion method.

3.1.12 Medical applications

Ultrasonic scanning for medical diagnostics can be performed on a wide range of human organs. Applications include the abdomen (liver, gall bladder, pancreas, spleen, kidneys, aorta and lymph nodes), obstetrics and gynaecology (evaluating the uterus and ovaries, with or without pregnancy), heart (adult and paediatric), eyes, vascular and neonatal. Organs such as the stomach and colon cannot be imaged because of their air content.

As well as the diagnostic uses of ultrasound, therapeutic ultrasound has been used for many years for the treatment of muscle disorders, such as trauma or atrophy, and can also be used to destroy abnormal mineral and salt build-up in ducts, hollow organs and cysts by using a shockwave effect.

3.1.13 Advantages of ultrasonic inspection

The main advantages of ultrasonic inspection compared with other methods of inspection are as follows:

- Excellent penetration of ultrasound into materials allows the detection of deep-lying defects. Parts from a few millimetres thick up to several metres long can be examined.
- The method is very sensitive and can locate very small defects.
- Defects can be sized and the position of internal defects within a component accurately established. The nature, shape and orientation of the defect can be determined.
- With the pulse-echo technique, access to only one side of a component is required.
- The ultrasound reflected back from defects is displayed almost instantaneously, allowing immediate on-site interpretation, and allows the method to be utilised for automatic systems, production monitoring and process control. Electronic monitoring of fast rising and falling defect signals, which an operator may miss, allow for very rapid inspection systems. A permanent record of the inspection can be made for evaluation at a later date.
- The entire volume is scanned from the front to the back surface.
- The technique can be very portable, with flaw detectors and probes being light and compact, allowing on-site inspection of difficult-to-access components possible.
- Signals can be processed by a computer, allowing defects to be characterised and a determination of material properties made. Thickness measurements of metal beneath paint coatings can be carried out with the multiple-echo method without the removal of the protective coatings.

3.1.14 Disadvantages of ultrasonic inspection

No system is perfect and ultrasonic techniques have the following drawbacks:

- It is often difficult to interpret a defect signal.
- Manual techniques require experienced operators and the training and experience periods can be quite long.
- Preparation and development of inspection procedures is not straightforward and good technical knowledge is needed.
- Irregular-shaped parts and parts with rough surfaces, such as in-service components, are difficult to test, as are cast components with a coarse grain structure.

- Single-crystal probes have a dead-zone in which defects will not be detected.
- Twin-crystal probes are usually focused and can only be used over a certain depth range.
- The ultrasound beam behaviour is unpredictable in the near field due to destructive interference of the wavefront leading to difficulties in detection or measurement of near-surface features.
- To allow the efficient transfer of ultrasonic energy between the probe and the component, a couplant must be used. Couplant loss can lead to false interpretation. Techniques have been developed that can be applied without the use of couplant, but they are usually specialised and can only be used under certain conditions.
- To characterise defects and calibrate the equipment, reference standards are needed.
- The couplant can be a contaminant, which requires removal before further processing can occur, *ie* painting/coating.
- Contact testing requires the surface profile to be reasonably good.

3.2 Summary

Ultrasonic inspection can offer a comprehensive inspection method suitable for many applications but does require a considerable understanding of capabilities and limitations before implementation, due to the relatively high cost associated with the method, such as training and equipment. It can, however, provide information and results not easily available by any other method.

Section 4 – Radiographic Testing

Radiography was one of the earliest NDT methods but, due in some way to health and safety implications, alternative methods are replacing it, for some applications, in industry. However, radiography remains one of the two main volumetric NDT methods.

4.1 Description of the method

Radiography is one of the two main volumetric testing methods, along with ultrasonics. Some materials, either because of their thickness or grain structure, may be difficult to penetrate with ultrasonics, or a permanent visual record may be required and, therefore, radiography may be an alternative.

Radiographic testing works by producing short-wave X- or gamma radiation and directing it at an object. Radiation penetrates matter to a certain extent and, if this penetration is enough for it to pass through the object, this radiation can be captured on a photographic film.

If an object has a high density, *ie* a thicker object, it absorbs more radiation causing less radiation to hit the film, which produces a lighter image. If an object has a low density, *ie* when the through section is reduced or there is a lower-density material such as slag (compared to the surrounding material), it will absorb less radiation causing more radiation to hit the film, producing a darker image.

This is shown below in **Figure 4.1a** and **Figure 4.1b**. The thinner section of the component and the defective area allows greater exposure of the film to the incident radiation, which comes from the radiation source. Once the film is processed, the radiograph is darker in these areas.

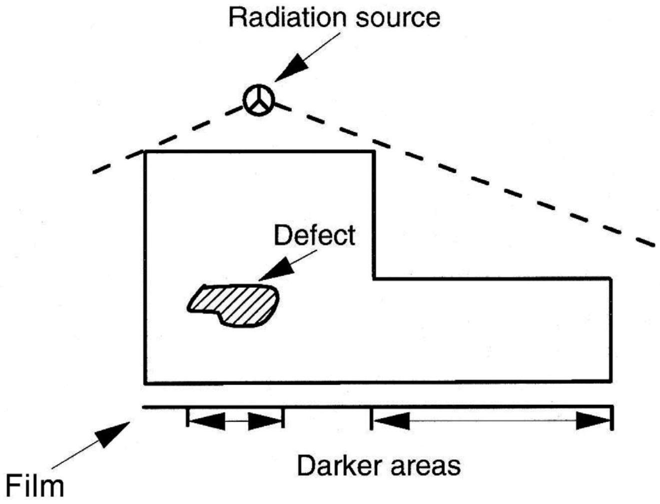


Figure 4.1a – Variation of different levels of radiation reaching film – side elevation

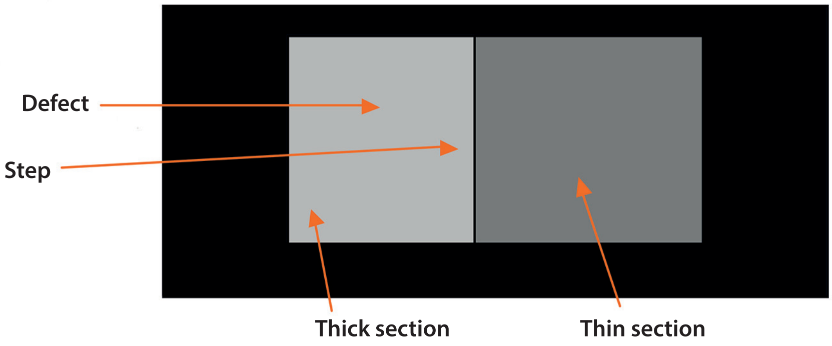


Figure 4.1b – Resultant radiograph

The image on the film cannot initially be seen; this is called the *latent image* and can only be seen when the film is developed. The quality of this image mainly depends upon three properties:

- Density
- Contrast
- Definition

4.1.1 Density

This is the degree of blackness on the radiograph. There will be minimum and maximum amounts of density to make the radiograph readable and give the required sensitivity.

$$\text{Density} = \text{Log}_{10} \frac{\text{Incident light}}{\text{Transmitted light}}$$

Typical densities are 1.5-3.5. (**NOTE**: There are no units as this is a ratio).

4.1.2 Contrast

Radiographic contrast is the degree of difference between density fields on a radiograph. If there are only blacks and whites on a radiograph, this would be high contrast. If only tones of a similar density are on the graph, this would be low contrast.

Radiographic contrast is a product of *film contrast* and *subject contrast*.

Film contrast is dependent upon the type of film used and the developing process used: films with large grains are fast films, *ie* small exposure times; films with small (fine) grains are slow films, *ie* long exposure times but better quality radiographs. Subject contrast depends on the subject itself, what screens and filters are used and the wavelength of radiation used. (A higher kV and hence smaller wavelength would reduce subject contrast.) Screens and filters are used to cut out unwanted radiation to improve the image. In the case of salt screens, to reduce the exposure times.

4.1.3 Definition

Radiographic definition is the degree of sharpness at the boundaries of density fields, *ie* edge clarity. There is an amount of inherent unsharpness in a particular film that is increased by a reduction in the wavelength of the radiation but is always present to some degree.

Geometric unsharpness is controllable by the gamma source size or the X-ray focal spot being as small as possible, the distance between the object and the film being as small as possible and the distance between the radiation source and the object being as large as possible.

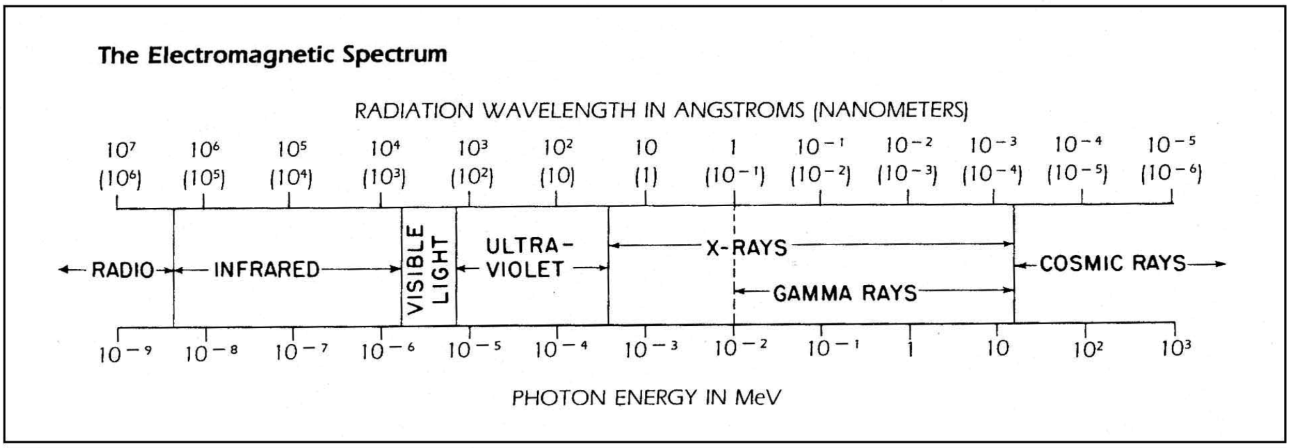


Figure 4.2 – The position of X- and gamma rays within the electromagnetic spectrum

4.1.4 Sources of radiation

4.1.4.1 X-rays

In industrial radiography, two sources of radiation are used: *X-rays* and *gamma rays*. Essentially they are the same, *ie* electromagnetic radiation, the difference being the way they are produced.

X-rays are produced by an X-ray set, which consists of a variable voltage generator, an X-ray tube and a control panel. **Figure 4.3** shows a typical X-ray tube. When a filament is heated up, a high-speed stream of electrons is fired from the cathode to the anode (this is usually a tungsten target, due to its high melting point, set into copper because of its good heat conduction). This interaction between electrons and the anode matter produces X-rays, which are then directed at the object.

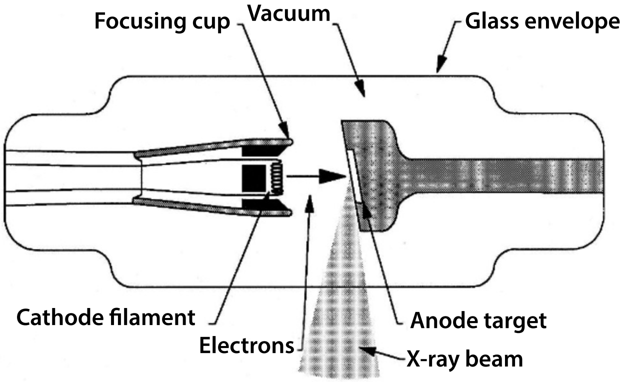


Figure 4.3 – Typical X-ray tube

An X-ray set has three major controls:

- The kilovoltage (kV), normally between 50 and 400 kV
- The milliamperage (mA), normally between 0 and 10 mA
- Time.

The kV regulates the wavelength. The shorter the wavelength, the greater the penetration of the X-rays. An increase in kV shortens the wavelength and therefore increases penetration.

The mA regulates the amount of radiation (which does not affect the penetration). An increase in mA gives an increase in the amount of radiation. The effect of this is to reduce the exposure time.

The mA control and the exposure time control are used together to control the exposure, which is measured in mA minutes, *ie* 8 mA minutes could be 2 mA for 4 minutes or 1 mA for 8 minutes. Therefore, using kilovoltage, mA and time, the operator has controllable exposure and penetration.

With X-rays, the X-ray beam is a mixture of wavelengths (a band of wavelengths).

4.1.4.2 Gamma rays

Gamma rays are produced when unstable radioactive isotopes give off energy (disintegrate) in order to become stable.

Originally, Radium 226 was used in radiography, which occurs naturally but because of its dangers (the main danger being the byproduct radon gas, which may have been responsible for Marie Curie's death), artificially-produced isotopes are now used. Cobalt 60, Iridium 192, Ytterbium 169 and Selenium 75 are four of the most common.

Gamma sources produce discreet wavelengths of radiation (either one or a few known wavelengths), therefore a source's wavelength cannot be changed to suit – another isotope source would have to be chosen to produce either a smaller or larger wavelength.

