J. Phys. E: Sci. Instrum., Vol. 16, 1983. Printed in Great Britain

Nondestructive testing using electromagnetic instrumentation

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Abstract. Mechanical, structural and geometrical properties of metals, such as the presence of defects, hardness, degree of heat treatment, and dimensions can often be tested nondestructively by electromagnetic methods. These methods include the use of eddy currents and magnetic particles, which are particularly effective for locating and sizing surface and subsurface defects, and the application of magnetic hysteresis. The paper describes the established techniques and some of their more recent developments.

1. Introduction

The nondestructive testing (NDT) of an object is its examination by a method which does not impair its usefulness. NDT is often carried out by a manufacturer with a view to safeguarding the integrity of his products but there are instances where it is obligatory. With aircraft, atomic reactors and processing plant, for example, an apparently minor fault in a component or structure subjected to fatigue may grow rapidly and eventually result in a catastrophe when in service. Additional faults may develop as a result of corrosion, wear, accident and ill-treatment, and the responsibility of performing NDT then rests on the user as, for example, with the periodic inspection of an aircraft when in service.

Nondestructive testing comprises the verification of dimensions, composition, internal structure and stability of an installation or component, as well as flaw detection, and the methods include the applications of radiological, ultrasonic, electromagnetic, dye penetrant and thermal techniques. Prior to the use of any of these methods, it is essential to perform a visual inspection with the naked eye and an appropriate optical instrument. This can often reveal defects, thus avoiding the necessity of further testing.

The selection of a NDT method depends on the shape, size, and the material of the object to be examined and also its function. For example, the testing of a steel casting to ascertain its internal structure can be performed either with x-rays or ultrasound, depending on the thickness. For a relatively thin casting, say less than 30 mm, the use of x-rays provides a higher degree of sensitivity to detection but for greater thicknesses, for which the penetration of x-rays is limited, the use of ultrasound is preferred. If one wishes to inspect for surface cracks the selection lies between surface ultrasonic, magnetic particle, dye penetrant and eddy current methods. Eddy current methods are more sensitive than the use of ultrasonic surface waves for crack depth determination, and magnetic particles are preferred to dye penetrants for revealing the presence of cracks but they can be applied only to ferromagnetic materials.

Except for the comparatively rarely used microwave method, which is mainly restricted to testing dielectrics, electromagnetic methods are restricted to testing metals. The most important of these is the eddy current method but magnetic particle and magnetic hysteresis inspections are often carried out. In addition to detecting flaws, electromagnetic methods can indicate changes in electrical conductivity, magnetic permeability and distances and, from the indications, one can determine properties such as hardness, degree of heat treatment and thickness of metal sheets and of nonmetallic coatings on metal surfaces. Objects within a very large range of shapes and sizes, such as engine castings, turbine blades, ships' screws, metal pipes, small bolts and ball bearings, can be tested by these methods.

2. The eddy current method

2.1. *General considerations*

The use of eddy currents for nondestructive testing was originally carried out on a large scale by Förster in Germany during the Second World War, and it has developed rapidly since then. With it, the sizes of surface and subsurface cracks in metals can be determined to within fractions of millimetres and values of electrical conductivities and magnetic permeabilities can be measured with accuracies of better than one per cent. An important advantage of using eddy currents is that, unlike ultrasonic and magnetic particle methods, contact between the detector and the sample surface is not required, so that careful surface preparation other than the removal of metallic adherents in unnecessary.

The method utilises a coil carrying an alternating current, at a given frequency, which is placed in the vicinity of a metal sample under test. The alternating magnetic flux generated in the sample induces eddy currents which produce a secondary magnetic flux in the coil which is generally out of phase with the primary flux. In this way the impedance of the coil is changed both in magnitude and phase by amounts dependent on the values of the electrical conductivity σ and the magnetic permeability μ of that part of the sample in which the eddy currents are induced, and also dependent on the sizes, shapes and relative positions of the coil and sample. Where greater sensitivity of detection is required a transformer coil may be used. Here the eddy currents are induced by the primary and secondary coil detects them but, with the high dynamic ranges of modern equipment, the use of a single coil generally suffices.

