NOTE
ARL/MET. 75

NOTE
ARL/MET. 75

COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF SUPPLY

AUSTRALIAN DEFENCE SCIENTIFIC SERVICE

AERONAUTICAL RESEARCH LABORATORIES

Metallurgy Note 75

CONSIDERATION OF THREE MODERN NON-DESTRUCTIVE TEST TECHNIQUES

by

I. G. SCOTT

MELBOURNE

JUNE 1971

PRINTED BY DEPARTMENT OF SUPPLY, CENTRAL DRAWING OFFICE, MARIBYRNONG, VICTORIA 3032

DEPARTMENT OF SUPPLY

AUSTRALIAN DEFENCE SCIENTIFIC SERVICE

AERONAUTICAL RESEARCH LABORATORIES

METALLURGY NOTE 75

CONSIDERATION OF THREE MODERN NON-DESTRUCTIVE TEST TECHNIQUES

by

I. G. SCOTT

SUMMARY

Studies have been made of three possible techniques suitable for use in NDT—namely—the transducerless generation of ultrasound, the use of radioactive gas and microwave testing. The first is in the very early stages of development, the second has been shown to be relatively successful but requires equipment which is not readily available at Aeronautical Research Laboratories, and the third method is limited to the use with non-conducting materials.

CONTENTS

1. INTRODUCTION

In recent articles Farrell[1] discussed possible applications of holography to non-destructive testing (NDT) and Scott[2] examined the use of stress wave emission (SWE). These "state-of-the-art" review articles typify an important aspect of work presently being undertaken at A.R.L. in connection with NDT, and parallel the active use and development of well-established techniques of NDT.

In this note three topics of possible application to the needs of A.R.L. in the field of crack detection are discussed: the transducerless generation of ultrasound, the use of radioactive gas, and microwave testing. The survey has been carried out in sufficient detail to permit its use as a starting point for further studies, and to permit meaningful comparisons to be made between possible new and existing techniques.

2. THE TRANSDUCERLESS GENERATION OF ULTRASOUND

In 1968, Wallace[3] and his co-workers at Cornell University described an ultrasonic flaw detection technique in which generation of ultrasound within the specimen was achieved without the use of a conventional transducer. Acoustic waves were generated by high frequency electromagnetic radiation incident on the specimen, normally in the presence of an applied static magnetic field. Similar findings were reported in 1969 by Sazonov[4] and in 1970 by Wusterberg[5] of Bundesanstalt für Materialprüfung, Berlin; whilst equipment was displayed at the Physics Exhibition 1970 by a group from University of Lancaster headed by Dobbs.[6] (This effect is not to be confused with the aircoupled acoustic test equipment described by Botsco[7] wherein, by using comparatively low frequencies and accepting some sensitivity loss, ultrasonic equipment was made to work under special conditions, e.g. the detection of defects in honeycomb structures.)

Unfortunately it was not possible to detect, in aluminium specimens, the presence of holes of less than 1 mm in diameter. Dobbs et al. found the sensitivity to be down by 40 db on that of a conventional transducer. Despite this low sensitivity the technique, which is clearly in its early stages of development, appears to be of interest in situations where contact with the specimen is not permitted. However, some contact with the specimen is normally necessary in order to apply a static field. Hence whilst the technique is truly "transducerless," it is not necessarily "contactless" and consequently is of lesser interest. It could also be argued that in many situations the mechanics of supplying a static field are far easier than those necessary for maintaining contact between transducer and specimen. Whatever is decided from these arguments, the technique remains of interest but possibly of limited application.

The basic work leading to the above developments took place in the mid-sixties, and was reviewed most recently by Mertsching[8], whose bibliography included Russian and East European references. Other review articles by Alig,[9] Meredith et al.[10] and Turner et al.[11] concentrated more on the work of U.S. physicists. Various models or explanations were employed.

The incident electromagnetic wave is assumed to penetrate the non-magnetic specimen for a distance which is short compared with the wavelength of sound waves in the material (the depth of penetration of the electromagnetic wave is limited by the skin effect to about 0·001 in.) If the specimen comprises a free electron gas which is associated with an isotropic matrix of positive ions, then the electrons of the gas can be set in motion by the action of the incident electromagnetic field. Some of the energy of electron motion can be transferred to the ion matrix, resulting in the generation and propagation of a sound wave in the specimen. Note that although the electromagnetic wave is restricted to a thin surface layer the acoustic wave can propagate in the main body of the specimen. Thus coupling between the fields of the external or incident electromagnetic wave and the acoustic wave takes place near the surface of the material.

Alig[9] developed firstly a theory which was applicable in the absence of a static magnetic field; Maxwell's equations were used as a starting point. Also it was assumed that the electrons were specularly reflected at the surface of the metal and that the total current density could be expressed as the sum of the electronic and ionic current densities. The equation of motion of the ions has been expressed by Quinn and Rodriguez[12]:

$$M\frac{\partial^2 \xi}{\partial t^2} = C_l \nabla(\nabla . \xi) - C_t \nabla \times (\nabla \times \xi) + ze\mathbf{E} + \frac{ze}{c}\mathbf{u} \times \mathbf{B}_o + \mathbf{F} \qquad (1)$$

where M = mass of positive ion
ξ = $\xi(\mathbf{r}, t)$ = displacement at time t of atom whose position of stable equilibrium is $\mathbf{r}$
t = time
C_l = elastic modulus for compressional sound waves
C_t = elastic modulus for shear sound waves
z = number of conduction electrons per atom
$-e$ = charge on electron
$\mathbf{E}$ = intensity of electric field in specimen
c = velocity of light
$\mathbf{u}$ = $\frac{\partial \xi}{\partial t} = i\omega\xi$ if assume disturbance has form $e(i\omega t - i\mathbf{q}.\mathbf{r})$
$\mathbf{B}_o$ = intensity of static magnetic field
$\mathbf{F}$ = collision force (a conduction electron with velocity $\mathbf{v}$ upon colliding with the matrix transfers momentum $m(\mathbf{v} - \mathbf{u})$)
$\mathbf{q}$ = wave vector
m = mass of electron