The amount of radiation given out depends upon the size of the source (the *activity*). Activity is measured in curies or becquerel – 1 becquerel is 1 disintegration per second (1 curie = 37 GBq). The becquerel is a small unit and in industrial radiography, gigabecquerels are used (109 becquerel). Therefore, exposure is controlled by the size of the source and, again, time of exposure.

Gamma sources reduce in activity as they disintegrate through time – this is called the *half-life*. Half-life is the time taken for the activity to reduce to half of its current level. All isotopes have different half-lives, *ie* Cobalt 60 is 5.3 years, whereas Iridium 192 is 74 days.

One of the problems with gamma sources is that they give off radiation in all directions at all times. With X-ray machines, once they are turned off, X-rays are no longer produced. This gives us different safety requirements with gamma sources.

After use, gamma sources must be kept in a shielded container to protect people from the radiation produced.

Although X-rays can be portable, it is more usual that they are static machines in an inspection area and require an external power source. Gamma sources are much more portable.

4.1.5 Safety aspects

One of the main considerations when choosing radiography as an NDT method is **SAFETY**. Radiation **destroys human cells**, therefore it must always be used in a controlled and safe manner. It cannot be detected by any of the five human senses: sight, hearing, smell, taste or touch. However, there are instruments available that can detect and measure radiation. These are listed below.

4.1.5.1 Personal dosemeters

Film badges/TLDs (thermoluminescent dosemeters) are detectors worn by all industrial radiographers that measure the dose a radiographer receives over a period of time, usually one month.

These badges are very good for recording doses to give a record over time but do not tell the radiographer how much radiation is being received at any particular moment.

Survey meters (dose rate meters) are instruments that can measure dose rates per unit time; therefore, they are used by radiographers to show the radiation being received at the time of exposure. They can also be used to check whether there is any radiation present before and after exposure, especially with gamma sources, which constantly emit radiation and may not be safely back in their containers.

4.1.5.2 Audible alarms

These are alarm/warning devices that should always be worn by radiographers working with gamma radiation. The alarm is triggered when the radiation dose exceeds a preset limit and increases in frequency as the radiation level rises. This will warn the radiographer about the radiation around and some of the modern ones measure and record the amount of radiation received (*ie* combined alarm/pocket dosemeters).

4.1.5.3 Pocket dosemeters (exposure meters)

These meters record an accumulative amount of radiation and can be used for measuring the dose received, for instance over one day, instead of waiting for the monthly badge results.

4.1.5.4 Geiger counters

These are probably the most well known radiation detectors and are often seen on TV clicking away in a radioactive situation; however, they are rarely used in radiography as they can only detect very low intensities – larger intensities would jam the instrument. They are often used for checking for radiation leakage at radiography cell doors or radiography cabinets. They are very sensitive.

4.1.5.5 Audio/visual alarms

These are alarms, such as the 'Gamma Alert', that are placed inside the radiation area and normally have an amber flashing light, which changes to red when the source is exposed and radiation is present. This is also accompanied by an audible warning.

As you can see, none of these instruments are perfect on their own but, if a combination is used, the radiographer can measure and record the radiation doses and work safely.

Radiography should be carried out wherever possible in a proper enclosure, called a radiography cell. These are rooms constructed with very thick walls or lined with high-density materials such as lead, which will reduce the level of radiation at the outside of the wall to an acceptable level. Where it is not possible to carry out radiography in a cell, a controlled area must be set up and barriers established at positions where the radiation levels are considered to be safe for non-classified personnel. The present legal requirement is 7.5 $\mu Sv/hr^{-1}$. The size of the controlled area can be reduced, by using shielding or collimators at the source. The intensity of the radiation is inversely proportional to the square of the distance from the source, *ie* if you double the distance away from the source, the radiation level is reduced by a factor of four.

4.1.6 Producing a radiograph

As discussed previously, when a film has been exposed by the radiation, that has passed through the object under test, there is no visible picture, only a latent image. To produce a viewable radiograph in which any defects can be seen, the latent image has to be developed, just like film in a camera.

Although automatic processing is now the most common method used to develop radiographic film, manual processing is still used in industrial radiography. In automatic processing, the film is fed via a series of rollers through a set of tanks similar to those used in manual processing and is dry and ready to view at the exit tray. Feeding the film into the automatic processor and manual processing are carried out in a darkroom as white light will further expose the film.

The film is processed in a series of tanks before being dried and ready to read. This sequence of events is as follows:

1. Developer tank.
2. Stop bath.
3. Fixer tank.
4. Final wash tank.
5. Wetting agent tank.
6. Dryer cabinet.

4.1.6.1 Developer

The developer (an alkali solution) reduces the silver halide grains that have been exposed to radiation to metallic silver.

4.1.6.2 Stop bath

This is usually a mild acidic solution (normally 2%) but could be a fresh water tank or even a water spray rinse.

The purpose of this is to arrest any further development and to remove the developing chemicals from the film.

4.1.6.3 Fixer tank

The main object of the fixer is to remove the undeveloped silver halide crystals and fix the remaining developed crystals. The fixer also hardens the film to make it easier to handle.

4.1.6.4 Final wash

After fixing, the film is washed to remove the fixing chemicals. Fixing chemicals left on the film lead to deterioration (the film is affected by yellow fog or turns the film brown).

4.1.6.5 Wetting agent

The film is put into a wetting agent, which promotes even drying.

4.1.6.6 Drying

Finally, the film is dried and is now ready to be viewed.

4.1.7 Viewing a radiograph

A special viewer using strong white light is used to view radiographs. Radiographs are normally viewed in a darkened room as it enables changes in density caused by defects or geometry to be seen more easily.

4.1.8 Radiographic film

Radiographic film, unlike photographic film, has an emulsion coating on both sides. This allows more silver halide crystals, which produce the dark images, to be available without building up too thick a layer, which might become unstable and slip, causing blurring of the images. This reduces the exposure time.

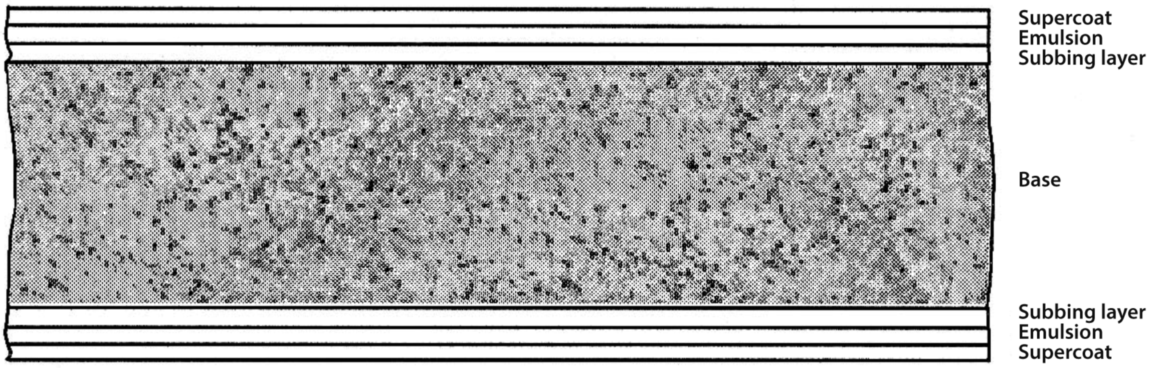


Figure 4.4 – A side view of a radiographic film and its make-up – same on both sides of the base

After exposure, the image on the film cannot initially be seen; this is called the latent image and can only be seen after the film has been processed.

4.1.9 Modern methods

Although radiography was one of the first NDT methods and, as stated previously, has been replaced for some applications, modern improvements to radiography have extended and widened its use. Below are some examples.

4.1.9.1 Digital radiography

Digital radiography was advanced after the speed and memory growth of computers allowed the production of digital images and for them to be transformed, stored and displayed on relatively inexpensive equipment.

With the advent of large thin-film transistor arrays, it allowed the use of large digital X-ray images. They can be seen in hospitals and scanning luggage at airports, as well as industrial radiography.

There are many ways of replacing film with digital means, but the most common, the amorphous silicon or selenium flat-panel detectors, use a camera based upon a charged-coupled device (CCD). The radiographic image is captured by the flat panels and then recorded digitally; this gives radiographers the obvious advantages of enhancement, magnification and storage of radiographic images, just like any other digital/computerised image.

4.1.9.2 Real-time radiography

Real-time radiography is transferring the radiographic image to a screen display and looking at it as it happens, *ie* in real time. Real-time radiography is not new, fluoroscopy (the original name for direct viewing of radiographic images) was used in 1897 at Brussels Station to view baggage, but the advent of computers and digital radiography has modernised the viewing and storage facilities of this method.

The method works by converting the radiation into light by means of fluorescent screens (hence fluoroscopy). The airport systems mentioned above in digital radiography are real-time systems.

4.1.9.3 Computerised tomography

This is a way of showing a *slice* through an image instead of a flat two-dimensional image. It is a way of viewing interior regions of interest without interference. Again, this method has been around since the 1940s, but computerisation and digital imaging have dramatically improved it. It is widely used in medical applications and is industrially used in the electronics industry for testing circuit boards.

4.1.9.4 Neutron radiography

Neutron radiography uses neutrons instead of X- or gamma rays to pass through the object and expose the film. The film used is the same as conventional radiography but works in the opposite way. With X and gamma, the radiation is absorbed with more dense materials and passes through lighter materials. Neutron radiation is absorbed by light materials but passes through dense materials with ease.

The equipment is expensive, bulky and there are extra dangers, *ie* bombarding with neutrons can make certain materials radioactive. (The only portable source is Californium 252, which is expensive.)

Its uses are generally for locating light materials inside dense materials, *ie* plastic explosives inside a metal shell, cracks in nylon liners inside a metal sphere and water entrapment and corrosion in aircraft wings.

4.1.10 Typical uses of industrial radiography

Although radiography can detect surface defects and cracks in certain orientations, it is mainly used to find sub-surface volumetric defects, such as voids, trapped gas, shrinkage, etc. Radiography is mainly used to find defects in welds and castings. It is considered to be the most effective method for inspecting small-bore thin-wall tubing welds as the majority of defects found are porosity and piping.

4.1.11 Advantages of industrial radiography

- Radiography can be used with most solid materials.
- Radiography has the ability to detect internal flaws.
- It provides a permanent record of the test.
- It discloses fabrication errors and often indicates necessary corrective action.
- It reveals assembly errors.
- The fact that radiographic examination is being carried out improves the quality of the welding.

4.1.12 Disadvantages of industrial radiography

- Radiography can only detect defects that are in a certain orientation.
- Radiography has difficulty detecting very small defects.
- It is impractical to examine parts of complex geometry.
- It requires two-sided access.
- Radiography requires many safety considerations and obviously, if used incorrectly, can be extremely dangerous.
- Generally, radiography is a high-cost NDT method, both in capital items, consumables and manpower.

Section 5 – Eddy Current Testing

Eddy current testing is a sophisticated method of non-destructive testing (NDT) in which shallow swirling electric eddy currents are introduced into a component, allowing the detection of surface and slightly sub-surface discontinuities.

5.1 Description of the method

5.1.1 Basic principles

Michael Faraday, an English scientist, first discovered eddy currents in 1832 whilst experimenting with some wire coils and a battery. He noticed that when he connected one of the coils to the battery, an electrical current also ran through a second coil, which was placed near the first one, albeit just for an instant.

When he disconnected the battery he noticed that there was a current in the second coil, again just for an instant. However, what was strange was that the current was running in the opposite direction to the first one. The current in the second coil was, in fact, a current that was induced by the first coil.

Faraday had managed to produce an electric current in a secondary coil by changing the magnetic field surrounding a primary coil. Magnetic theory forms a large part of eddy current theory – the basis of eddy current testing is electromagnetic induction.

Eddy currents can only be formed when using an alternating current (AC) as the current in the primary coil needs to constantly vary, *ie* zero to maximum positive and back to zero – zero to maximum negative and back to zero, which is known as a *sine wave* (see **Figure 5.1**).