This phenomenon was first analysed by Förster (McMaster 1959) for a coil of radius r_0 encircling a rod of nonferromagnetic metal having magnetic permeability μ very nearly equal to that of free space, i.e. $4\pi \times 10^{-7}$ H m^{-1} and remaining constant for all values of exciting current. Förster's analysis produced relationships between the inductive (ωL) and resistive (R) components of the coil impedance (figure 1), which were normalised by dividing them by ωL_0, the inductive component of impedance of the coil with the rod absent. Points were plotted for different frequencies $\omega/2\pi$ which were normalised by the use of the dimensionless parameter $\omega\mu\sigma r_0^2$. A family of curves were produced, each representing different coil diameters as expressed by the normalised parameter η, called the fill factor, and equal to the ratio r/r_0^2 where r is the radius of the rod.

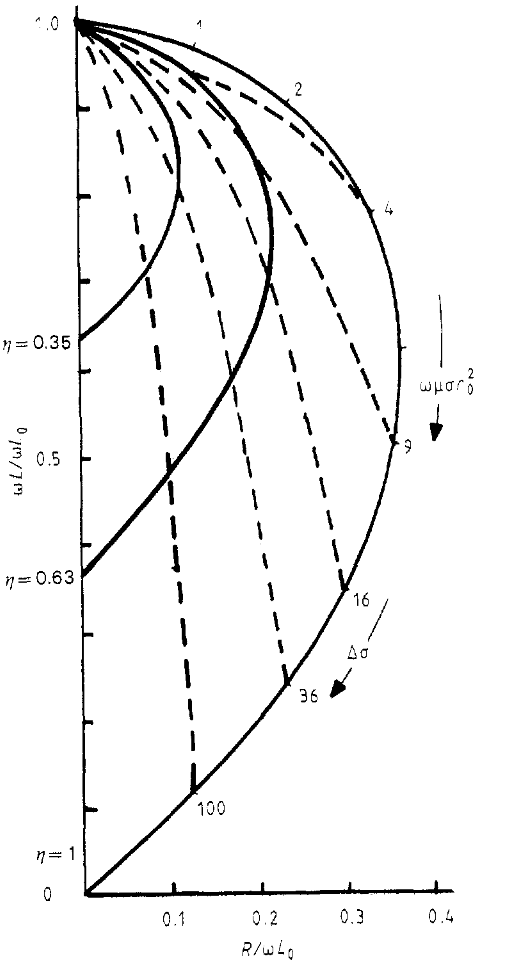

Figure 1. Normalised components of impedance of a coil encircling a nonferromagnetic metal rod for fill factors η having different values (full curves). Broken curves join points for which values of the parameter $\omega\mu\sigma r_0^2$ are constant (after Förster (1954)). By courtesy of Inst. Dr Förster.

Using Förster's normalisation technique, a single set of curves suffices to predict the components of impedance of a coil encircling a metal rod, irrespective of dimensions and of the electrical conductivity σ of the rod, provided that the coil is not too close to the ends of the rod. Thus, for example, the values of $\omega L/\omega L_0$ and $R/\omega L_0$ for a copper rod ($\sigma = 60$ MSi m^{-1}) and a frequency of 40 kHz are the same as for an aluminium rod ($\sigma = 40$ MSi m^{-1}) and a frequency of 60 kHz for the same coil and fill factor, because $\omega\mu\sigma r_0^2$ remains constant. Alternatively, for a fixed frequency and fill factor the impedances are similar when the radii of the respective coils have a ratio equal to $(40/60)^{1/2}$.

Using Förster's curves, variations of electrical conductivity and radius of a metal rod can be measured simultaneously. Given values of frequency, initial conductivity and radius are represented by a fixed point on figure 1, for a coil of given radius. Variations of σ and r are indicated by changes of impedance along the $\Delta\sigma$ (full curves) and $\Delta\eta$ (broken curves) respectively. Thus, for example, a change in structure or the presence of a defect which gives rise to a variation in σ can be determined independently of any changes in the cross-sectional dimensions of the rod. In practice, one simply measures the impedance vector perpendicular to the tangent to the $\Delta\eta$ curve at the point in question.