In Alig's treatment the C_l and $\mathbf{B}_o$ terms were omitted (only shear waves were considered) and the final term was rewritten as $zm/\tau(\langle\mathbf{v}\rangle - \mathbf{u})$
where $\langle\mathbf{v}\rangle$ = average electron velocity in a specified direction
$\mathbf{u}$ = ionic velocity in the same specified direction
τ = average relaxation time for electron on Fermi surface

The Poynting theorem was used to calculate the power transferred from the incident electromagnetic wave to the acoustic wave. The efficiency of power transfer η was calculated and given by

$$\eta = \left(\frac{i}{2\pi}\right)\left(\frac{zm}{M}\right)\left(\frac{\omega_p{}^2\omega^3 l^5}{s^2c^3}\right)I_1 \qquad (2)$$

where ω_p = electron plasma frequency = $(4\pi\sigma/\tau)^{\frac{1}{2}}$
σ = classical electrical conductivity
ω = frequency of incident magnetic field
l = electronic mean free path
s = velocity of transverse sound in metal
I_1 = (see later)

When a thin indium film formed one of the walls of a resonant rectangular microwave cavity operated at a frequency of 9·3 GHz, the substitution of appropriate parameters resulted in

$$I_1 = -2\pi i(s/\omega l)^5$$

whence
$$\eta = (zm/M)(\omega_p/\omega)^2(s/c)^3. \qquad (3)$$

(Note that similar calculations can be made for the converse process, i.e. the generation of electromagnetic radiation by acoustic waves.) Agreement with experiment was poor.

A similar expression to (2) was obtained when a magnetic field was present, but differed in the meaning assigned to I_1. For an aluminium film several mm thick and subjected to electromagnetic radiation in the presence of a static magnetic field, one has

$$\eta = (zm/M)(c/s)(\omega_c/\omega_p)^2 \qquad (4)$$

where ω_c = cyclotron frequency. (The cyclotron frequency is defined from $\omega_c = eB_o/Mc$ where the symbols have been previously identified.) Two findings emerge—the acoustic power generated is proportional to the square of the field strength both above and below the helicon absorption edge*—this has been confirmed for crystals of Nb and Sn up to 110 kG—and secondly the generated signal intensity is independent of temperature change. For less than 5 kG fields, Houch et al.[13] failed to obtain an ultrasonic signal—this field intensity is close to the helicon absorption edge and because the sample thickness is very much greater than the acoustic wavelength one would expect the acoustic wave to be damped by a different mechanism. Alig calculated that the ratio of power generated for no field to power generated for a 10 kG field was about 200 : 1.

Meredith et al.[10] used a procedure similar to that used by Alig, making the same assumptions about specular reflection of the electrons at the surface, separating current density into ionic and electronic contributions and using the Quinn and Rodriguez equation of motion of the ions. Thereafter the solutions diverged somewhat, differing geometries being considered, namely (i) $\mathbf{B}_0$ was made parallel to the metal surface and perpendicular to the propagation vector $\mathbf{q}$ and (ii) $\mathbf{B}_0$ was made normal to the surface and parallel to $\mathbf{q}$ (the so-called "helicon geometry," i.e. the situation which encourages helicon generation). In the first instance it was found that ξ only responded to the component of the r.f. field whose magnetic vector was parallel to $\mathbf{B}_0$. The generated sound wave was largely compressional for low $\mathbf{B}_0$, but at higher values of the field the sound wave was a mixture of compressional and shear waves, the latter being polarised at right angles to $\mathbf{B}_0$. In the second case pure shear waves were excited at room temperature (a temperature effect was postulated in contrast to Alig) which had a wavelength close to that of ordinary sound but which were rapidly attenuated. Much of the work was confirmed experimentally including the cosine variation of signal amplitude which had been predicted earlier. For the helicon geometry it was predicted that the generated shear displacements were largest in the lighter elements because ξ was inversely proportional to the density[10].

Mertsching[9] used a treatment based on that of Alig and showed how transverse waves could be generated in the absence of a magnetic field, whilst in a high magnetic field making angle ϕ with the polarising vector **E** of an incident electromagnetic wave, ultrasonic waves polarised perpendicular to both **E** and **B** were generated with a much greater efficiency given by

$$\eta_t = \frac{B^2 \sin^2 \phi}{\pi \rho v_s c} \tag{5}$$

where ρ is the density and

v_s is the ultrasonic wave velocity.

Calculations can also be made in terms of surface impedance (see later). The above treatment was applicable only for specular reflection of electrons at the surface for either no magnetic field or for a magnetic field perpendicular to the surface. Otherwise many of the early assumptions were invalid—for diffuse scattering calculations have been made only for zero magnetic field.

Mertsching reported that generation of ultrasonics has been observed in a variety of materials (Al, Bi, Ag, Cu, Sn, and Nb) at frequencies in the range 0·1 to 10 MHz in an external field. In the absence of a magnetic field similar effects have been reported in indium at 9 GHz. In the R.F. range, generated ultrasonic power is proportional to magnetic field strength, independent of temperature and varies with orientation as predicted. It appears that at microwave frequencies diffuse scattering is more likely than the presently assumed specular scattering—which gives incorrect results. (Southgate's[14] calculations show that for the diffuse scattering case and for high frequencies, e.g. greater than 1 GHz, no advantage is to be gained in using a static field.)