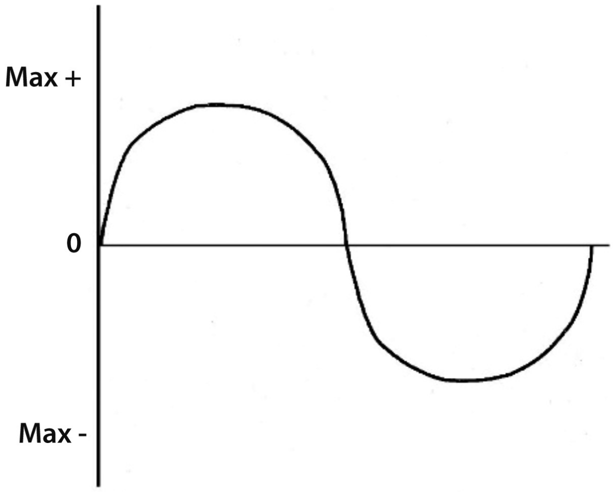


Figure 5.1 – AC sine wave

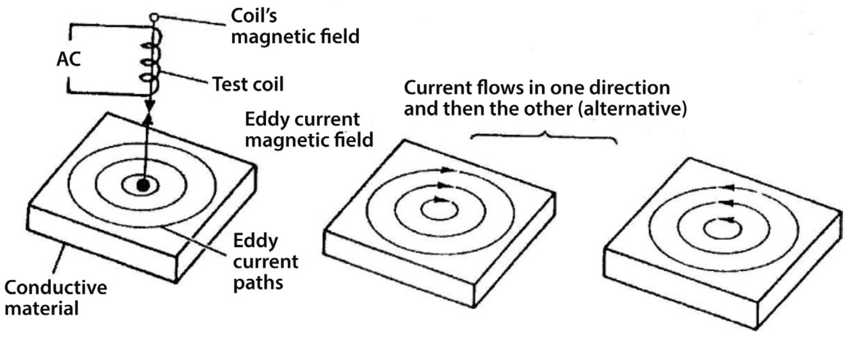


Figure 5.2 – A primary coil inducing eddy currents in a component

Eddy current testing uses this basis by using a primary coil to induce eddy currents in the component under test. For this to happen, the component under test must be electrically conductive. Metals are good electrical conductors but the conductivity of different metals varies considerably. The higher the conductivity, the more current is induced into the metal.

When using eddy currents, it is the change in impedance that is measured. Impedance is a combination of two properties: resistance in the wire of the coil and the inductive reactance of the coil (this is the effect caused by the AC current lagging behind the AC voltage).

The resistance will not vary much but there are variables that can greatly affect inductive reactance:

- The number of turns of wire in a coil.
- The size of the coil.
- The amount of current in the coil.
- The frequency of the current in the coil (frequency is the number of cycles per unit time, *ie* sine waves per second).

To summarise, if a primary coil is placed near an electrically-conductive metal sample, eddy currents will be induced into the sample. The eddy currents will produce a secondary magnetic field in the sample and, if this secondary magnetic field changes (there may be an interference such as a surface crack for example), then the impedance of the coil will change. These changes in impedance can then be detected and measured.

The magnetic field that surrounds the inspection coil is at its strongest next to the coil and gets progressively weaker the further away it is; therefore, the depth of penetration of eddy currents is limited.

Another factor which affects the use of eddy currents is *permeability*. Some conductive materials are permeable, which means that they can be magnetised. If materials are ferromagnetic, *ie* highly permeable, this will lead to inconsistencies in the test results. This can, however, be overcome by magnetically saturating the component.

Previously, we have stated that the conductivity of a material is an important factor in eddy current testing and the higher the conductivity the more induced current; however, because of this, it produces a stronger secondary magnetic field which opposes the coil's magnetic field more strongly. This strong opposition limits the depth of penetration and therefore the higher the conductivity or permeability, the less the penetration.

The conductivity of a material is measured using the *International Annealed Copper Standard (IACS)*, which gives unalloyed annealed copper a figure of 100. All other materials are measured against this (see **Table 5.1**).

Table 5.1 – Conductivity of metals

Metal	% IACS
Silver	105
Copper	100
Gold	70
Aluminium	61
Sodium	41
Magnesium	37
Tungsten	30.5
Zinc	29
Iron	18
Lead	8.4
Zirconium	3.4
Titanium	3.1
Stainless steel	2.5

If any of the above metals are alloyed, the conductivity can change dramatically. (The only exception to this is stainless steel, which is already an alloy.)

The depth of penetration can be increased by reducing the coil's frequency. This has the effect of changing the magnetic field more slowly and so has less opposition by the secondary magnetic field (see **Figure 5.3**).

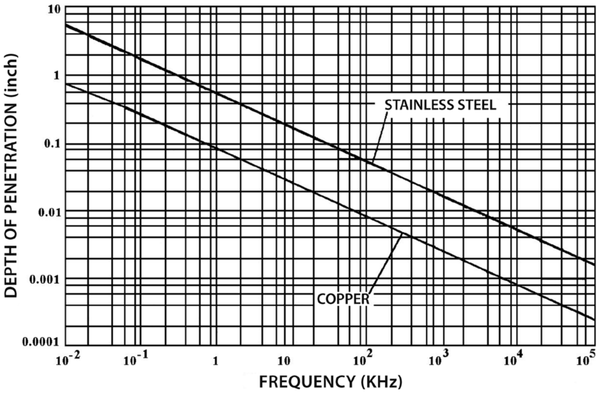


Figure 5.3 – Graph of frequency *versus* depth of penetration in stainless steel and copper lines

Typical frequencies used in eddy current testing are around the region of 200 Hz to 6 MHz.

There are three other terms used in eddy current testing that need to be outlined: *lift-off*, *fill factor* and *edge effect*.

5.1.2 Lift-off

As the eddy current coil is lifted away from the test-piece, less and less of the magnetic flux reaches the test-piece, until at some distance the magnetic flux created by the coil fails to reach the test-piece altogether – this is called the *lift-off* distance.

The requirement for the space between the test-coil and the component under test to be constant is one of the problems of testing complicated shaped samples.

Although lift-off is troublesome in many eddy current applications, it can also be very useful in others. For example, it is possible to use variations in lift-off to measure the thickness of non-conductive coatings.

5.1.3 Fill factor

This is a term used with encircling and internal coils and is based on how well the component being tested fills the encircling coil or how well the internal coil fills the hollow component it is inspecting. Again, this can produce both problems and advantages (see **Figures 5.4** and **5.5**).

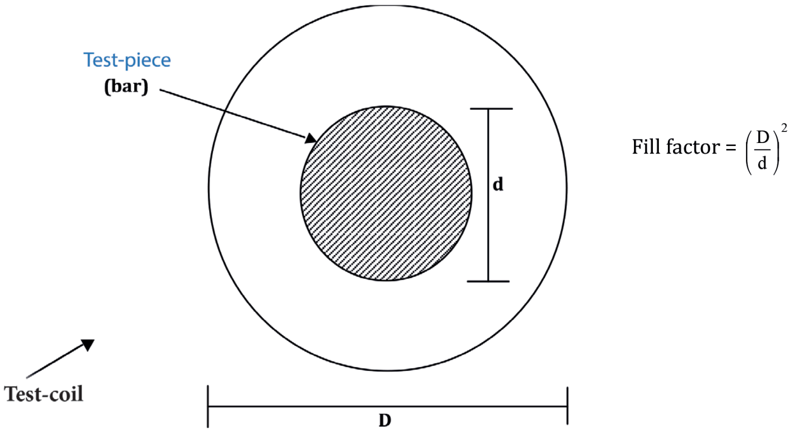
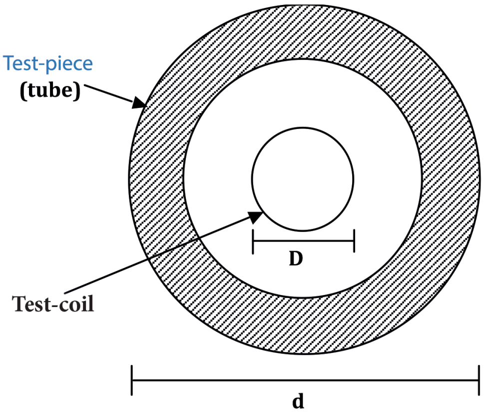


Figure 5.4 – Encircling coil



$$\text{Fill factor} = \left(\frac{D}{d}\right)^2$$

Figure 5.5 – Internal coil edge effect

As an inspection coil approaches the edge of a part being inspected, the eddy currents are distorted as they cannot flow beyond the edges of the test-piece. This results in a non-relevant indication known as the *edge effect* – see **Figure 5.6**. This effect needs to be avoided and, to inspect closer to the edge, a smaller diameter coil may be used.

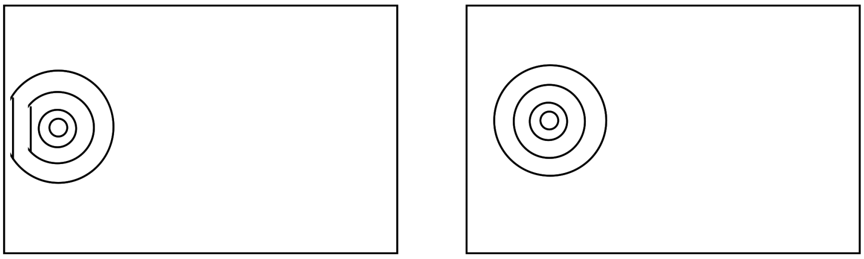


Figure 5.6 – Edge effect

Other changes in the material can give rise to conductivity changes and will therefore affect eddy current testing.

We have already mentioned alloying a metal (*ie* adding one or more different metals to produce an alloy of the base metal), but there are other factors that can change conductivity:

- Changes in the hardness of the metal due to heat treatment.
- Changes in the temperature of the metal.
- Residual stresses in the material.
- The material being clad with a different conductive material.

All of these factors will change the conductivity of the metal and therefore the results of eddy current testing.

5.1.4 Equipment

Eddy current coils basically consist of *encircling coils*, *internal* (or *bobbin*) *coils*, *probe coils* (*surface coils*) and *array probes*.

The test-piece is passed through an encircling coil, which obviously has a larger outside diameter than the part. Typically, bar, wire, tubes, etc, are tested using encircling coils. They are usually fed through the coil at high speed as the cross-section is inspected simultaneously.

Circumferential discontinuities are difficult to detect; however, longitudinal discontinuities and outside diameter variations (due to changing fill factor) can be detected. As you can imagine, accurate centring is essential.

Internal coils are used to inspect the inside diameter of tubular objects. These should still be accurately centred and work in a similar way to encircling coils.

Probe coils, sometimes called *surface coils*, are fitted into a probe, which scans the surface of the test-piece in a similar way to an ultrasonic probe (although couplant is not required). Probe coils are very sensitive to small discontinuities and can be shaped to fit irregular shapes. However, one disadvantage is a slow scanning speed and only a small area can be tested, as opposed to encircling and internal coils.

Array coils use many coils of the same type to scan larger areas more quickly. The information from each probe is collected by a computer, which pieces the information together giving two-dimensional inspection data. Array coils are often used in automated inspections to maximise the speed and accuracy of data acquisition.

The type of coil used depends on the shape and size of the component and the faults for which it is being inspected.

There are three main variations with each of the four types of coil: *absolute, differential* and *reflection (transmit-receive)*.

Absolute coils are a single coil that does not make a reference to another coil.

A differential coil consists of two or more coils connected and will either compare one area of the test-object with another, or compare an area of a test-object with an external reference.

Reflection coils use one coil to excite the test-piece with eddy currents and a separate coil to sense the changes that occur during the test.

The eddy current coil is connected to the unit or set, which is made up of an oscillator, bridge, amplifier and a display. There are various varieties of display, which could be:

- A direct meter with a pointer
- A meter with a phase-controlled rectifier
- A cathode-ray tube (CRT) with either A- or B-scan representation, flying dot or ellipse
- A time slit method
- Strip charts
- Most modern equipment is a full impedance plane with either LCD or electro-luminescent display.

5.1.5 Specific examples

Eddy current testing is used in four major areas:

- Thickness testing
- Alloy sorting and conductivity testing
- Crack detection
- Dimensional measurement.

5.1.5.1 Thickness testing

With thickness testing, eddy currents are used to measure the thickness of a known material using reference samples and knowing the depth of penetration of the eddy currents. Obviously only thin sections can be measured in this way (known as *foils*).

The thickness of non-conductive coatings can be measured using the lift-off effect of eddy currents. Lastly, the thickness of a conductive coating on a conductive base can also be measured, as long as the two materials have differing conductivities.

5.1.5.2 Alloy sorting

Alloy mixes or conductivity measurement can be carried out using eddy currents by using known reference pieces as calibration standards. As different metals or alloys of the same material have different conductivities when they are mixed, they can be separated using eddy currents to find the differing conductivities.

We can measure the conductivities of certain materials and also detect changes in hardness, heat treatment and microstructure because all of these change the conductivity of the metal. An example of this is the depth of case hardening and the presence of soft spots in precipitation-hardened steel caused by machining abuse.

5.1.5.3 Crack detection

Cracks, pits and corrosion can all be detected using eddy currents as all of these will interrupt the eddy currents and change the impedance. This will show on the display as an indication.

Reference pieces containing artificial discontinuities can be used as calibration references. The skill of the operator is also required to evaluate these indications.

5.1.5.4 Dimensional measurement

Dimensional measurement of regular shapes is possible using eddy currents – especially bar, rod, wire and tubes. These can have the outside measurements checked for variation using the fill factor of eddy currents, *ie* if the outside diameter along a bar either gradually or suddenly increases or reduces, the fill factor would change and be detected.

5.1.6 Advantages

- Eddy current testing can be used to locate and measure a variety of physical properties.
- It can be used as an automated high-speed testing process in some aspects, *ie* encircling coils.
- Results can be kept as a permanent record in some displays.
- Results can be displayed in numerous ways.
- Eddy current testing gives excellent reproducibility of results.
- Suppression of unwanted signals is available with eddy current equipment.
- Eddy currents are very sensitive to small surface cracks if the correct equipment is used.
- Eddy current testing does not require couplant.