An important parameter in eddy current testing is the penetration depth δ at which the eddy current density reduces to a fraction $1/e$ (i.e. -4.3 dB) of its value at the surface, i.e.

$$\delta = (2/\omega\mu\sigma)^{1/2}. \tag{1}$$

With aluminium, for example, δ ranges from about 3.5 mm to 0.1 mm corresponding respectively to frequencies of 1 kHz and 1 MHz. However, with modern equipment, a dynamic range of up to 100 dB is attainable and variations in structure occurring at a depth of about 20δ are detectable. Figure 1 shows that the resolution between the $\Delta\sigma$ and $\Delta\eta$ curves reduces rapidly when $\omega\mu\sigma r_0^2$ is less than 15, e.g. for a frequency of about 10 kHz with a 10 mm diameter coil encircling an aluminium rod. On the other hand there is an increase in sensitivity in determining σ and, if we known that η remains constant, there is no need to resolve the curves, and conditions are thus ideal for measuring changes in conductivity. At high frequencies it is seen that the inductive impedance ωL of the coil increases thus providing greater sensitivity in measuring surface phenomena such as surface breaking cracks. The depths of these cracks can be measured even if they are greater than the penetration depth, because the eddy currents follow their boundaries (figure 2).

Förster extended his analysis to the testing of tubes, and the corresponding curves (McMaster 1959) are modified to take the tube thickness into account. At higher frequencies, where the eddy currents do not penetrate to the inner surface, the curves become identical to those for rods.

The impedance of an encircling coil depends on the total effect of the eddy currents in the region enclosed by the coil. To pin-point changes in a sample one scans the surface with a probe-type coil, which is a solenoid having its axis perpendicular to the surface. This can be done when the curvature of the surface remains sensibly constant over the region of the coil diameter.

An advantage of using a probe coil is that a ferrite core of high relative permeability (typically about 100), which remains constant for all values of magnetic field, can be inserted and thus increase its inductance. Because ferrite cores have low electrical conductivities, often less than 1 Si m^{-1}, eddy current induction within them is negligible.

Dodd and Deeds (1968) have derived theoretical impedance variations for a single-turn coil above a plane surface. In practice, it is not feasible to use this type of coil because of its very low inductance, although the theory does predict, to some extent, the behaviour of the impedance variations for a solenoid coil. The author and his colleagues (Hajian *et al* 1983) have modified the theory of Dodd and Deeds to predict the impedance variations with an air-cored solenoid probe coil and they provide a reasonable agreement with measured values.

The impedance plots for probe-type coils differ from those for encircling coils in that the curves indicating change of fill factor are replaced by those showing variations of normalised

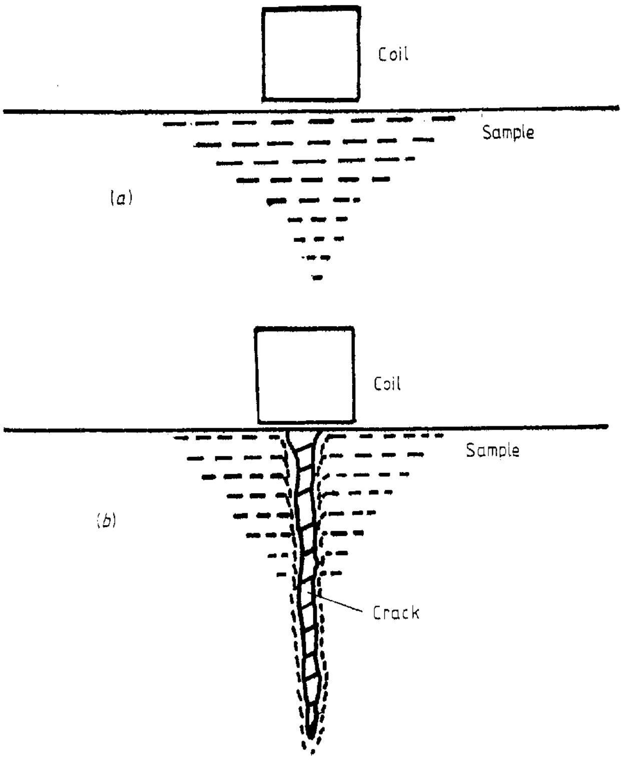

Figure 2. Sections through eddy current distribution beneath a probe coil for (*a*), a defect-free sample; (*b*), a sample containing a surface crack.