Turner et al.[11] preferred to develop a macroscopic model to explain these happenings. As before, the model was valid only for small penetration of the electromagnetic radiation into the specimen. The microscopic mechanism whereby force was communicated to the lattice was considered not to be revelant and a calculation was made for the total force per unit volume

---

* A helicon is a circularly polarised electromagnetic wave which is self sustained in an electron gas when propagated parallel to a sufficiently high magnetic field. An absorption edge is the wavelength corresponding to an abrupt discontinuity in the intensity of an absorption spectrum.

acting on the electron system. Calculation of the change in surface impedance was made for $\mathbf{B}_0$ applied perpendicular to the axis of a coil which contained a metal plate and, in later tests, a metal slab. The results were compared with experimental results for gallium plates and slabs. The resonances reported by Turner et al. are likely to arise from helicon absorption edge effects or plate effects (whereby a field build-up of radiation occurs because of multiple reflection). Their use to increase sensitivities does not appear practical at this stage.

Wallace et al.[3] described tests which show how these ideas can be used; experiments were carried out at room temperature using a maximum static field of 15 kG. With a laboratory arrangement (a square cross-section metal bar was positioned in the airgap of a magnet; small coils were arranged on either side of the bar to excite and detect ultrasonic waves), holes of diameter about 1 mm. were located. This sensitivity is scarcely sufficient for non-destructive testing. The present analysis shows that increased efficiency of power transfer can be achieved by increasing the strength of the static field (which is already approaching the region where special techniques are necessary to produce stronger fields), reducing specimen density (hardly a realistic approach) or reducing v_s—which is dependent on test frequency and specimen material.

Legg and Meredith[15] give some detail of equipment and experimental results. Standard equipment for pulse echo measurements was used with the crystal being replaced by coils. Best results were obtained when separate tuned transmitting and receiving coils were used. A greater ease of detection (c.f. Wallace et al.) was claimed, although the detected defect was the same size in both cases. Flaws more than 20 mm. below the surface of an aluminium specimen could not be detected using the generated compressional wave. For steel specimens the results conflicted with simple theory—with $\mathbf{B}_0$ parallel to the test coil (and specimen surface) shear waves were dominant having a strongly frequency-dependent amplitude (it may have been coincidence that the peak echo amplitude occurred at the same frequency as that of the tuned coil). Legg and Meredith concluded that "electromagnetic generation is . . . not a feasible alternative to the water immersion technique." It is necessary to improve the signal-to-noise ratio, and at present this is most easily done by increasing the efficiency of power transfer or increasing the power input. Neither can be increased indefinitely. The idea of using v.h.f. is attractive because thereby the detectable defect size is reduced, but the attenuation is likely to be excessive either because of the material or the surface finish. (Midgley[16] claimed that the attenuation of helicon waves could be controlled by means of a steady current parallel to the direction of propagation. It would appear that by this means the "effective" attenuation of the generated ultrasound could also be controlled.)

3. THE USE OF RADIOACTIVE GAS FOR DEFECT DETECTION

In a recent paper, Eddy[17] showed how a radioactive isotope of the gas krypton could be used for the detection of defects in metallic materials. Krypton 85, which has a half-life of 10·27 years, decays with the emission of beta-particles; there is also some emission of gamma rays but this accounts for only 0·05 per cent of the total activity. The gas may be absorbed by the material of the specimen or selectively adsorbed by newly-formed surface defects. In either case, changes in the amount or distribution of measured activity can be identified with certain chemical or physical changes in the specimen.

3.1. Radioactive Charging of Specimen

Two forms of preparatory treatment to which specimens may be subjected have been designated "kryptonation" and the "krypton exposure technique" (sometimes called KET).

Kryptonation is the name given to the process whereby Kr^{85} is incorporated (by absorption) into the lattice structure of the test material to depths of 5 to 10 micron. Diffusion of the gas depends on the symmetry of the metal lattice, interatomic spacings and atomic sizes. The krypton atom (diameter 4·2 Å) is large compared with many metallic atoms, e.g. aluminium has an atomic diameter of 2·86 Å (see Tiner and Asunmaa[18]). Hence the krypton atoms tend to concentrate in the more open regions of the metal lattice (e.g. in micro-fissures). To achieve satisfactory rates of diffusion, temperatures above 100°C and pressures of up to 5000 p.s.i. may be needed. Under these conditions the kinetic energy of the gas may be used to form quasi-stable radioactive compounds whose rate of change of radioactive decay is altered markedly when subjected to physical or chemical disturbance. (These compounds have been called "kryptonates"—a term patented by Parametrics Inc.)

The equipment used by Tiner and Asunmaa[18] is shown schematically in Figure 1. The krypton was stored in the left-hand enclosure and transferred to the pressure vessel situated in the right-hand enclosure. The centre section contained the pumping and purification system. The krypton was cryo-pumped to the pressure vessel.

The krypton exposure technique is used solely for the detection of defects. The specimen material is degassed under vacuum, and then surrounded by a krypton atmosphere at near ambient temperature. Krypton is adsorbed, and subsequently escapes, more readily from old surfaces of material than from freshly fractured surfaces, i.e. cracks. The object of the subsequent surface radioactivity measurement is to define regions of above-average concentration. The apparatus required for the KET is similar to that shown in Figure 1, the pressure vessel and furnace being replaced by a vacuum chamber. The rate of decay of the measured radioactivity is very much greater than for kryptonation—apparently because the adsorbed gas rapidly leaks away from the surface. It is therefore dependent on the rate of desorption rather than the rate of radioactive decay.