5.1.7 Disadvantages

- Eddy currents can only be used on electrically-conductive materials.
- The permeability of ferromagnetic materials gives inconsistent and false readings.
- The depth of penetration is very limited because of the skin effect of AC fields.
- Only AC fields can generate eddy currents.
- Depending on the equipment used, some features cannot be detected, usually when the indicator is a gradual or a sharp change and whether the equipment is set up to measure such a change.
- When using encircling or internal coils, the part or coil must be accurately centred.
- The indications found are sensitive to orientation, with the most sensitive being when the indication is at 90° to the flow of eddy currents.

Section 6 – Magnetic Particle Testing

Magnetic particle testing is a relatively simple non-destructive testing (NDT) technique that can be used in the detection of surface and slight sub-surface discontinuities in magnetic materials.

6.1 Description of the method

6.1.1 Basic principles

Magnetic particle testing is an NDT method in which a magnetic field is created in a component at and just below the surface of the material.

Any discontinuities, such as cracks, that intersect the magnetic field lines at 90° (this will give the maximum response, but the intersect angle can be as low as 45° and still give a response) can be highlighted with the application of detection media.

A crack in the path of the magnetic field lines or flux acts like a barrier. To get past this barrier, the flux *jumps* over the crack to continue on its path. The site where the flux leaves the metal surface to jump over the crack is called a *flux leakage*.

The detection media applied to highlight the crack can be liquid based, this is called *ink*, or a dry powder. Both are, in essence, very small ferromagnetic particles, either dry or suspended in liquid.

When the detection medium is applied to a surface that contains a flux leakage from a discontinuity, the small ferromagnetic particles are pulled in, attracted by the flux leakage, and form what is called an *indication* – see **Figure 6.1**.

When a component is being inspected using magnetic particle testing, the operator is looking for the presence of these indications.

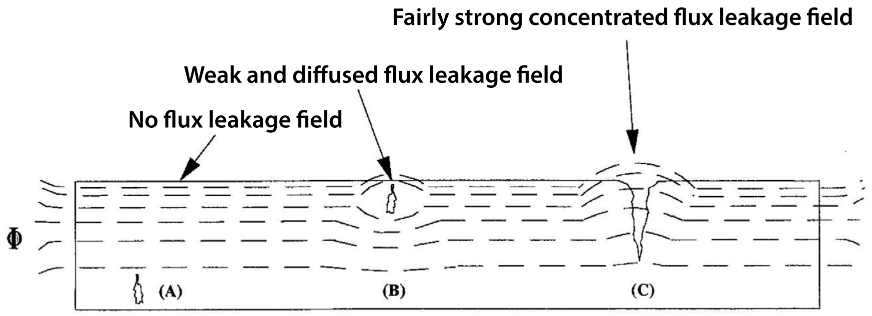


Figure 6.1 – How discontinuities lead to flux leakages

6.1.2 Magnetic properties of materials

Generally speaking, magnetic particle testing is limited to the detection of surface or near-surface discontinuities in ferromagnetic material. We will now look at the magnetic properties of materials.

Materials differ with regard to their interaction with magnetic fields; some materials are easy to magnetise whilst others are impossible to magnetise.

Permeability describes how easily a material can be magnetised; a material with a high permeability figure is easier to magnetise than a material with a low permeability figure.

A material's permeability is determined by dividing the magnetising force applied to a material into the magnetic flux density achieved in the material – permeability has no units, it is just a figure. For example, the permeability of a vacuum is 1.0.

There are three material categories that are related to permeability: *diamagnetic* (shown in **Figure 6.2**), *paramagnetic* (shown in **Figure 6.3**) and *ferromagnetic* (shown in **Figure 6.4**).

6.1.2.1 Diamagnetic material (in a vacuum)

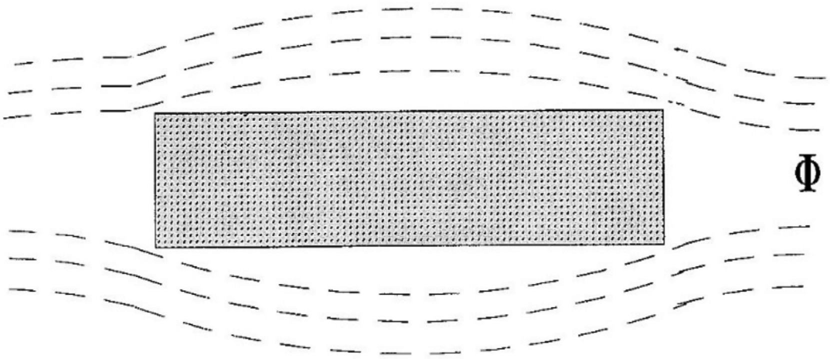


Figure 6.2 – The magnetic flux passing through the vacuum surrounding the diamagnetic material

Diamagnetic materials have a permeability value slightly less than 1.0. For example, the permeability of lead is 0.999983; this means that it is easier for the magnetic flux to pass around a diamagnetic material and travel through the vacuum. We can say diamagnetic materials will slightly repel a magnetic field.

6.1.2.2 Paramagnetic material (in a vacuum)

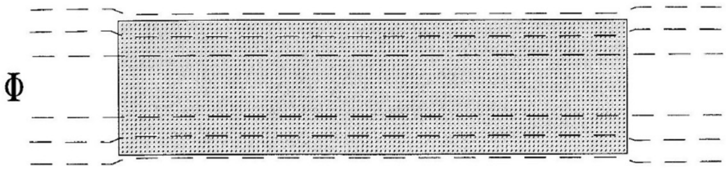


Figure 6.3 – The paramagnetic material weakly attracting the magnetic flux

Paramagnetic materials have a permeability value slightly greater than 1.0. For example, the permeability of aluminium is 1.000021; this means that it is slightly easier for the magnetic flux to pass through the paramagnetic material than to travel through the vacuum. We can say paramagnetic materials are very weakly attracted by a magnetic field; however, the strength of magnetic flux will be too low for any practical application of magnetic particle testing.

6.1.2.3 Ferromagnetic material (in a vacuum)

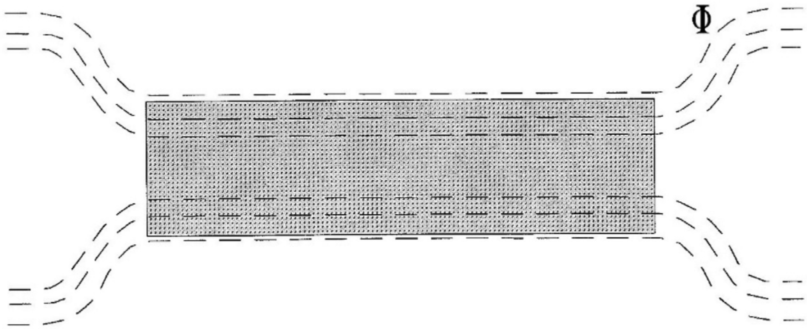


Figure 6.4 – The ferromagnetic material strongly attracting the magnetic flux

Ferromagnetic materials have a permeability value much higher than 1.0. For example, the permeability of nickel is 600; this means that it is much easier for the magnetic flux to pass through the ferromagnetic material than to pass through the vacuum. We can say ferromagnetic materials are very strongly attracted by a magnetic field.

Ferromagnetic materials are the only materials that can be tested by magnetic techniques and include iron, nickel, cobalt and gadolinium, as well as many of their alloys.

6.1.3 Magnetic domain theory

We have now introduced the concept that only ferromagnetic materials can be tested with magnetic techniques and from now on we will only look at ferromagnetic materials.

We have discussed the basic concept that we are seeking the presence of the flux leakage caused by discontinuities, but what happens when we magnetise a ferromagnetic material? Ferromagnetic materials consist of atoms that form into sub-microscopic reactions, which we call *magnetic domains*. These domains can be thought of as tiny bar magnets (one domain is typically made up of 10^{20} atoms) as they, like bar magnets, have positive and negative poles at opposite ends.

When a material is not magnetised, the domains are in a random orientation, with the net effect that the poles cancel each other out (**Figure 6.5**).

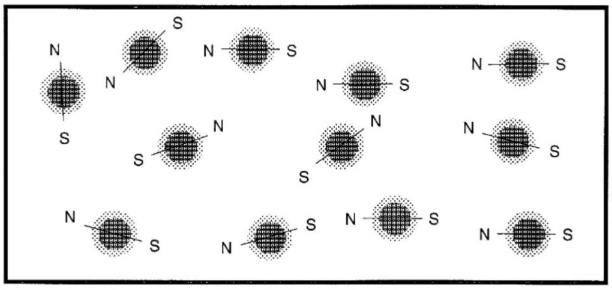


Figure 6.5 – Position of domains in unmagnetised material

When the material is subjected to a magnetising force, the domains will align themselves parallel with this magnetising force. All the positive poles will point in one direction and all the negative poles will point in the opposite direction. At this point the material is magnetised and is a magnet (**Figure 6.6**).

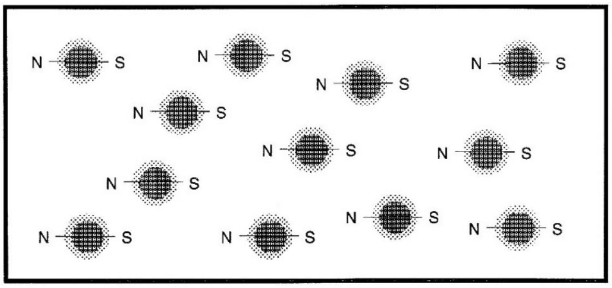


Figure 6.6 – Position of domains in magnetised material

Once the external magnetising force is removed, some of the domains will move to a random orientation once more, leading to the level of magnetic flux dropping proportionally. The ability of ferromagnetic materials to retain a certain amount of magnetism is called *retentivity*.

The important point to note for magnetic testing purposes is that it is usually considered best to apply detecting media whilst the magnetising force is being applied, this is called the *continuous method*. If we magnetise a component and apply detecting media after the magnetising force has stopped, this is called the *residual method*.

6.1.4 Magnetising techniques

We have looked at the background theory of what happens to a ferromagnetic material when it is under the influence of a magnetising force, but how do we generate this magnetising force? Many different techniques are employed that give rise to distinct magnetisation directions: *circular* and *longitudinal*. We will first consider circular magnetisation.

6.1.4.1 Circular magnetisation

If an electric current is passed through a component, such as the bar shown in **Figure 6.7**, a circular magnetic field will be produced around the component at right angles to the direction of the electric current which produced it. Bench units, which we will discuss in more detail later, are commonly used to test small components. The component is clamped in place in the bench unit and a current is passed through it to produce circular magnetism.

As discussed earlier, discontinuities can be located if they intersect the magnetic flux at 90° (but this intersect angle can be ±45°). This means that we are looking for discontinuities along the longitudinal axis of the bar and this method of magnetisation is called *current flow*.

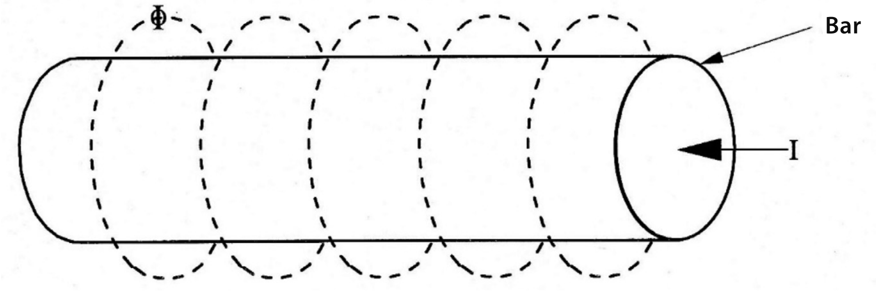


Figure 6.7 – The magnetic flux surrounding a bar component and direction of current I

The electric current can be either alternating current or direct current. If we magnetise a component using AC, we will get what is called the *skin effect*, which means the magnetic flux will be concentrated at the surface and down to a depth of approximately 1 mm. Consequently, an alternating current is best suited to the detection of surface-breaking discontinuities.

If we magnetise a component using a direct current, the magnetic flux will penetrate from the surface down to a depth of approximately 10 mm; however, an indication of a discontinuity at this depth would be extremely difficult to interpret, so in practice we can say direct current is suitable to locate discontinuities that are surface-breaking and also discontinuities that are approximately 3-4 mm deep.

An excellent technique for producing circular magnetism in hollow components such as rings and tubes is to use a central conductor or *threaded bar,* which is typically made from brass or copper (see **Figure 6.8**). The bar is passed through the component opening and a current is passed through the bar, providing circular magnetism in the component.