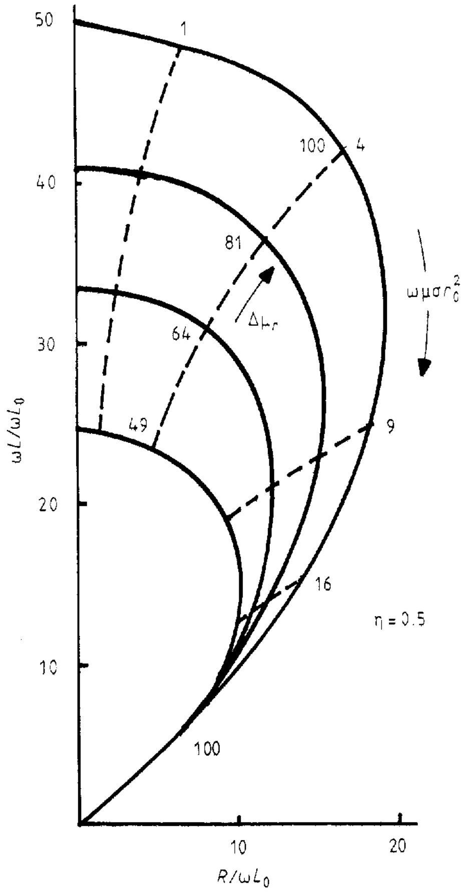

Figure 3. Normalised components of impedance of a coil encircling a ferromagnetic metal rod, fill factor 0.5, for different values of relative magnetic permeabilities μ_r (full curves). Broken curves join points for which the values of the parameter $\omega\mu\sigma r_0^2$ are constant (after Förster (1954)). By courtesy of Inst. Dr Förster.

'lift-off' i.e. the ratio of the height of the base of the coil above the surface of the test sample to the radius of the coil. Because the coupling between the coil and sample is not as close as that for an encircling coil, the value of $\omega L/\omega L_0$ is greater than zero for zero lift-off and infinite frequency.

For maximum detectability of defects and other localised structural changes, the use of small-diameter coils, typically about 2 mm, is necessary and this requires the use of high frequencies (e.g. 100 kHz to 1 MHz) to provide adequate sensitivity of impedance measurements. Calibration for crack-depth measurements is achieved by testing on cracked samples which are then broken open for visual checking of crack size. An accuracy of better than 25% can be achieved for measuring surface cracks 1 mm in depth.

Eddy current methods are also used to test ferromagnetic metals, particularly mild steel tubes and welded steel structures. If the sample is kept in a state of magnetic saturation with either a coil carrying a direct current or a strong permanent magnet placed in a suitable position, the differential magnetic permeability $\Delta B/\Delta H$ is constant for all values of eddy current density and the curves shown in figure 1 are applicable. For unsaturated ferromagnetic samples, however, this is not so and the magnetic permeability μ becomes variable. Unfortunately, the variations both in μ and the fill factor (or normalised lift-off) produce impedance changes having similar phases and thus cannot be resolved from one another. Hence separate sets of curves must be produced for different values of fill factor. Figure 3 illustrates a set of curves, obtained by Föster (1954) for a coil encircling a rod with a fill factor value of 0.5, with the assumption that any cyclical changes in μ caused by the eddy currents are negligible. However, provided that the initial permeability is sufficiently high, e.g. μ_r is greater than 50, the effects of fill factor on the magnitude of impedance are small compared with those of μ. The curves show that the resolution between changes in μ and σ increases with decreasing values of $\omega\mu\sigma r_0^2$, but the effects of the variations of μ become small compared with those of σ at higher frequencies.

2.2. *Instrumentation*

Basically, eddy current detection involves the comparison, using an inductance bridge, of the impedance of the detecting coil with that of another coil, called the comparison coil, and having a known value of impedance. In some cases the comparison coil forms part of the circuitry in the body of the instrument while in others it is a coil similar to the detecting coil and located either at a standard sample or at a different part of the object under test. It is necessary for the instrument to be calibrated before use, e.g. with the detecting probe at a sample of known electrical conductivity, for conductivity measurements, or at a sample of the material of the object under test containing real or simulated defects of known size, for flaw detection. In any case the calibration should be made either with similar conditions of lift-off, or fill factor, or with the impedance variations caused by these factors phased out.