3.2. Detection of Radioactivity

Both the absorption and adsorption technique require that radioactivity be measured. Radioactivity levels are strongly time dependent, particularly in the KET process.

Microautoradiography technique requires the use of special nuclear track emulsion replicas and electron microscopy. A thin formvar film is attached to the metal surface and a thin nuclear track emulsion is deposited on top of the formvar film. After a suitable exposure time, the emulsion is processed without separation from the specimen. The formvar film and emulsion are then floated off the metal surface in distilled water and examined using an electron microscope. The replica structure of the metal surface and the distribution patterns of the beta-exposed silver grains are superimposed. Each silver grain or filament on the replica indicates a radioactive source in the structure of the metal at that point. The ratio of the number of silver filaments to the number of nuclear disintegrations (i.e. the recording efficiency of the nuclear emulsion) is about 30 per cent. Kodak 649 spectroscopic film has a suitable emulsion, by means of which the presence of amounts of Kr^{85} of order 10^{-12} gm can be detected (this is equivalent to a 6 micron defect, which is very large compared with Eddy's[17] claim of 10 Å $\equiv$ 10^{-3} micron).

Conventional autoradiography can also be used but very long (up to five days) exposure times may be needed. The autoradiograph of the leading edge of a turbine blade section was shown by Eddy.[19] Definite cracks were visible and were indicated by black exposure lines perpendicular to the edge. The kryptonated turbine blade was painted white before being covered with liquid film emulsion, so that the darkened portion of the film was easily observed; Kr^{85} was found to concentrate in the cracks.

Eddy[19] carried out tests on turbine blades which had been kryptonated for three hours at a pressure of 100 p.s.i. and a temperature of 149°C. The activity of the resulting blade sections was estimated at $0{\cdot}06\ \mu c/cm^2$, (equivalent to 6 c.p.s.) from measurements made with an end-window G-M counter using appropriate corrections for geometry, absorption and backscatter differences from a standard source. A 3/32 inch diameter avalanche detector system was also used to scan the leading edge of the blade. None of the measurement processes indicated cracks which could be correlated with visible cracks, but the cracks were readily found by autoradiography. Eddy claimed that the amount of activity in the defects was not significantly greater than the background activity. A technique was sought which would combine the speed of electronic detectors and the spatial resolution of autoradiography. A low-level light intensification system was developed and was used in conjunction with the KET. This incorporated a phosphor layer chosen for its high conversion efficiency of beta rays from Kr^{85} to photons, coupled with a fibre optic bundle, designed to have high spatial resolution. The individual fibres were 16 micron in diameter. The various systems were compared by examining a kryptonated plate that had been cracked, but not broken, by fatigue. The plate had a flat surface and contained two drilled holes. The outlines of the holes were not as well defined by electronic imaging as by autoradiography, although examination of the cracked region and its periphery indicated that a close correspondence existed between the two detection methods. Similar tests on turbine blades with count rates of 7000 c.p.m. showed that electronic imaging was very much faster than autoradiography. The minimum determinable defect size was claimed to 8·4 Å.

3.3. Application of Technique

Kryptonates tend to retain their radioactivity for long periods since the Kr^{85} is absorbed; hence it is necessary to ensure that, where specimens are made sufficiently radioactive to permit crack detection with reasonable exposure times, the remaining radioactivity does not constitute a health hazard. With the KET process, subsequent radiation is not a problem as was shown by Eddy[19] who carried out tests on turbine blade sections in which the sections were subjected to a one-hour exposure to Kr^{85} at a pressure of 13 p.s.i. and a temperature of 22 C, i.e. there was adsorption of the Kr^{85}. In this experiment it was shown that the samples had lost 90 per cent of their initial activity after nine hours. This loss rate indicated that the residual activity in a blade after 24 hours was reduced by a factor of almost fifty. Thus by the time the crack-detection process is completed there is very little residual activity remaining in a turbine blade and it is ready for installation in an engine. The count rate produced in this experiment indicated that the initial activity levels for the first three hours were higher than the levels obtained from kryptonation. The kryptonation process resulted in blades with a count rate of about 7000 c.p.m. which is comparable with the count rates three to four hours after exposure by the KET.

Chleck et al.[20] exposed kryptonated aluminium alloy samples of 7075–T6 and 7075–T73 to 10 per cent sodium chloride solutions. Counts were taken on both sides of each sample and the data plotted as the activity loss against the time of exposure to the salt solution. The scatter of the data for the two sides of the same alloy sample was much greater for the sample in the T73 condition, this being attributed to the additional surface inhomogeneities introduced by this heat-treatment. Whereas the activity loss for the T6 alloy remained sensibly constant for the duration of the test, the activity loss of the T73 alloy decreased markedly only during the early stages of the test. Chleck concluded that the alloy in the T73 condition had a greater corrosion resistance which was in accord with prior evidence.

Figueroa[21] examined the possibilities of using these techniques to study fatigue cracking. He assumed that material containing fatigue damage would absorb more Kr than undamaged material and that the loss of krypton from kryptonated material could be related to fatigue damage (i.e. cracking). Reasonable confirmation of the latter assumption was obtained.

Tiner and Asunmaa kryptonated 7075–T6 specimens at 110°C and 300 p.s.i. Typical micro-autoradiographs of these specimens after subjection to fatigue damage at 45,000 p.s.i. maximum stress after kryptonation showed the Kr^{85} first tended to migrate along slip markings. However, when cracks or fissures started to appear, the krypton concentrated there and large areas close to the cracks were denuded of krypton.