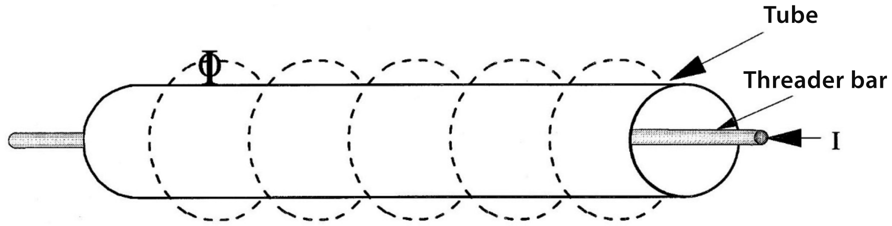


Figure 6.8 – A hollow component on a central conductor: the threaded bar technique

Advantages of the central conductor technique include the fact that the threader bar can be insulated, so even if it touches the component, no current is passed through, so there is no danger of burns occurring and several components can be tested on the bar simultaneously. Some components may require circular magnetisation but are far too large to test by using a current flow technique through the whole component; in this case *prods* can be used (see **Figure 6.9**).

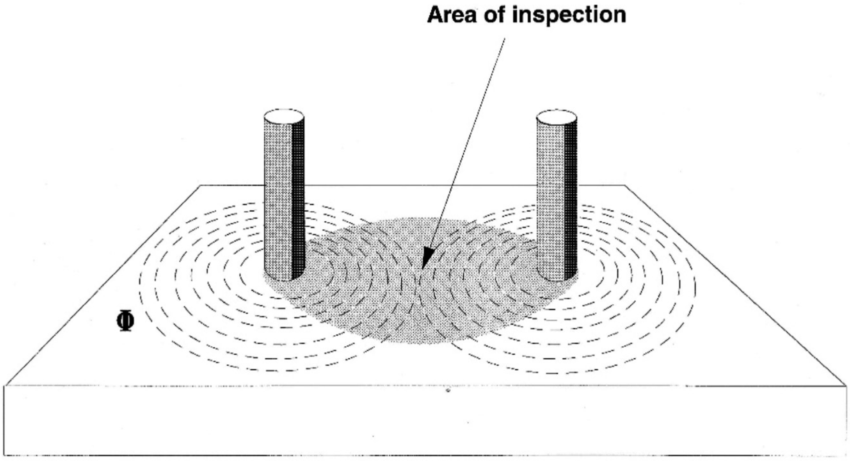


Figure 6.9 – Energised prods with a circular magnetic flux pattern

Prods are electrical contact points that are typically manually held against a component by the operator a specified distance apart. This way the current value can be kept reasonably low to reduce the likelihood of burning the component.

The operator can then use a multiple prod position technique to fully inspect the surface of even very large components weighing many tonnes.

6.1.4.2 Longitudinal magnetisation

Permanent magnets were often used to perform magnetic particle testing. We need the magnet as a U-shape, such that both poles can be placed on the component surface simultaneously, allowing the magnetic flux to flow from the north pole of the magnet to the south pole through the surface of the component under test (see **Figure 6.10**).

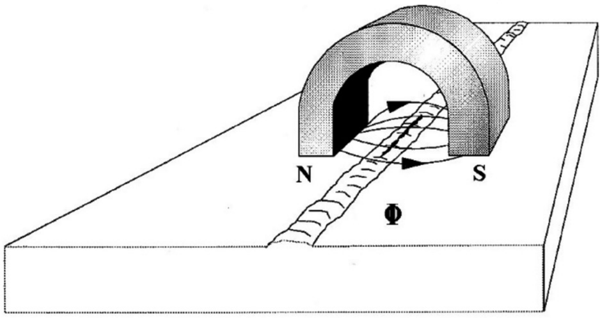


Figure 6.10 – A permanent magnet used to locate a crack in a weld

Because the magnetic flux flows from pole to pole, we call this *longitudinal magnetisation*.

Discontinuities will be detectable once more at 90° (±45°) to the flux direction. One major advantage of a permanent magnet is that no power source is required, hence they are very flexible in terms of where they can be used; however, they tend to deteriorate with age and use, so are less commonly used today compared to electromagnetic yokes.

A similar technique to a permanent magnet is the *electromagnetic yoke*. It produces longitudinal magnetisation but will need a power supply, which may be alternating current or direct current (see **Figure 6.11**). Yokes commonly have jointed legs, which allow variable spacing of the poles.

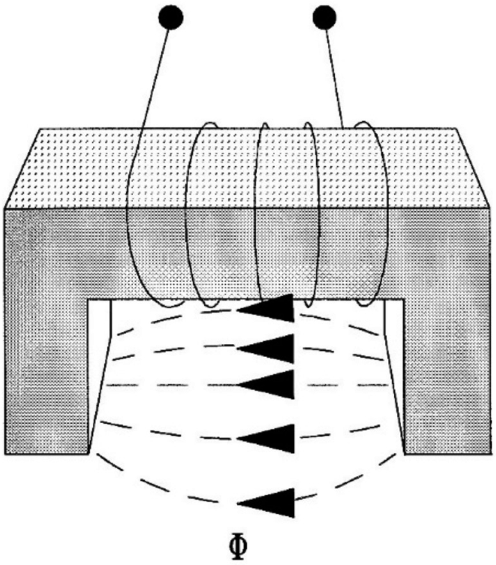


Figure 6.11 – An energised electromagnetic yoke with magnetic flux passing between the two yoke legs

To detect transverse discontinuities in a component such as that in **Figure 6.12** below, an excellent technique would be to use *encircling coils*. The component can be placed inside a rigid coil or, alternatively, a flexible cable can be wrapped around the component.

Once a current is passed through the coil, a longitudinal flux is generated in the component.

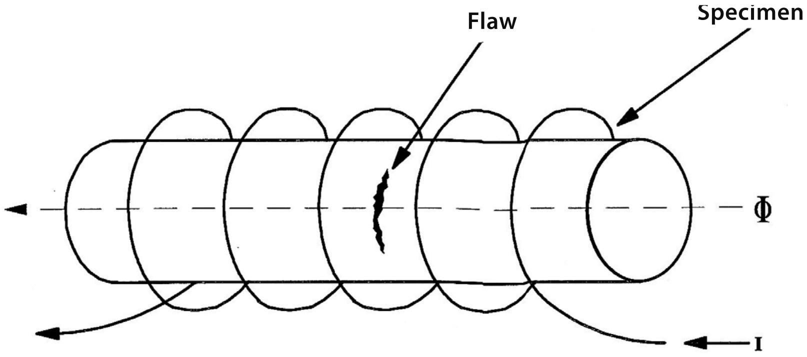


Figure 6.12 – The longitudinal flux generated by the encircling coil technique will allow transverse discontinuities to be located

A typical rigid coil will have between three and five turns.

Another common technique for producing longitudinal magnetisation is to use the magnetic flow facility of bench units, which we will look at in more detail in a later section. The component is clamped in place in the bench unit and magnetic flux is passed longitudinally through the component allowing for the detection of transverse discontinuities.

We have now looked at a number of common magnetisation techniques, but often a single component is subjected to more than one magnetisation technique – why is this? We earlier discussed the fact that discontinuities are more easily detected when they intersect the magnetic flux at 90° (±45°), but a component may contain discontinuities in any orientation, so if we applied a magnetic flux to a component in only one direction, the discontinuity may be running in the same direction as the flux and will very likely be missed.

To try to ensure discontinuities in any particular orientation are located, magnetisation is carried out in two directions 90° apart (as a minimum).

As an example, a simple bar-shaped component, such as a shaft, is to be tested with a bench unit. The first magnetisation technique could be current flow to look for longitudinally-orientated discontinuities and, after a full inspection for longitudinal discontinuities, we could then use magnetic flow to look for transverse discontinuities.

6.1.5 Demagnetisation

After we have finished testing a component, is that the end of the story? Typically not, it is possible that components will retain some magnetism after testing, this is called *residual magnetism*. Residual magnetism could be a problem later in the component's service life – an extreme example would be if the magnetised component is installed near a compass. Further processing steps can also be affected, such as galvanising operations or welding. Machining chatter can also be caused by machining chips sticking to the component.

It is important that we remove the residual magnetism. This process is called *demagnetisation* and there are several ways in which this can be accomplished. Most of these use a reverse magnetising force opposite to the magnetising force used initially. This reverse magnetising force is called the *coercive force*.

One common demagnetisation technique is to pass a magnetised component through a coil carrying either alternating current or reversing direct current. This will provide the coercive force required for demagnetisation.

Heat treating a component above the material's curie point, which is approximately two thirds of the material's melting point (for iron this is approximately 870°C), the material becomes paramagnetic and the domains randomise. This is a very thorough way to demagnetise a material but obviously not always practical.

It is common for three separate demagnetisation sequences to be performed. The first is carried out prior to any magnetisation; the second between different magnetisation directions, *ie* between circular and longitudinal magnetisation; the final one is carried out after the last magnetisation operation.

6.1.6 Equipment for magnetic particle inspection

6.1.6.1 Magnetising portable equipment

Portable equipment, generally speaking, is magnetising equipment small and light enough to be carried and used by one operator, the simplest examples being permanent magnets and electromagnetic yokes, which we have already looked at.

We have also briefly mentioned prods, which have a small portable power supply, usually up to 1500 A half-wave direct current or alternating current, generated typically from an 110 V or 240 V circuit.

6.1.6.2 Magnetising mobile equipment

Mobile units are more powerful but are much heavier and, as a result, are mounted on wheels to enable them to be towed to where they are needed. They normally operate from a 240 V or 480 V circuit and provide an output up to 6000 A half-wave direct current, or alternating current mobile units are used with *wander leads*, which can be clamped to a component for current flow circular magnetisation, or formed into a coil around a component to provide longitudinal magnetisation.

6.1.6.3 Heavy-duty equipment

This category of magnetising equipment is stationary and is called heavy duty because of its size and output capabilities. They can generate up to 20,000 A full-wave direct current from an input of typically a 240 V-480 V three-phase alternating current.

Bench equipment, multi-directional units, automatic units and special purpose units fall into the heavy-duty category. Bench equipment typically will have a reservoir of detection media to apply to a component. Current flow, magnetic flow, threaded bar and rigid coil methods of magnetisation can be employed with a typical bench unit.

Multi-directional units are designed to produce circular and longitudinal magnetic fields in a component, at almost the same time reducing inspection times.

Automatic units are purpose-built machines, designed for mass inspection of identical items. Although the majority of test inspection is performed by operators, some systems have been built which are fully automatic, including the interpretation of detected indications.

Special-purpose units may be manual, automatic or semi-automatic. They are designed for the inspection of one specific part or class of parts, which are usually large and heavy. Part manipulation is often an integral part of the design.

6.1.7 Detection media

There are two basic types of detection media: dry powder and wet suspensions (which are called inks). They both contain very fine ferromagnetic particles and the main difference is that in ink, particles are suspended in a liquid carrier fluid, which typically can be either water or light oil, commonly paraffin.

Dry particles are carefully applied to a component by *floating* them into a component surface, which is being magnetised with a pulsating current form such as alternating current, or half-wave rectified current to provide particle mobility.

Inks are typically applied by spraying or flowing onto the surface. A pulsating current is not a prerequisite when using ink. The ferromagnetic particles for both ink and dry powder come in various colours to increase contrast and reliability. Red and black are common and are viewed under white light. Particles can also be coated in fluorescent compounds and are viewed in ultraviolet light. The fluorescent compounds absorb ultraviolet light, which is invisible to the human eye, and emit the energy as a visible wavelength, usually yellow green. Indications then give off light, making the fluorescent detection media very sensitive to small discontinuities.

6.1.8 Lighting

As discussed earlier, inspection is performed with either white light or ultraviolet light; it is important that an operator ensures the correct lighting levels are used for inspection. White light can be artificial or natural sunlight, but when ultraviolet light is being used the levels of white light must be kept very low in an inspection booth.

6.1.9 Magnetic field indicators

It is important that an operator is confident that an adequate level of magnetic flux is running through a component and in the desired direction. A technique may specify a current value to use on a component, which has been calculated from the cross-sectional size of the component – what if this calculation was incorrect? To this end, several types of flux indicator are commonly used. One type consists of three strips laminated together. Two outer plain strips sandwich an inner strip containing artificial defect slots of various widths to give an indication of field strength; if only one indication is visible, this shows a low field strength, if all three indications are visible, this shows a higher field strength.

Another type consists of eight sections of mild steel braised together forming artificial defects. Flux direction can be shown very easily with this type of flux indicator. A similar type to this consists of two artificial defects at 90° to one another beneath a cover plate, which can be set to one of four sensitivity levels by altering the gap between the artificial defects and cover plate.

A *Hall-effect* meter, which is a tangential field strength meter, is an instrument containing a semi-conducting crystal; accurate readings of magnetic flux can be made with this type of equipment.

To check the effectiveness of demagnetisation, a *residual field strength meter* is used. If the reading is above the allowable level, demagnetisation will be repeated and rechecked with the residual field strength meter.

6.1.10 Plant performance tests

The performance of permanent magnets and electromagnets performance will typically be checked with a *weight lift test*.

Current flow and magnetic flow techniques will be checked using a test-piece with a series of holes drilled to specified depths. Indications of these holes must be visible at specified current values. Failure to see an indication at the correct current setting may indicate an equipment or ink problem, which should be identified and rectified before any testing of components is carried out.

6.1.11 Components

Magnetic particle testing is very versatile and can be used to test a large range of components, from small forgings to large castings. Restraints are that only ferromagnetic components can be tested and only discontinuities down to approximately 3-4 mm can be reliably detected.