Most eddy current instruments indicate the voltage output of the bridge and a phase-sensitive detector indicates its phase with respect to a reference voltage, so that its components can be resolved (figure 4). The bridge is initially balanced with the coil

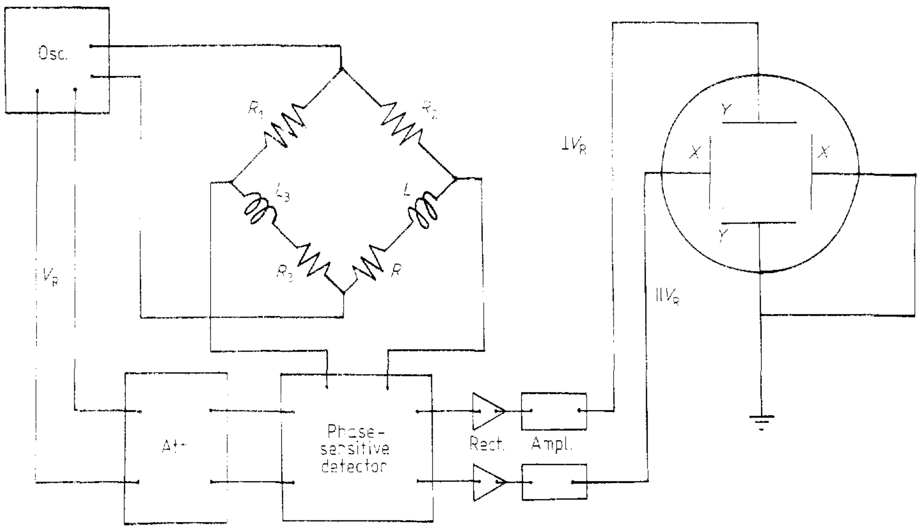

Figure 4. Simplified circuit of typical eddy current testing instrument.

in a standard position, e.g. with crack detection, at a defect-free part of the sample under test (i.e. at a fixed point on the impedance curve (figure 1)). When the impedance of the detecting coil changes, the bridge loses balance and an output voltage is observed. It can be shown (Blitz *et al* 1981b) that, for small changes, the components of the output voltage are proportional to those of the impedance of the coil. With the simpler type of instrument the magnitude of the voltage output is displayed on the scale of a rectified voltmeter and the desired phase can be obtained by means of a phase adjuster. For example, lift-off effects can be eliminated simply by adjusting the phase to a value for which there is no change in the meter reading when a probe coil is raised or lowered above the sample, and then changing the phase by an angle of 90°. More sophisticated instruments provide a visual display on a storage oscilloscope and often have the facility for automatic bridge balancing. Thus an unwanted component of output voltage, e.g. that due to lift-off, can be rotated in phase so as to produce a horizontal line on the screen: the desired component is then determined from the vertical deflection. Eddy current instruments are usually designed to operate at several frequencies and many do so over a continuous frequency range, often from 1 kHz to 2 MHz.

Some types of eddy current equipment are designed specifically for tube testing. Here a continuous length of tubing, typically from 10 to 25 mm diameter and often several metres long, can be fed at constant speed through two encircling coils in close proximity to one another, thus enabling the detection of local changes in structure with the effects of changes in fill factor phased out. Gradual variations in output of the instrument indicate changes in electrical conductivity and abrupt variations signify the presence of defects. The choice of frequency affects the sensitivity in measuring these changes, i.e. low frequencies (e.g. 5–20 kHz) for those due to conductivity and higher frequencies (e.g. 25–50 kHz) for those governed by the presence of defects. A pen recorder is often used to produce a permanent record of the magnitude of the output although a meter or cathode ray oscilloscope is retained for the purpose of monitoring.

Other applications, often conducted with simple and portable equipment, have been designed for determining thicknesses of coatings such as paints, plastic layers and anodic films on metallic bases as given by the degree of lift-off. Calibration is effected by placing a probe coil on top of coatings having different known thicknesses.