Graham[22] found that the adsorption of Kr^{85} was dependent on the number of sites available for adsorption; the number of sites was lowered by the presence of a chemisorbed layer. In the case of steel it appeared that a layer of Fe_2O_3 provided fewer sites than a surface layer of Fe_3O_4. Surface finish and the presence of anodised (or similar) coatings are also likely to affect adsorption.

3.4. Discussion

In their present state of development, both radioactive gas techniques are only suitable for work on small objects such as fatigue specimens or turbine blades. Larger pressure vessels and furnaces or vacuum chambers are required if these techniques are to be employed on larger components. Automated radioactive gas handling facilities are also required before the way is cleared for widespread application of these techniques. The effect on the specimen after exposure to the radioactive material appears to be minimal and, if proper handling facilities are available, parts would be ready for replacement in service after a period of only days.

The gas is likely to be available locally from the Australian Atomic Energy Commission, but perhaps not in large quantities. In the United States of America it is currently available as a 5 per cent mixture with Kr^{84}. Other gases which could be substituted for krypton are radioactive argon and nitrogen. Argon^{40} would appear to be the best substitute because it has an atomic diameter of 3·82 Å which is slightly less than that of krypton. Radioactive nitrogen would be unsuitable for it has a smaller diameter (1·5 Å), a relatively short half-life, and is likely to react chemically with the specimen.

Spragg[23] suggests that a very small end window Geiger-Muller tube with suitable collimation and reduction of background is likely to be satisfactory for activity counting despite the low expected levels of activity. Alternatively a small plastic scintillator detector could be used. This would take the form of a cone, having a window as small as required, mounted in a small perspex carrier and using a photomultiplier to register the pulses; the background would be 1–2 c.p.m. This plastic detector could be shaped to fit any particular curved surface such as the knife edge of a blade. Hence several detector surfaces could be made, each for its specific function, and these could be interchanged on the photomultiplier tube surface at will. The approximate costs of electronic equipment are:

(i) G-M tube system—$300, with additional tubes at $30 each;
(ii) plastic scintillator—$1500, with photomultiplier tubes at $130 each and $30 for plastic scintillator rod.

As nuclear emulsion is relatively cheap, the use of autoradiography technique would reduce instrumentation costs. The mechanical handling system including radioactive gas, storage facilities, pumping equipment, furnace, etc., is estimated to cost about $10,000.

4. MICROWAVE TESTING

A number of basic eddy current formulae are derived from the study of an electromagnetic wave emanating from an energising coil and incident on the surface of a specimen. Commonly encountered frequencies appear to have an upper limit of about 100 kHz. Beyond this frequency penetration of the specimen is severely limited because of the skin effect. From a purely mathematical aspect (i.e. disregarding the possibility of a change in mechanism), at any higher frequency the metal would tend more and more to act as a reflector of the electromagnetic wave. The changed mechanism would presumably operate if the skin effect became too thin to sustain the flow of eddy currents.

Microwaves are electromagnetic radiation of frequency between one and 100 GHz (or waves whose wavelength is 10 cm. or less), i.e. radiation which lies between radio waves and infrared waves. The characteristics of these waves are predictably similar to light waves—microwaves can be focussed, reflected, directed, etc.; they readily penetrate many transparent or non-metallic materials and they are absorbed by certain materials at particular frequencies; they are reflected from conducting material. Although in general they obey the laws of optics, because the wavelength is so much greater than that of light, the reaction with objects normally encountered is more akin to the reaction of lightwaves with microscopic objects, e.g. diffraction gratings. Microwave components and techniques have been developed principally in connection with radar.

Suitable NDI applications of microwaves are listed by Epstein and Rowand[24] and include defect location, thickness measurement (other applications include moisture content determination and measurement of dielectric properties) in non-metallic materials. Defects which can be detected include voids, delaminations in layered material, unbonded areas in honeycomb structures. Microwaves can also be used to measure the degree of cure of epoxy adhesives. Microwaves were focussed on to a small area to improve resolution of defect location,[25] and were used for detecting flaws in bowling balls and honeycomb panels, for measuring the thickness of plastics and the thickness of non-conducting coatings on conducting materials.

Measurements on plate and sheeting are most commonly made by utilising standing wave effects. Transmission of microwaves in a non-conducting or dielectric material is accompanied by absorption, reflection and refraction. At any specimen interface there will be some reflection according to changes in velocity or impedance mismatch. Within the specimen there will be absorption and scattering of the incident wave together with attenuation as a function of dielectric strength. The incident wave is transmitted through the specimen and measurements are made of changes in phase and amplitude; measurements are also made on the reflected wave. As a result of phase changes during wave propagation, the reflected wave will reinforce or suppress the incident wave giving rise to interference effects (c.f. blooming of optical components). Accurate measurement of thickness is possible. Calibration curves are vaguely similar to sine waves, but no ambiguity results if a prior measurement can be used to establish the specimen thickness to better than $\lambda/4$ (where λ is the wavelength of the wave). Furthermore, slight changes in frequency can be used to keep the operating point on the most sensitive part of the calibration.