Surface cracks of discontinuities are more detrimental to the service life of a component than sub-surface discontinuities and magnetic particle testing can be very sensitive in terms of locating surface discontinuities.

Quenching and grinding cracks, fine in-service fatigue cracks, stress corrosion cracks, seams, laps, hot tears, cold shut, surface ruptures and non-metallic inclusions are all readily detectable in a variety of components with magnetic particle testing.

6.1.12 Specific applications

Magnetic particle testing is widely used in industry for final inspection of manufactured components, receiving inspection and in-process inspection for quality control. In-service inspection for maintenance and overhaul is often used in the transportation industries as well as plant and machinery maintenance and inspection of large components. With in-process testing, serious discontinuities can be located early; re-work at this stage may save the component and, even if the component cannot be saved, time and money will be saved by scrapping the component early. Final inspection will still be required to ensure no rejectable discontinuities are contained within the component, which may have originated during further manufacturing processes.

Within the transportation industries, magnetic particle testing is used extensively during planned overhaul and maintenance schedules. Critical components such as engine, suspension, breaking parts, etc, of aircraft, rail and heavy goods vehicles are tested.

Large expensive plant within manufacturing and the power generation industries also undergo regular inspection programmes to reduce the likelihood of potentially fatal and always expensive breakdowns.

6.1.13 Advantages of magnetic particle testing

- Magnetic particle testing is a sensitive method for locating surface and slight sub-surface discontinuities in ferromagnetic materials.
- Indications are produced that can have very good definition of the actual discontinuity.
- The method is relatively simple to learn.
- Components of virtually any size or shape can be tested.
- Cracks which are filled with foreign material may still be detected.
- Discontinuities do not have to be surface-breaking like a crack, for example non-metallic inclusions may be located.
- Portable equipment can be used to test components *in-situ*, an electrical supply is not necessary in all cases.
- The method is very rapid. An indication of a discontinuity is formed virtually instantaneously.
- Testing is possible in some cases on painted or coated components.

6.1.14 Disadvantages of magnetic particle testing

- Only ferromagnetic parts can be tested.
- To ensure a part is fully tested, it is often necessary to apply two magnetic fields 90° apart in separate operations.
- Residual magnetic fields may be a problem – demagnetisation is often required.
- High currents are often needed to magnetise a part, which may lead to arcing between the part and electrical contact, which can burn the part. This can cause parts to be scrapped.
- Post cleaning is usually needed to remove residual consumables.
- Often the part will have been de-greased prior to inspection, leaving the part susceptible to corrosion. Protection after testing is often required.

6.2 Summary

Magnetic particle testing is a very versatile method of testing ferromagnetic components to a high degree of sensitivity for surface and slight sub-surface discontinuities. It can be performed during the manufacture of a component and during regular maintenance routines to help ensure the component conforms to its designed structural integrity.

Section 7 – Penetrant Testing

Penetrant testing is a simple non-destructive testing (NDT) method used to locate surface-breaking discontinuities in metals and many non-metals using a penetrating liquid.

7.1 Description of the method

7.1.1 Basic principles

By its very nature, penetrant testing is a simple straightforward testing method; however, it is also very easy to make a mistake during the process and so invalidate the test.

Penetrant testing has its roots in the rail industry with a test then called the *oil and whiting* method. This method involved immersing a cleaned component into dirty crankcase oil diluted with kerosene (dirty oil worked better than fresh unused oil) and, after the component had been allowed to drain, it was then cleaned with solvent. The component was then covered with *whiting*, which is powdered chalk. Any oil trapped in the discontinuities would bleed back into the whiting, giving an indication.

Penetrant testing has not changed too much over the years, penetrants are more sensitive now but in essence the process is the same.

Following are the six basic steps involved in penetrant testing:

7.1.2 Pre-cleaning

It is absolutely vital that a component which is to be penetrant tested is perfectly clean and dry. This also applies to the surfaces of any discontinuities that may be present.

Any contaminants (which include oil, grease, paint, rust, etc) will restrict the entry of penetrant into discontinuities and can very easily lead to serious discontinuities being missed.

An example of this is an aircraft incident, where an engine component failed during take-off, killing two passengers. A subsequent accident investigation proved that the problem was caused by incorrect pre-cleaning. The discontinuity was full of contaminant and therefore no penetrant could enter it, so the operator had no chance of finding the discontinuity.

Pre-cleaning may be done with one process, or several different stages may be required depending on how many different types of contaminant are to be removed. We can categorise pre-cleaning methods into *physical* and *chemical* methods.

Physical methods include wire brushing and abrasive blasting. These methods are good for removing paint and rust but are incapable of removing contaminants within discontinuities. It is also a strong possibility that abrasive methods will cause plastic deformation, especially to soft materials, and can close up discontinuities – this does not mean the discontinuity has gone, it just means that it will no longer be able to be located using penetrant testing. If this happens, one of the chemical cleaning methods, *acid etching*, must be carried out to remove the smeared material closing the discontinuity.

Other types of chemical cleaning include: detergents, which can be acid- or alkaline-based; steam cleaning, which is usually carried out on large components; vapour de-greasing, in which a component is lowered into a tank containing heated trichloroethylene; solvent cleaning, which is often performed during *in-situ* tests with rags dampened with solvent; and ultrasonic cleaning tanks, which contain solvent – the part is immersed in the tank and ultrasonic vibrations help to clean the part.

After the part is cleaned, it is often required with certain cleaning methods to thoroughly rinse the part with water to remove any chemical cleaning residues, which may adversely affect the penetrant testing process. Typical examples would be acid or alkaline residues, which can severely affect the sensitivity and hence the discontinuity detection ability of penetrants. Even the water used to help remove chemical residues will constitute a contaminant because it will stop the penetrant entering discontinuities.

As stated earlier, components must be absolutely clean and dry before penetrant application. It is common practice to dry parts that have been subject to any type of water-based cleaning in a hot air re-circulating oven. It is also important that parts dried in an oven are allowed to cool before penetrant application.

7.1.3 Penetrant application

Penetrant can be applied using any one of a number of methods, *ie* spraying, brushing, immersion, electrostatic application, etc. The method of application is not important, what is important is that the test area is fully wetted with penetrant and the penetrant remains in contact with the surface under test for the correct length of time. The time period in which the penetrant is allowed to remain on a part is called *contact time*, *penetration time* or *dwell time* and can vary from as little as five minutes upto four hours, depending on the specification and type of discontinuity being sought. There is a danger with the longer contact times of penetrant drying on the surface. The operator will need to keep re-applying penetrant regularly to prevent this occurrence.

How does the penetrant enter discontinuities? The process is called *capillary action*, which is the tendency of liquids to penetrate into small openings such as cracks. The positive force that causes the movement of certain liquids along narrow or tight passages is called *capillary pressure*. The narrower the tube, the higher the capillary pressure and the level that the liquid reaches up the tube will also be higher. The same applies to discontinuity width: the tighter the crack, the higher the capillary pressure.

If a drop of penetrant is put on a test-surface, the drop spreads out or wets the surface of the part. If we measure the contact angle between the penetrant and a test-surface, we can see if the penetrant has good wetting ability. If the contact angle is less than 90°, the penetrant is said to have good wetting ability (a typical contact angle of a good penetrant will be 8-10°).

We can see the effect of capillary pressure in **Figure 7.1**. A narrow glass tube is placed in water and capillary pressure draws the water up the tube.

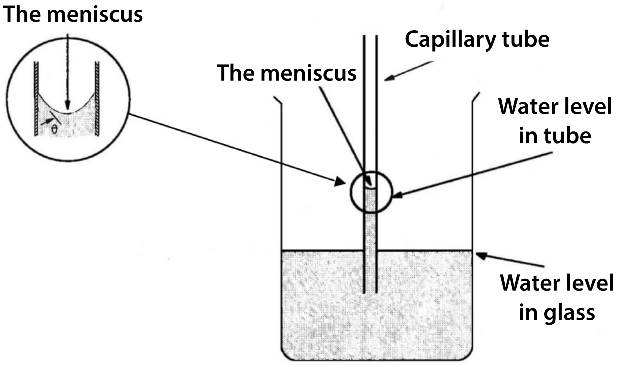


Figure 7.1 – Capillary action

When penetrant is placed on the surface of a component that has a discontinuity, the capillary action draws penetrant into the discontinuity, displacing the air within. Bubbles can sometimes be seen rising to the surface of the penetrant on a component containing a large discontinuity.

Another important property of penetrants is *viscosity*, which is the resistance of a fluid to flow. A high viscosity penetrant will take longer to enter a given discontinuity than a lower viscosity penetrant.

7.1.4 Penetrant removal

Penetrant removal is another step that, although quite straightforward, is easy to do wrong. If this step is not carried out correctly, the entire test needs to be performed again.

An ideal situation is where excess penetrant only is removed from the component's surface and no penetrant is removed from discontinuities.

There are three different methods for removing excess penetrant, depending on the type of penetrant used. We will look at each removal method in more depth.

7.1.4.1 Solvent removal

This penetrant system is very often used *in-situ*. It is very portable and consists of three pressurised spray cans: the first contains solvent, which is used for both pre-cleaning and for removing excess penetrant from a component; the second contains the penetrant; and the third contains the developer.

To remove excess penetrant from a component after the required dwell time has elapsed, the bulk of the excess penetrant is manually wiped off using dry lint-free tissue. A second wipe of the surface is then carried out using tissue moistened with solvent (it is very important that solvent is never sprayed directly onto the surface as this may flush penetrant out of the discontinuities and the test will be ruined). A third wipe is then made with dry tissue. If any penetrant has been missed, the dry tissue will have a penetrant stain and another wipe with a solvent-moistened tissue will finally remove the last of the excess penetrant.

7.1.4.2 Water removal

Although penetrants are oil-based, some are made containing an emulsifier to enable the penetrant to be removed with water. These penetrants are ideal for use on large numbers of small components, or components with rough, uneven surfaces, such as those found with some types of castings.

Typically, with large numbers of small components, they will be immersed in penetrant using a basket and, after the correct penetration time, transferred to a wash station tank equipped with air/water lines and a drain. The air/water mixture provides a low-pressure coarse droplet water spray, which is ideal for removing excess penetrant.

7.1.4.3 Post-emulsified removal

As stated earlier, penetrants are oil-based and some are designed to have a separate emulsifier added after the penetrant time has elapsed. One type of emulsifier is used diluted in water and is a type of detergent, this is called a *hydrophilic emulsifier*. With this type, a first stage water spray is used to mechanically scrub most of the excess penetrant from the surface. The hydrophilic emulsifier is then applied by immersion. The remainder of the penetrant/emulsifier mixture can then be removed using a water spray rinse after the correct contact time has elapsed.

A second type of emulsifier in use is oil-based and is called a *lipophilic emulsifier*. These are used undiluted and are faster acting than hydrophilic emulsifiers. No first stage wash is required and, after the penetration time has elapsed, the part is immersed in a tank containing the emulsifier. The excess penetrant/emulsifier mixture is then removed with a water spray. The big advantage of the post-emulsified system is that wide shallow discontinuities are less likely to have the penetrant washed out of them if the emulsification step is done correctly. On the other hand, emulsification time is very important and, if emulsifier is left on too long, penetrant in the discontinuities may very well be washed out, leading to operators missing serious discontinuities.

7.1.5 Development

After excess penetrant has been removed, a developer is applied to the surface of the component. It acts as a blotting agent, drawing penetrant out of the discontinuities to the surface to form an indication.

Developer can also provide a contrasting background as well as spreading the penetrant out over a larger area, making indications easier to see.

Several types are in common use; we will look at each in turn:

7.1.5.1 Dry developer

Dry developer is a very light, fluffy white powder. It is often applied by electrostatic spray or by placing a component in an enclosed dust storm cabinet. Dry developers will stick to wet areas, such as penetrant in discontinuities, so it is vital that, after water washing, parts are correctly dried before application of the developer.

Dry developers are the least sensitive type available, so are usually used with high-sensitivity type penetrants. They do give good indication resolution as penetrant bleed-out from discontinuities is minimised.

7.1.5.2 Water-based

Two types of water-based developers exist: *soluble* and *suspended*. Soluble types have the developer powder dissolved in the water and so, once mixed, do not require agitation, whereas with suspended developers, the developer particles do not dissolve and require agitation prior to and during use.

Because both types are water-based, a component will not require drying after the water wash stage but will require drying after the application of developer, which can be done by dipping or flowing. Pooling of the developer should be avoided as a thick heavy powder coating will be left once the water has evaporated, which may mask small defects.

7.1.5.3 Solvent-based

This type of developer has particles suspended in a volatile solvent. The solvent can mix with penetrant in discontinuities, lowering the viscosity and making it easier to draw the penetrant to the surface to form an indication. This is why developers of this type are considered the most sensitive.

They are mainly contained in pressurised containers so application is by spraying.

Drying of a component after the wash cycle and before developer application is required and, as the developer is solvent-based, it will self-dry almost instantaneously.

7.1.5.4 Film-type

This type of developer is applied by spraying and is used rarely and only in special applications. Once the solvent base dries it leaves a plastic film coating. Indications formed have good resolution and the film can be peeled to provide a permanent record.