Recent developments (Blitz and Peat 1981a, Libby 1970) include the use of two or more frequencies applied simultaneously, to enable characterisations of defects in more detail and also to separate out changes in σ and μ characteristic, for example, of variations of hardness and the presence of heat-affected zones in welded steel structures. Other recently developed techniques are the use of pulsed and also microwave eddy currents. With the former method (Libby 1970, Waidelich 1970, 1981), high-power pulses are generated for short periods at regular intervals and are capable of much greater penetration than continuously generated eddy currents. Penetration of up to 10 mm has been achieved in steel. The method also has the advantage of reducing the effects of lift-off. Eddy currents at microwave frequencies (e.g. 1000 MHz) are generated by ferromagnetic resonators such as YIG spheres typically of less than 1 mm diameter and situated in direct magnetic fields. They have been successful in detecting surface cracks only 0.5 mm deep and also in monitoring crack growths in stressed materials.

3. The magnetic hysteresis method

A well known method of testing ferromagnetic material is to subject a sample to magnetic hysteresis (Blitz *et al* 1969) whereby the cyclical variation of either magnetic flux density B or magnetic polarisation J with the applied magnetic field H is by means of a closed curve, called the hysteresis loop. At frequencies of greater than about 10 Hz the shape of the loop is modified by the effects of induced eddy currents. The electrical and magnetic properties of the sample which determine the characteristics of the loop are dependent on other physical properties such as degrees of alloying and heat treatment, as well as the presence of residual stresses and gross defects.

The basic type of hysteresis tester consists of two identical transformer coils connected in series and carrying an alternating current of several amperes at a fixed frequency, usually 50 Hz. One coil encircles the sample and measures B and the other, containing air, detects the value of H. The secondaries of each of these coils are fed respectively to the Y- and X-plates of a cathode ray oscilloscope, so that the B–H hysteresis curve appears on the screen. Förster has produced such an instrument, called the *Ferrograph* which can also indicate a J–H curve. This instrument is intended principally to examine objects of small cross-sectional dimensions, e.g. a few mm, and of simple geometries, such as wires, pipes and ribbons. It is highly suitable for testing the properties of magnetic tapes and cores and also of magnetic powders contained in glass tubes.

A hysteresis method which is more suitable for testing the mechanical properties of ferrous metals also makes use of two identical transformer coils, which are both indicators of B (figure 5). Depending on the nature of the test sample, either encircling or probe-type coils may be used. The coils are orientated at right angles to one another to avoid any magnetic flux coupling. As before, an alternating current having a fixed frequency (usually 50 Hz) is fed through the primary coils of the transformer, which are in series. The secondary coils, however, are wound in opposition so as to produce a 180° phase difference and the output is fed to the Y-plates of a cathode ray oscilloscope. The X-plates are connected to a time base, synchronised with the primary source, which is normally adjusted to produce the length of one cycle.

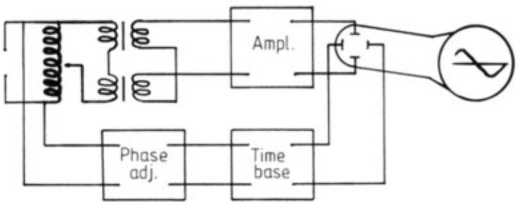

Figure 5. Simplified circuit of Magnatest. By courtesy of Inst. Dr Förster.

In the absence of any samples at the coils, a horizontal straight line appears on the oscilloscope screen. On placing two identical ferromagnetic samples in identical positions at each coil, they both experience similar hysteresis cycles but, because of the 180° phase difference, the resultant trace on the screen remains as a horizontal straight line. However, if there are any differences between the magnetic permeabilities, electrical conductivities, or the shapes and sizes of the samples, the oscilloscope display is not a horizontal straight line but a curve which is characteristic of these differences.

The *Magnatest* (Inst. Dr Förster, Reutlingen) available in different forms, is an instrument based on the above-mentioned principles. A reference sample is located at one coil and the sample to be tested at the other. The resultant indication is compared with patterns drawn on a graticule, placed in front of the oscilloscope screen, and obtained from calibrations with samples having known properties. Tests which can be made with

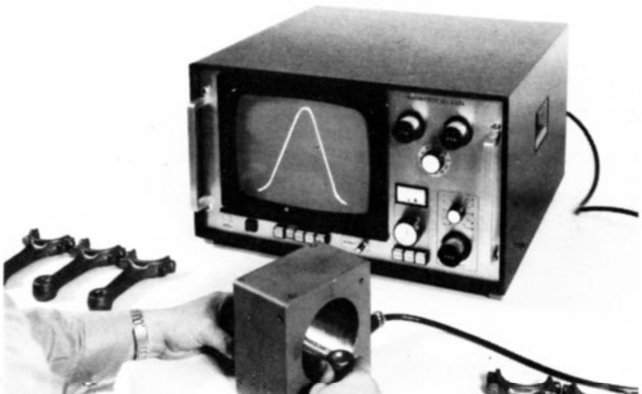

Figure 6. The Magnatest QS 3204. By courtesy of Inst. Dr Förster (now superseded by the Magnatest I 3610).