Lavelle[26] claimed that thickness changes of 0·1 mm in 150 mm thick specimens could be measured. Hochschild[27] claimed that non-conducting coatings less than 0·001 inch thick on metals could readily be measured. The technique, although non-contacting, is very sensitive to movement between sample and source; Lavelle quoted a 60 per cent error for a 0·005 inch movement. Hochschild described an unusual technique for measuring metal thickness—two microwave instruments on either side of the metal situated a known distance apart were used to measure the distance of the metal surface from the instrument (c.f. radar measurement of distance). Oval horns 9 inches long can be used to produce a collimated beam of microwaves from a distance of twenty feet and can sense a change in position of a few thousandths of an inch. Botsco[28] used a standing wave arrangement (at 9·4 GHz) to search for laminar defects in fibreglass re[illegible] material which comprised ten-ply sheets having a total thickness of one-sixteenth of an inch. Delaminated areas about one inch square were detected several plies away from the surface (detection of this size of defect in material two-inch thick has also been reported), but the technique failed for tight laminations.

Defect detection in plastics is most commonly carried out by means of a scattering technique. At low frequencies (Rayleigh region) scattering is likely to be small. At higher frequencies, where the size of the scattering object (e.g a spherical void) is close to the wavelength of the electromagnetic radiation, scattering reaches a maximum. In this case $2\pi a \simeq \lambda$ where a is the radius of the void, and λ is the wavelength of the radiation within the material. This is the region in which most tests are made (resonance region). At still higher frequencies, the scattering reaches a constant value until the optical frequency range is reached. Molecular interactions take place when a microwave beam propagates in dielectric material. The magnitude of these interactions is determined by displacement of the charge carriers which shows up as changes in dielectric constant and/or phase angle. Displacement or polarisation mechanisms include the rotation of atoms and molecules in the direction of the field (orientation polarisation), distance changes between adjacent atoms (atomic polarisation), distortion of the shape of the electron bond (electronic polarisation), and the movement of free charges within the material (space charge polarisation).

Lavelle[26] set glass spheres (representing defects) ten to forty mm. in diameter in 3-inch cube blocks of epoxy resin. These spheres were easily detected using a scattering technique, but size measurement was inaccurate. It was possible to devise certain geometrical arrangements where interference from normal scattering completely masked any defect effect. Stinebring[29] also found difficulty in measuring the size of defects but was able to detect voids of one-eighth inch diameter in one-inch diameter material or large unbonded areas in fourteen-inch diameter material (i.e. penetration was high). Hochschild[27] pointed out that scattered radiation is frequently measured at right angles to the incident beam.

Rockowitz and McGuire[30] give a detailed practical description of tests done on honeycomb ablative material in which it was required that voids less than ten per cent of material thickness be found in the presence of density variations of up to ±5 per cent. A frequency was chosen (69 GHz) which gave maximum scattering for the minimum defect size. A klystron was operated in the pulse-modulated mode (1 kHz modulation frequency) and with an output of 0·6 watt. Measurements of absorption or attenuation of microwaves can be made but are not commonly used for defect detection. Absorption techniques were used by Stinebring in the detection of improperly cured rocket propellant, and excellent correlation was obtained with results from tensile specimens. (In addition test time was dramatically reduced.) Similarly a change in microwave attenuation was found when the ratio of resin to accelerator in epoxy resins was varied. A double horn system was developed which permitted compensation for the variations in density. There was some discussion of angles—if the incident beam meets the specimen surface at an oblique angle then total reflection can occur from the back surface of the specimen. This is generally undesirable since the receiver is not then situated in the optimum position to receive defect derived signals.

Instrumentation is not particularly complicated—modular construction of units permits rigs and changes in rigs to be rapidly accomplished. Equipment generally comprises a microwave generator or klystron (although Gunn-effect solid-state devices are now being introduced) with which are associated attenuators, phase shifters, detectors, and matching units in the form of elements of a system of waveguides. (A cost figure of a few thousand dollars was given by Stinebring in 1965.) A clear and simple description of instrumentation is given by Owston[31] who claimed that 3 cm equipment is most commonly used because the components are of reasonable size and cost; 8 or 10 cm components are either large or very expensive and small defects cannot be detected with wavelengths around 1 cm. A suitably coupled diode is generally used as detector. Both Lavelle and Owston describe the magic tee, a microwave component which comprises four waveguides meeting at a junction. Power injected into an arm splits into two other arms; equality of phase and amplitude in reflected power results in a zero output from the fourth arm. (The magic tee has its counterpart for low frequency testing in the a.c. bridge.)

By recording both phase and amplitude of signal output, readings can be displayed in the form of an impedance diagram which may be used (as in eddy current work) to choose frequencies or shift phases so that unwanted variables may be suppressed.

Typical generators for microwaves are rarely capable of outputs in excess of one watt. Provisionally recommended maximum safe power level for human subjects is about 20 mw cm.$^{-2}$ for whole body radiation at wavelengths less than 10 cm. Hence except within the waveguide the equipment is relatively safe. The equipment permits measurements to be made without contact with the specimen (in fact in a sense remote measurements are possible). For non-conductors penetration of the specimen is relatively easy; for metals only surface effects can be studied because the microwaves are almost completely reflected. To some extent this can be considered an advantage because measurements can be made which are unaffected by internal variations in composition. On the other hand the method is not particularly sensitive and appears to be best suited to the detection of large defects. A further disadvantage is the need to use comparatively bulky waveguides.

A completely different use of microwaves has been described by Hruby and Fernstein.[32] Microwave radiation is directed normal to the test surface, the depth of the crack being in the direction of the radiation. Rotation of the crack in this direction is not important because the radiation is initially unpolarised. However, the crack or defect acts as a waveguide and reflects some of the original sound signal as a polarised wave which can be detected by the radiating device. Tests were made at a frequency of 30 GHz (which was modulated at one kHz to facilitate noise reduction) on aluminium and steel specimens containing slots about 0·002 inch wide and of varying depths. The limit of depth resolution appeared to be about 0·02 inch.