7.1.6 Inspection

There are two distinct categories of penetrant and the difference is in the type of dye used to make it.

One type is called colour-contrast penetrant and is made with an intense red dye – inspection is conducted using white light. The second type is called *fluorescent penetrant* and is made with a fluorescent dye.

In white light, an indication with fluorescent penetrant would be very difficult to see; however, if inspection was carried out in a darkened inspection booth using ultraviolet light, the indication would be a bright glowing yellow/green colour. The dye absorbs ultraviolet light, which the human eye cannot detect, and re-emits this energy at yellow/green wavelengths – this can be seen in **Figure 7.2**.

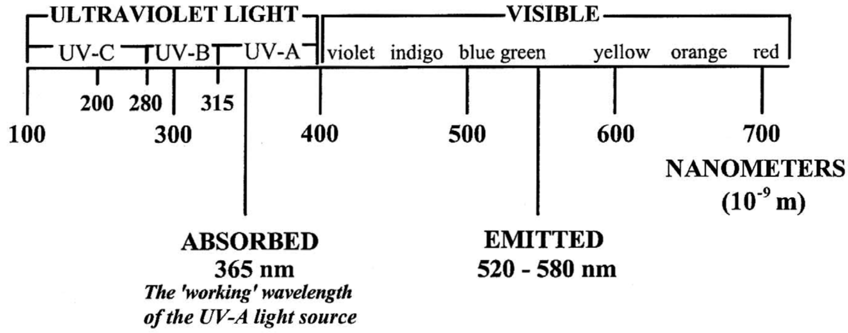


Figure 7.2 – The electromagnetic spectrum

Fluorescent penetrants are considered to be more sensitive than colour-contrast penetrants. The penetrants are further sub-divided into removal methods, as discussed earlier.

A third type of penetrant also exists, which is called *dual-mode* or *dual-sensitivity*. Dual-sensitivity liquid penetrant contains dyes that are both coloured under white light and fluorescent under ultraviolet light. However, the intensities of the visible colour (usually red) and the fluorescent colour (usually orange) are less than the colours produced by the single mode visible and fluorescent liquid penetrant, respectively.

7.1.7 Post-cleaning

Why is it important to post-clean a component after a liquid penetrant test? Penetrant residues could interfere with subsequent processes, or they could lead to corrosion problems. In some applications, cleaning is critical, for example in nuclear applications or with components that come into contact with liquid oxygen. Any trace of hydrocarbon penetrant residue would react violently with the liquid oxygen.

It may be satisfactory to use an airline to blow off dry developer powder, or a more thorough method such as a vapour de-greaser may be needed.

7.1.8 Equipment

As stated earlier, a simple portable penetrant test system consists of three pressurised spray cans containing solvent remover, colour contrast penetrant and solvent suspended developer. With some cleaning cloths and an adequate light, an operator can perform a test almost anywhere.

In a testing facility, it is very common to have penetrant testing lines utilising bulk penetrant consumables in large tanks, which permit the immersion of single large items, or numerous small items immersed into the penetrant in baskets.

A typical penetrant testing line is shown below in **Figure 7.3**.

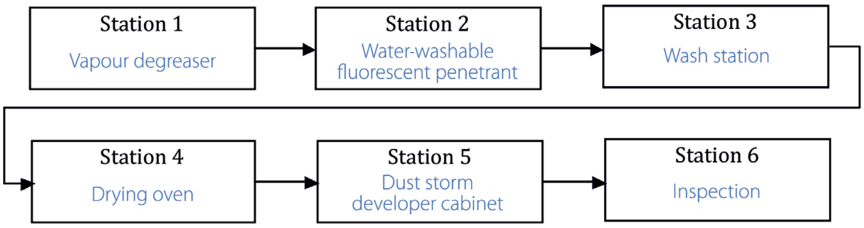


Figure 7.3 – A typical penetrant line

At Station 3, a low-intensity ultraviolet strip light would be installed to help during the washing phase of the test. At Station 6, a high-intensity ultraviolet lamp would be used to inspect the components.

To monitor the day-to-day performance of the penetrant materials, a plant performance check is carried out at the start of every shift. Various types of test-blocks are in use and a common type is shown in **Figure 7.4**. Indentations are made one side of a block, which causes cracking of the chrome plating on the opposite side. The indentations are made using light to heavy forces, creating five different sizes of crack. If the penetrant system is new and locates four of the cracks, the daily check should locate four cracks every time. If one day only three can be located, this indicates a problem, which must be located and rectified before testing can be resumed.

An operator must also work to written test instructions or a technique sheet, so that no matter who performed the test, it is done in exactly the same way. The technique sheet may also have acceptance criteria information, which is usually stated by the customer and will let the operator know which discontinuities are acceptable and which are not.

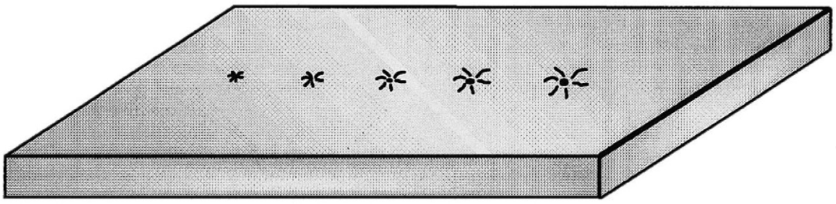


Figure 7.4 – Plant performance test-piece

7.1.9 Components

The big advantage of penetrant testing is its versatility. It is not just confined to testing ferromagnetic metals like magnetic particle testing. It is not even confined to testing metals – glass and plastics are also suitable for testing with penetrants. Small items or very large items can be tested easily.

The drawback is that penetrant testing can only locate surface-breaking discontinuities; processing discontinuities such as cracks, laps, seams, porosity, hot tears, cold shuts and lack of fusion are readily located, as well as in-service discontinuities such as fatigue cracks and stress corrosion cracks.

7.1.10 Specific examples

Anodic flaw detection uses chromic acid to anodise the surface of a component and acts like a penetrant. After the acid has been washed off, any chromic acid in discontinuities bleeds out and leaves a brown stain indication. Anodic flaw detection also has the advantage that metallurgical problems are also revealed.

Leak testing is another application of penetrants, with the quality of the welded joints of tanks and vessels being determined by applying penetrant to one side and inspection for leaks performed from the opposite side.

Penetrant testing is widely used in every industry and finds particular use in aerospace and power generation, where many non-magnetic high-temperature high-strength alloys are used.

Normal penetrant may contain small quantities of sulphur or halogens, which may be detrimental to stainless steel or titanium alloys subjected to high-temperature service conditions. If this is the case, special halogen and sulphur-free penetrant should be used.

Penetrant testing is used to test items such as turbine blades and shafts as well as valves, critical pressure vessels and the austenitic stainless steel piping in pressurised water reactors.

7.1.11 Advantages

- An easy method to learn.
- Very versatile and can be used to examine metals and non-metals.
- Sensitive to small surface-breaking discontinuities.
- Post-emulsifiable systems can detect wide, shallow discontinuities.
- Very good for high-volume production.

7.1.12 Disadvantages

- Pre-cleaning has to be thorough.
- Will not detect discontinuities below the surface.
- Rough surfaces or surfaces with porosity can produce excessive background, which will interfere with inspection.
- Fluorescent penetrants in particular are sensitive to contamination, which will severely affect performance and so extensive plant performance checks may be required for bulk consumables.

Section 8 – Thermal and Infrared Testing

Thermal and infrared testing is a relative newcomer to the world of non-destructive testing (NDT). It involves monitoring the temperature variations of objects in the infrared portion of the electromagnetic spectrum.

8.1 Description of the method

8.1.1 Basic principles

Heat can be transmitted by conduction, convection and radiation. With thermal and infrared testing, only energy transmitted by radiation is of interest and this energy is called *infrared*.

The infrared part of the electromagnetic spectrum is between the visible and microwave portion of the spectrum, between 0.75 µm and 100 µm. The two common infrared bands used in infrared thermography are short-wave at 2-5 µm and long-wave at 8-14 µm. These bands are the parts of the infrared spectrum in which transmission through the atmosphere is high (water and carbon dioxide cause high absorption in other parts of the infrared spectrum).

Generally, if objects are at ambient temperatures, long-wave infrared would be selected, and if objects are at elevated temperatures, short-wave would be selected.

A thermographer views an object with a thermal imager to measure the infrared emitted from the surface. However, to confuse matters, heat sources behind the imager can reflect from the surface making the object appear hotter than it really is. Even the heat from the body of the thermographer can cause this effect on objects at ambient temperature.

Some objects are transparent to infrared and hot sources behind such an object will cause false hot-spots. An experienced thermographer can recognise these false hot-spots and take steps to avoid them. For instance, reflections can be recognised by changing the viewing angle, which would result in the false hot-spot also changing, whereas a real hot-spot would not.

Genuine hot-spots will also conduct heat away through the rest of the object, leading to a thermal gradient. False hot-spots would not show this effect.

One factor that the thermographer needs to know for accurate temperature measurement is the object's emissivity value. A theoretical perfect energy emitter is called a *blackbody* and has an emissivity value of 1.0. All objects have a value less than this, with dark diffuse surfaces generally having a high emissivity value and highly-polished metallic surfaces having a low emissivity value.

Usually, if an object has an emissivity value less than 0.5, accurate temperature measurement is difficult. The object can be coated with paint or tape of a known emissivity value and an accurate temperature measurement can then be made. If a map of temperature distribution is produced, this is called a *thermograph*.

8.1.2 Techniques

There are two distinct techniques used in thermography: *passive* and *active*. In passive thermography, the temperature of an object is measured without special external heating and is used to locate hot-spots such as overheating electrical and mechanical components.

In active thermography, an external heat source is applied to a component and the thermographer looks for temperature variations caused by the presence of discontinuities within an object.

We will now look at active thermography in detail. **Figures 8.1** and **8.2** show a typical test set-up. With active thermography, the camera can be placed on the same side of the target as the heating units, this is called *reflection mode imaging*. If the camera is placed on the opposite side from the heating unit, this is called *transmission mode imaging*.

The heating units (xenon lamps being common) heat the surface for a short period of time. This heat will then start to pass into the test-object via conduction and is, in essence, a thermal wave. The thermal wave will behave like an ultrasonic wave and will reflect off any surface that it encounters, such as the backwall of the component or a discontinuity. The thermal imager will detect the reflected thermal waves heating the surface of the component, with the reflected thermal wave from a discontinuity reaching the surface before the reflected thermal wave from the backwall of the component as it does not have as far to travel.

Figure 8.3 shows a plot of surface temperature *versus* time from the test shown in **Figure 8.1**. An estimation of discontinuity depth can be made using the time of the returning thermal waves.

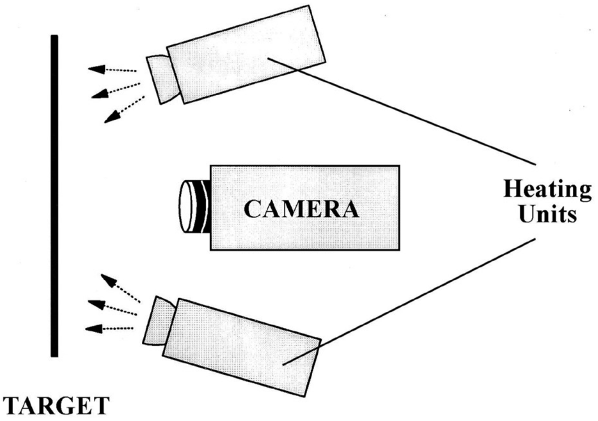


Figure 8.1 – Thermography – reflection mode

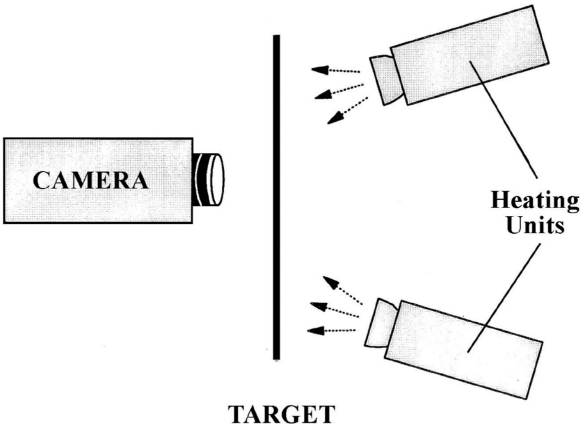


Figure 8.2 – Active thermography-transmission mode

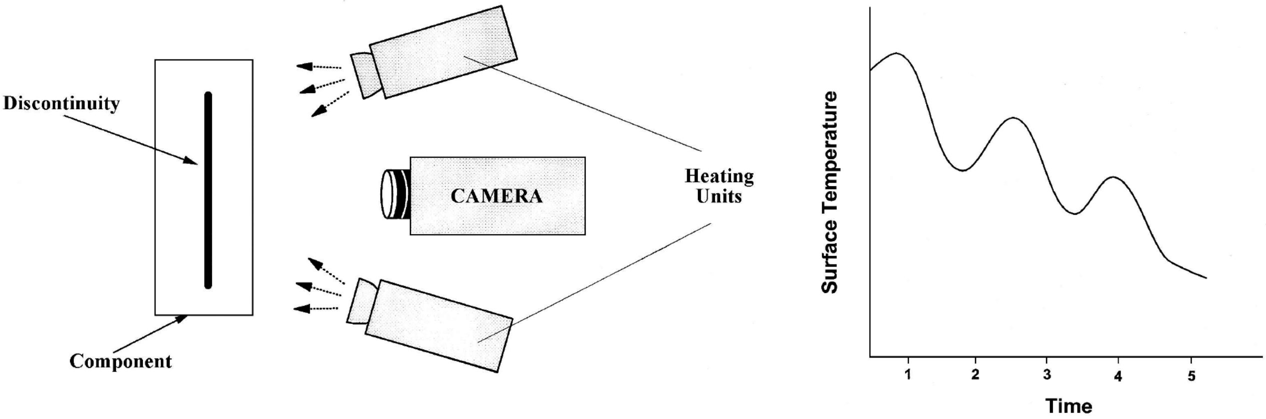


Figure 8.3 – The first peak shows the surface being flash-heated, the second peak shows the reflected thermal wave from the discontinuity and the third peak shows the reflected thermal wave from the component backwall

As a rule of thumb, a discontinuity should be at least as wide as it is deep for it to be detected. Thick components, therefore, are not ideal components for thermal and infrared testing.