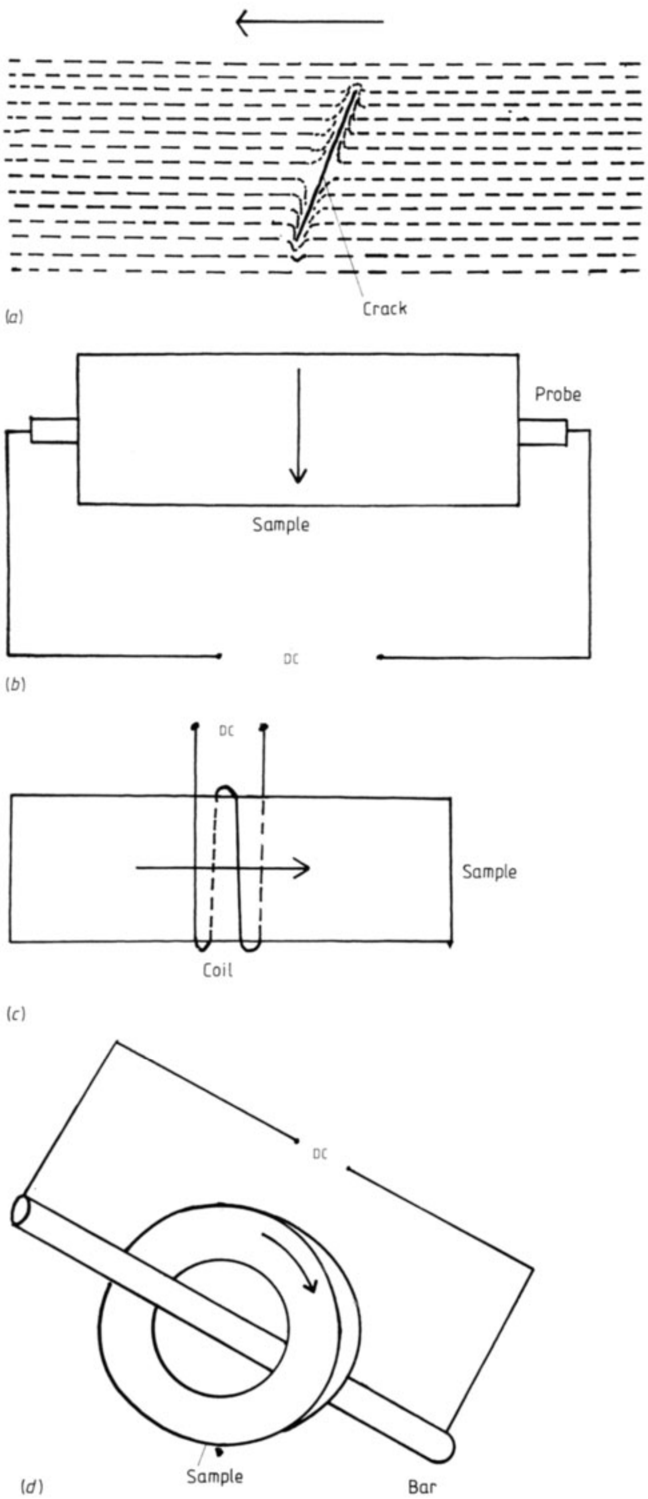

Figure 7. Applications of magnetic field for magnetic particle inspection (arrows indicate directions of field). (*a*), Distribution of magnetic lines of force (broken lines) on a surface containing a crack; (*b*), current applied directly to the sample; (*c*), use of encircling coil; (*d*), use of threading bar.

the Magnatest include the measurements of hardness of turbine blades, bolts and crankshafts, drawability of sheet metal, grain structure of various components, sorting ball bearings of different sizes and many others (Blitz *et al* 1969). Sizes of encircling coils vary from 5 to 500 mm inside diameter depending on the size of sample. Probe coils have diameters at the lower end of this range and are usually operated at higher frequencies (up to 100 kHz). One version of the Magnatest is designed to operate at only 1 Hz, at which frequency the effects of eddy currents are negligible, so that measurements obtained are independent of electrical conductivity. Figure 6 illustrates Förster's Magnatest QS3204 for the hardness testing of automobile engine components. This instrument has now been superseded by the more refined Magnatest I 3160.