5. CONCLUSIONS

Three new possible NDI techniques have been examined. Of these, the transducerless generation of ultrasound is considered to be in the early stages of development, and considerable improvement in sensitivity is required before it can be satisfactorily utilised. It is difficult to see how this can be accomplished without a breakthrough in some previously neglected region.

The radioactive gas technique is likely to be hard to apply to complex aircraft structures in the course of field testing. Possibilities do exist wherey elements of a structure may be kryptonated and covered with suitable sensitised film which could be removed, processed, examined and replaced at intervals. It is much more likely that the technique could be used for examination of specimens undergoing fatigue testing in the laboratory. Impending fatigue failure could be noted either by increase of readings from traversing counters or by using film. Some problems may exist with respect to shielding of operators. Co-operation with A.A.E.C. would be necessary.

The microwave testing of plastic materials is not presently of major importance at A.R.L. and the mode conversion technique is clearly not fully developed. The latter procedure holds considerable promise particularly as no contact with the specimen is needed. The probability is high that waveguide-to-specimen distance will be critical—however automatic compensation for this interfering variable appears to be fairly easy. In addition specimen material variations are unlikely to be troublesome.

ACKNOWLEDGEMENT

Information on radioactive gas was collected and prepared by G. G. Martin.

REFERENCES

1. Farrell, A. J.
   Consideration of acoustic holography for non-destructive testing applications.
   Aero. Res. Labs. Department of Supply. Note I. 72. (Jan. 1970).

2. Scott, I. G.
   Stress wave emission (SWE).
   Aero. Res. Labs. Department of Supply. Note MET 72. (Sep. 1970).

3. Wallace, W. D., Houck, J. R., Bowers, R., Maxfield, B. W., and Gaerttner, M. R.
   Transducerless method for ultrasonic flaw testing in metals.
   Rev. Sci. Insts. **39**, 12, pp. 1863–4. (Dec. 1968).

4. Sazenov, Y.
   Contactless methods of excitation and recording of ultrasonic vibrations.
   Defektoskopiya No. 5, pp. 13–17 (1969).

5. Wusterberg, H.
   Contactless electrodynamic ultrasonic transducers and their application in ultrasonic inspection.
   6th International Conference in NDT. Hanover (May 1969).

6. Dobbs, E. R.
   Electromagnetic generation of ultrasonic waves in metals.
   P. 7, Ultrasonics for Industry, 1970 (Supplement to Ultrasonics). See also Transducerless generation of ultrasound, p. 166, non-destructive testing (June 1970).

7. Botsco, R.
   The eddy sonic test method.
   Matls. Eval., pp. 21-26, **26**, 2 (Feb. 1968).

8. Mertsching, J.
   Theory of electromagnetic waves in metals and their interaction with ultrasonic waves.
   Part III, Phys. Stat. Solid, **37**, 2, pp. 465-522 (1970).

9. Alig, R. C.
   Direct electromagnetic generation of transverse acoustic waves in metals.
   Phys. Rev. **178**, 3, pp. 1050–8 (Feb. 1969).

10. Meredith, D. J., Watts-Tobin, R. J., and Dobbs, E. R.
    Electromagnetic generation of ultrasonic waves in metals.
    J. Acous. Soc. America, **45**, 6, pp. 1393–1401 (1969).

11. Turner, R., Lyall, K. R., and Cochran, J. F.
    Generation and detection of acoustic waves in metals by means of electromagnetic radiation.
    Canadian J. Phys., **47**, 21, pp. 2293-2301 (Nov. 1969).

12. Quinn, J. J., and Rodriguez, S.
    Helicon-phonon interaction in metals.
    Phys. Rev., **133**, 6A, pp. A1589-94 (Mar. 1964).

13. Houck, J. R., Bohm, H. V., Maxfield, B. W., and Wilkins, J. W.
    Direct electromagnetic generation of acoustic waves.
    Phys. Rev. Lett., **19**, 5, pp. 224–7 (July 1967).

14. Southgate, P. D.
    An approximate theory of skin-effect acoustic generation in conductors
    J. Appl. Phys., **40**, 1, pp. 22–9 (Jan. 1969).

15. Legg, K. O., and Meredith, D. J. Flaw detection in metals using electromagnetic sound generation. J. Phys. D: Appl. Phys., **3**, pp. L62-3 (Oct. 1970).

16. Midgley, D. Analysis of helicon-wave propagation. Electronics Letters **6**. 16, pp. 497-8 (6th August, 1970).

17. Eddy, W. C. Krypton flaw detection system designed. Aviation Week and Space Techy., p. 85 (June 9, 1969).

18. Tiner, N. A., and Asunmaa, S. K. Microautoradiography of Kryptonated Aluminium Alloys. Matls. Res. Stds., pp. 23-5, 49, 50 (April 1970).

19. Eddy, W. C. Evaluation of cracks in turbine-blading leading edge by use of Kr^{85} gas. Isotopes Radn. Techy., **7**, 3, pp. 277-84 (1970).

*20. Chleck, D., et al. Development of Krypton-85 as a universal tracer. Report NYO-2757-5, Parametrics Inc. (Feb. 1966).

*21. Figueroa, C. G. Krypton potential in aerospace. Nucleonics in Aerospace, pp. 230-34. Plenum, New York (1968).

* Both these references were taken from Carden, J. E. Radio-release in Review with Special Emphasis on Kr^{85} Clathrates and Kryptonates. USAEC Report ORNL-IIC-18 (July 1969).

22. Graham, M. J., et al. Low temperature oxidation and Kr adsorption studies on polycrystalline and single crystal iron surfaces. J. Electrochem. Soc., **117**, 4 p. 213 (1970).

