AC-FIELD MEASUREMENT

In essence, the AC-field measurement technique measures and interprets field perturbations in a region containing a surface flaw. ACPD, as it was originally called, has a long history of malpractice but was so eminently suitable for laboratory monitoring of fatigue cracks that it was reassessed for this purpose. The technique consists of impressing an AC current into the region containing the flaw and exploring the surface-voltage distribution with a probe. Given that the flow of an electric current will be perturbed by the presence of a surface crack or defect, measurements of differences in potential in the vicinity of the crack should allow interpretation in terms of defect size.

Early attempts to use this technique were unsuccessful due mainly to the fact that spurious signals were measured concurrently with the desired surface voltage. This had two effects: first, the spurious signals, a source of error, were not constant, and secondly, the presence of these error voltages made theoretical interpretation of the measured potential impossible. It was thus necessary to calibrate by using similar measurements on specimen blocks containing notches or cracks of known depth. This type of calibration can and did lead to further errors in interpretation. It should be noted that the use of calibration blocks is common to many other NDT systems but it should be recognized that it is not good practice. The use of a notched specimen to show that an instrument is working properly is of course acceptable. Through advances in electronics, and through careful design of circuitry, it proved to be possible to avoid the problem of parasitic signals and a new instrument, the Crack Microgauge (U7) was produced (Dover *et al.* 1980, 1981). For the first time this instrument allowed the user to measure the AC-field distribution accurately and hence to interpret the crack size from a theoretical model of the field perturbation due to a crack. Accurate and reproducible field measurements together with good field modelling remove the need for calibration and this represents a significant step forward for this technique.

One of the key features of the original design of the Crack Microgauge was the use of a phase sensitive detector and narrow band filtering so as to reject the unwanted spurious signals and this feature has been further enhanced in the new version, the U8. This instrument has opened up the possibility of new application areas including the detection of subsurface flaws and improved accuracy on non-ferrous metals, as well as implementing several useful in-service inspection facilities such as battery operation, automatic display of crack depth and automatic rejection of spurious signals. In addition, whereas the U7 setting-up procedure involved a 'balancing' of the instrument to eliminate the common-mode signal, a new front-end amplifier in the U8 improves isolation, virtually eliminates the common mode signal and therefore removes the need to balance. These combined improvements now allow virtually any probe design or lead attachments to be employed with the system. The U8 also features an in-built microprocessor which not only provides a direct read out of the crack depth, but also allows different crack shapes to be measured accurately. This has been achieved using the theoretical models described later for the AC-field around different crack geometries, and 'modifying' the simple one-dimensional infinite crack solution. Other functions of the microprocessor include an automatic crack-monitoring feature, programmable probe-tip spacing for both the cross-crack and reference readings, and external control of the unit to allow interfacing with a variety of monitoring and measurement systems. These features are incorporated to meet the engineering requirements of in-service inspection referred to earlier. Ease of operation and interpretation as well as reliability are high engineering priorities.

Principle of operation

When passing through a conductor, an alternating current is not distributed uniformly through the depth of the material, but instead it is mainly carried in a surface layer, an effect often referred to as the 'skin effect'. This can be exploited to advantage for surface cracks in steel structures as a high frequency and low current can produce measurable surface voltage variations and the equipment becomes easily portable. The skin depth, δ, is usually defined as follows:

$$\delta = (\pi\mu\sigma f)^{-\frac{1}{2}}, \tag{1}$$

where μ is the magnetic permeability, σ is the electrical conductivity, and f is the AC frequency.