Discontinuities near the backwall may be difficult to detect because the reflected thermal waves from the discontinuity and backwall may arrive back to the surface at the same time. If this is the case, the transmission technique may be used, in which the imager is set up on the opposite side to the heat source.

8.1.3 Equipment

Physics tells us that any object above absolute zero will emit infrared energy, therefore an instrument is needed that can detect this energy. A basic instrument will need an optical system to collect and focus the infrared, which is not as simple as it sounds. For instance, glass does not transmit infrared over the entire spectrum of interest, typically germanium, zinc sulphide or zinc selenide is used to manufacture lenses for instruments working in the long-wave infrared band and silicon, sapphire or quartz is used to manufacture lenses for instruments working in the short-wave infrared band. Filters may be incorporated into an instrument to limit the spectral range of infrared reaching the detector.

The detector itself can be either a *photonic* or *thermal* type. A photonic detector is limited in its spectral range and so will be selected depending on which infrared band the instrument is to be used to detect, for example a detector made from mercury cadmium telluride may be used in the long-wave infrared band and a detector made from indium antimonite may be used in the short-wave infrared band.

Photonic detectors have a high sensitivity and react to temperature changes very quickly, but they must be cooled to sub-zero temperatures (typically –196°C) to work efficiently. They work on the principle that incident photons will excite the detector and may produce either an electrical output, or the conductivity of the detector will be changed.

Thermal detectors react to temperature changes much more slowly than photonic detectors because a thermal detector needs to be heated up by the infrared emitted by the target.

Two types of thermal detector are common: a *bolometer* absorbs the heat emitted by the target and the resistance of the detector changes, producing an output signal; a *pyroelectric* detector is made with a certain type of crystal which produces a state of electrical polarity in response to a change in temperature and so will not produce an output when viewing a static thermal target. A *chopper* is used with pyroelectric detectors to overcome this problem. The chopper periodically blocks out the energy reaching the detector so the image is no longer a static thermal target.

Thermal detectors are not spectrally selective, *ie* they respond to infrared no matter what wavelength of infrared energy is incident on the detector. Thermal detectors are slower and have less sensitivity than photonic detectors but have the advantage of operating at ambient temperatures, *ie* they do not require sub-zero cooling.

Once the detector converts the incident infrared into an electrical signal, the instrument electronics amplify and condition the signal and provide an output, which could be a temperature figure or a *thermogram* (a thermal map or thermal image of a target), depending on the instrument configuration.

Some instruments are designed not to produce a thermal image but just to measure a spot temperature of a target area. Instruments of this type are called *infrared radiation thermometers*, the basic configuration of which is shown in **Figure 8.4**.

If we add a scanning system, which often comprises mirrors and prisms, to the basic configuration in **Figure 8.4**, we can build up a thermal map or thermogram of the target. Scanning instruments of this type are called *thermal imagers*.

A line scanner can be used on moving targets, for example steel strip in a rolling mill. The line scanner can be fixed above the steel strip, which will move at a constant rate in one direction. The scanner scans across the strip at 90° to the direction of strip movement and, in this way, a thermogram of the steel strip is made.

Another type of instrument design called a *focal plane array* employs many detectors in an array formation on the focal plane. Each detector forms one picture element or *pixel*, so mechanical scanning is not used in a system of this type. Each detector is viewing the target 100% of the time and so can respond to changing thermal conditions very quickly. Focal plane array images also have very good spatial resolution.

If a system is not corrected for target infrared radiance, it is called a *thermal viewer* and will be used for qualitative inspections, *ie* locating thermal anomalies on a target (*ie* hot-spots). A thermal viewer will not give accurate target temperatures.

If a system is corrected for target infrared radiance it is called an *imaging radiometer* and will be used for quantitative inspections, such as condition monitoring, and will be able to determine accurate temperatures of thermal anomalies.

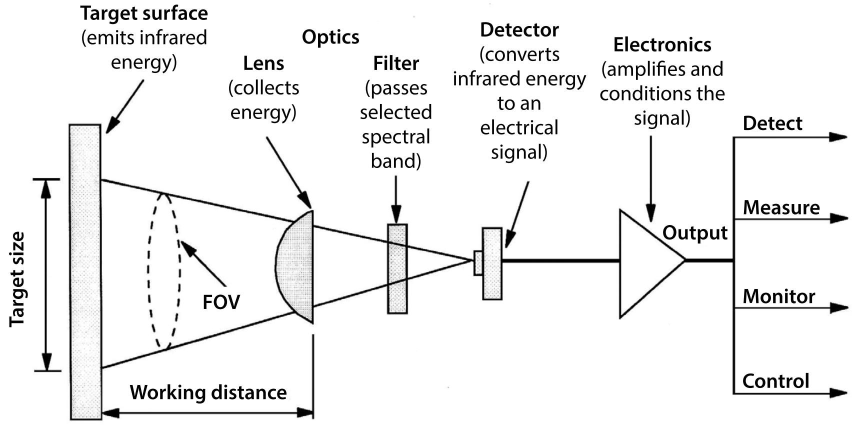


Figure 8.4 – Basic configuration of an infrared radiation thermometer

8.1.4 Data processing

An important part of the inspection equipment used by thermographers is a personal computer, which can have sophisticated image processing software installed, enabling on-site image processing to be carried out. This can be invaluable especially with active thermography, when thermal anomalies may be transient in nature. The computer will have data capture, recording and report generation facilities.

An additional invaluable tool used by the thermographer is a digital camera, which will enable a normal white-light image to be made of a target containing a thermal anomaly.

8.1.5 Heat source

As stated earlier, active thermography requires the surface of a component to be heated. This ‘heat injection’ may be a flash pulse, wide pulse or a series of periodic pulses. The amount of heat applied to a component must be sufficient to produce a signal-to-noise ratio from a discontinuity that can be detected by the thermal inspection system, but must not be so high that the heat injection causes damage to the component’s surface.

Heat can be applied by high-intensive xenon flash lamps, lasers, incandescent lamps or heat guns. It is also possible to increase the thermal gradient through a component by heating one side whilst cooling the opposite side.

8.1.6 Detector coolant

Some types of detector require cooling to very low temperatures and this cooling is often provided by using liquid gas, such as liquid nitrogen, at –196°C. The instrument will require regular additions of liquid gas, so a supply should be available for long inspection sessions.

8.1.7 Procedure

A detailed written instruction should be available to the thermographer to allow an inspection to be carried out to the customer’s requirements. The written instruction should include all relevant information the thermographer will need, for instance relevant health and safety data. The thermographer may be required to survey operating electrical systems, which will typically have stringent health and safety requirements.

8.1.8 Components

Thermal NDT methods have been used in applications where traditional methods, such as radiographic testing, electromagnetic testing and ultrasonic testing, have encountered problems.

These applications relate to high-integrity components manufactured from new materials or advanced materials, including ceramics, composite materials, plastics and semi-conductors, etc. Voids, disbonds, delaminations, foreign matter (inclusions), badly-cured areas and surface cracks can be detected.

8.1.9 Specific applications

Thermal infrared testing has very many uses, here are just some applications.

The military have been developing infrared systems for a number of years for reconnaissance, target acquisition, heat-seeking missiles, fire control and navigation.

Civil uses include law enforcement, fire-fighting and building integrity.

Medical uses rely on the fact that damaged biological tissues are hotter than normal tissue, so infrared can be used for mammography, soft tissue injury and arterial constriction.

Environmental applications include earth resources, pollution control and energy conservation. A building can be inspected to look for heat leaking through the building or roof envelope and is particularly suited to locating water intrusion, which will cause severe heat loss through damp insulation.

Industrial uses include predictive maintenance, manufacturing and NDT. We will now look at some industrial applications in more detail.

8.1.10 Predictive maintenance

Mechanical systems contain many moving parts; the friction of these moving parts causes heat. Bearings are a low-friction moving component, so will normally not overheat.

Overloading, lack of lubrication and contamination of lubrication will all lead to overheating and damage of the bearing. Regular thermal surveys will detect early signs of overheating, allowing maintenance to be performed to extend the life of the bearing. This same principle can be employed on any machine.

Electrical systems can also be monitored for any anomalous temperature rises, which can be caused by loose or corroded connectors and partially broken wires, leading to increases in resistance. It is safe to inspect a live electrical system as thermography is non-contact and it would be common practice for an electrical engineer to accompany the thermographer during a site survey.

Because thermal testing is non-contact and can rapidly inspect large areas of a component, the method is widely used to test power generation sub-systems, such as boilers and process heaters or boiler tubes, and also items such as steam tubes. With boiler insulation, the refractory lining will deteriorate with time and, as it starts to fail, hot-spots will form on the outer shell of the boiler. Thermal testing can locate localised areas where the refractory lining is starting to fail at an early stage, allowing timely repair to be carried out before the shell is permanently damaged or a burn-through occurs.

Thermal testing of boiler tubes can detect overheating caused by blockages at an early stage and so prevent the tubes from bursting.

8.1.11 Manufacturing

Quantitative quality control of manufacturing processes is frequently carried out with thermal equipment. A good example would be in the manufacture of paper. A line scanning system can be installed at the drying station to monitor temperature distribution across the moving paper line. If the temperature is incorrect, it will affect the final quality of the paper product. The line scanner will detect any thermal problems and alert the operators, who can take steps to correct the problem.

8.1.12 Non-destructive testing

Active thermal techniques can be used to detect internal component discontinuities as stated earlier. Active thermal techniques are also suitable for detecting the wall thinning of tubes caused by internal corrosion without internal access being needed.

Passive thermal techniques are frequently used to locate water ingress into air frames. If a plane lands after a flight at altitude, the water is likely to be ice, or at the very least, much lower than ambient. The metal aircraft skin will quickly heat up, allowing cold spots from water ingress to be located.

8.1.13 Advantages of thermal and infrared testing

- Both active and passive techniques can be applied to a wide variety of components or assemblies to enable many conditions to be detected.
- Inspection is carried out remote from a component; inspection inside high-temperature environments is possible.
- Inspection is very rapid, large components can be imaged.
- Accurate temperature distribution of a component can be made, the results can be stored electronically and this can allow regular inspections to be made and compared to the previous results, allowing early detection of any temperature rise.
- Thermal testing can be carried out on materials such as composites, which can be difficult to test with other forms of NDT.
- Imaging of internal discontinuities allows accurate interpretation to be made, particularly with computer-based image processing software.

8.1.14 Disadvantages of thermal and infrared testing

- Equipment can be very expensive.
- Reflective surfaces can lead to false hot-spots.
- Careful spectral filtering is required to image material that is partially transparent to infrared energy.
- To accurately measure a component’s temperature, the emissivity value must be known.
- Interpretation of results can be difficult due to the many variables involved; experience is essential.

8.2 Summary

Thermal and infrared testing has very many applications and is one of the most versatile NDT methods available.

Section 9 – Other Methods and Competencies

There are other NDT methods and competencies listed in this section. Further details of these methods and competencies can be obtained from the British Institute of NDT.

9.1 Other methods

- Computer Radiographic Interpreter
- Digital Radiographic Interpreter
- Alternating Current Frequency Modulated (ACFM)
- Guided Wave
- Weld Inspection.

9.2 Scopes of competencies

- X-rays
- Gamma rays
- Dye penetrants
- Fluorescent penetrants
- Fixed installations
- Portable equipment
- Composite materials
- Materials and components
- Structures
- Light metals
- Dense metals
- Plate
- Bars and billets
- Forgings
- Condenser tubes
- NDT instruction writing
- Critical defect sizing
- Single frequency
- Multiple frequencies
- Butt welds in plate
- Butt welds in pipe
- 'T' joints
- Nozzles
- Nodes
- Wavemaker
- Teletest
- MSS.

Issued by the British Institute of Non-Destructive Testing
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