4. Magnetic particle testing

The magnetic particle method (Blitz *et al* 1969) can be used to test ferromagnetic bodies of virtually any size and ranging from a small pin to the propeller of an ocean liner. In the basic form of the technique, iron filings are scattered on the surface of a sample and, when a magnetic field is applied, the filings simulate the lines of force. In the absence of any defects the lines are uniform but the presence of a crack, either at or just below the surface, gives rise to their deviation so as to provide a magnified profile of the defect (figure 7(*a*)). Greater sensitivity of detection is obtained with the use of a 'magnetic ink' consisting of a suspension of Fe_3O_4 particles suspended in paraffin, which is applied either by dipping or spraying. It is essential that the surface be thoroughly cleaned and degreased prior to magnetic particle application.

The simplest method of magnetising is the use of current ranging from 500 to 4000 A, depending on the size of the sample, either directly (figure 7(*b*)) or through a heavy coil (figure 7(*c*)). Figure 8 illustrates a portable crack detector (Magnaflux Ltd) fitted with probes and capable of passing a current of up to 750 A, as supplied by a half-wave rectifier, through the sample. Maximum detectability is established when the applied magnetic field lies perpendicular to the direction of the defect.

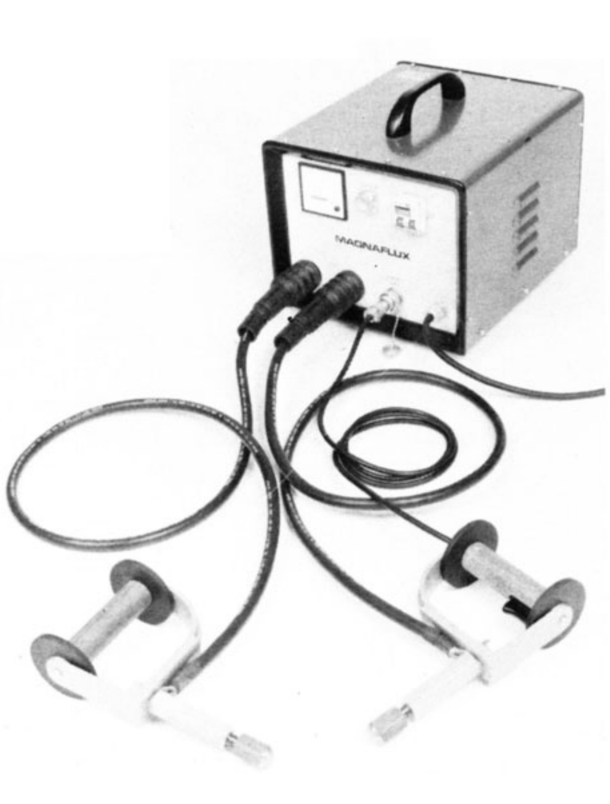

Figure 8. Portable crack detector. Courtesy of Magnaflux Ltd.

A steel tube can be tested by inserting inside it a heavy copper bar, known as a threading bar, carrying the current (figure 7(*d*)). The lines of force follow circular paths thus enabling the easy observation of longitudinal cracks. An encircling coil can be used to test for transverse cracks.

The visual detection of any defects is facilitated by the use of dyed or fluorescent inks and viewing with a lamp. An ultraviolet lamp is employed with fluorescent inks.

5. Conclusion

The hysteresis and magnetic particle methods of testing are now well established and there does not appear to be much scope for their future major development. This is in contrast with the eddy current method which the author feels is a powerful and still little-understood technique still in its infancy. Another possibility of future advancement in electromagnetic testing is the use of the Hall effect for measuring DC flux changes but, with available techniques, the sensitivity of detection at present is not high.

Acknowledgments

The author is indebted to Messrs Magnaflux Ltd, Wells–Krautkramer Ltd and the Inst. Dr Förster for their kind assistance in preparing this paper.

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