23. Spragg, W. T. Private communication.

24. Epstein, G., and Rowand, R. R. NDT methods for composites, reinforced plastics. Materials Engng., pp. 59-62 (Oct. 1969).

25. Some recent NDT developments. Materials Engng., pp. 64-70 (June 1969).

26. Lavelle, T. M. Microwaves in nondestructive testing. Matls. Eval., **25**, 11, pp. 254-8 (Nov. 1967).

27. Hochschild, R. Microwave non-destructive testing in one lesson. Matls. Eval. XXVI, 1, p. 35A (Jan. 1969).

28. Bofsco, R. J. Non-destructive testing of plastics with microwaves. Matls. Eval., XXVIII, 6, pp. 25A-32A (June 1969).

29. Stinebring, R. C., and Harrison, R. H. Non-destructive testing of rocket components using microwaves and low frequency ultrasonics. Matls. Eval. XXIII, 1, p. 17 (Jan. 1965).

30. Rockowitz, M., and McGuire, L. J. A microwave technique for the detection of voids in honeycomb ablative materials. Matls. Eval., XXIV, pp. 105-8 (1966).

31. Owston, C. N. Application of microwaves to non-destructive testing. Brit. J. of N.D.T., pp. 26-30 (June 1969).

32. Hruby, R. J., and Feinstein, L.	A novel non-destructive non-contacting method of measuring the depth of thin slits and cracks in metals. Rev. Sci. Insts., **41**, 5, pp. 679-683 (May 1970).

Postal Address: Chief Superintendent,
Aeronautical Research Laboratories,
Box 4331,
MELBOURNE, Victoria, 3001.

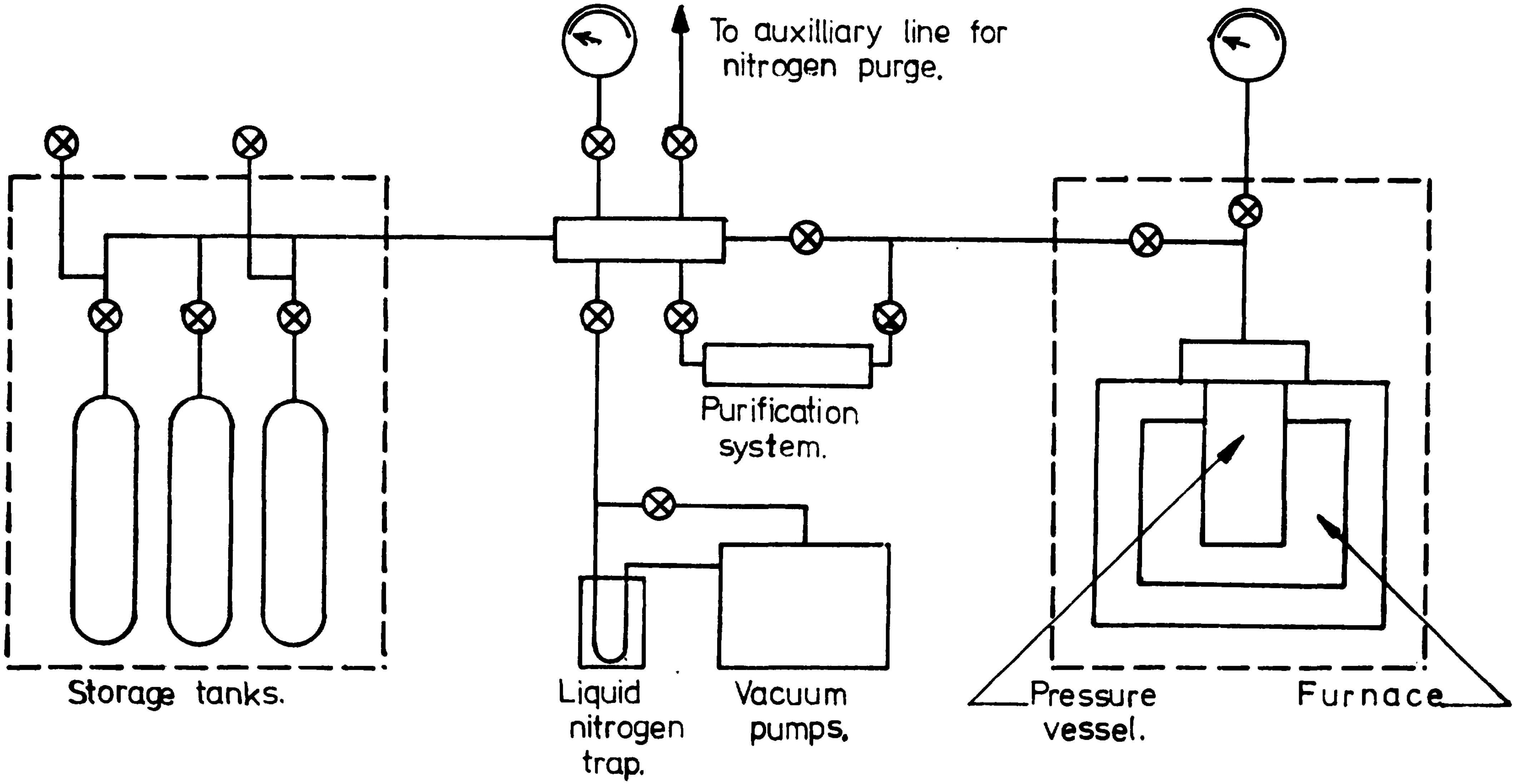

FIGURE 1: Kryptonation apparatus used by Tiner and Asunmaa.