The Crack Microgauge uses a frequency of about 6 kHz so that for many magnetic steels the skin depth is of the order of 0.1 mm. In operation the AC field is impressed across the region expected to contain the crack so that it flows uniformly, perpendicular to the plane of the flaw. In this way it is possible to make potential difference measurements using a probe with a fixed contact separation distance Δ to give a local reference value V_1 just before the crack, followed by a second reading V_2 when the probe straddles the crack. In a uniform field these two readings can then be related as follows (see figure 1):

$$V_1/\Delta = V_2/(\Delta+2d_1)$$

so that

$$d_1 = (\tfrac{1}{2}\Delta)(V_2/V_1-1). \tag{2}$$

Thus, given the local measurements of potential difference and the contact spacing the depth d_1 can be obtained directly. This depth is a one-dimensional measure obtained on the assumption that the surface field is uniform in the neighbourhood of the crack and on the crack

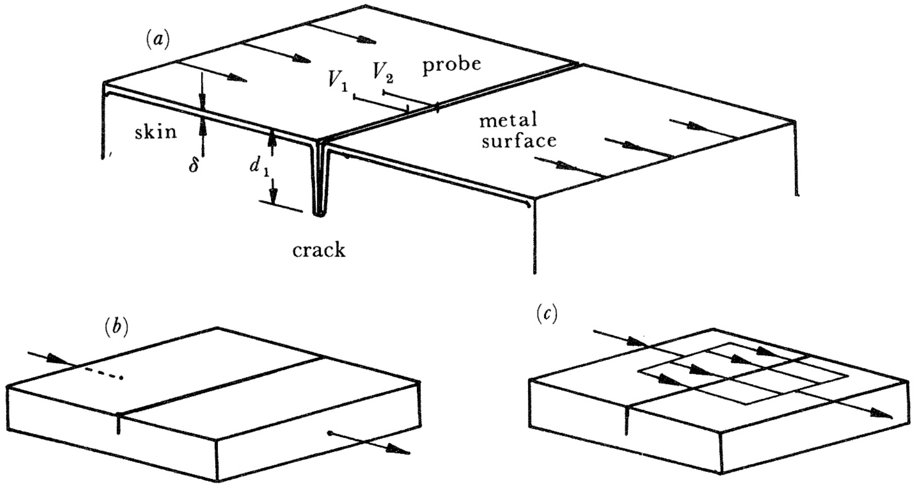

FIGURE 1. Measurements required for crack depth prediction in a uniform AC field distribution.

face. In many contexts, the component and crack geometries produce a non-uniform surface field, but it has been found possible to model such fields in a wide variety of cases using an unfolding algorithm which is described in the following section.

The simple thin-skin equation (2) for the depth d_1 is very widely used in practice but it is important to bear in mind the factors which will produce significant differences between d_1 and the true depth d. Experience has shown that the principal effects are:

(i) the finite aspect ratio of real cracks which produces significant non-uniformity of the field;

(ii) the departure from a thin-skin situation which occurs with cracks in non-magnetic materials, even for large aspect ratios;

(iii) the presence of occasional electrical contacts across the crack faces;

(iv) the discrepancies which arise due to parasitic probe loop voltages produced by the presence of a probe loop area, and the slot or crack cross-sectional area;

(v) non-uniformity of fields due to component geometry;

(vi) the presence of a fluid environment, such as seawater;

(vii) changes in material properties, as at a weld;

(viii) the presence of mechanical stress.

It was realized at an early stage in the development that it was essential to minimize the probe loop area which gives rise to (iv). Later, it became apparent that the parasitic effect from slot cross section was similarly important and that it was possible to quantify these effects with a simple model (Mirshekar-Syahkal *et al.* 1981; Mirshekar-Syahkal & Collins 1982; Charlesworth & Dover 1982). When the skin depth is small compared with the flaw dimensions and the surface current is uniform the ***B*** field is uniform outside the specimen and the flux is proportional to the loop area. The thin-skin formula may be shown to be modified in this case to become

$$d = d_1(1+P)/(1+S),$$

where P and S are dimensionless parameters describing the probe and slot induction effects. This simple theory describes several important features consistent with experimental observation. In fact, stemming from this work, probe loop effects have been virtually eliminated by modification to the electronics in the latest version of the Crack Microgauge which ensure that only signals with phase orthogonal to that of the probe loop voltage are measured.

The thick-skin effect (ii) has been found to be important in experiments on non-magnetic materials such as titanium, nickel alloys, stainless steels and aluminium. For example, in an investigation of cracks on the threads of titanium and nickel-alloy bolts (Michael *et al.* 1983) it was seen that at 6 kHz the skin depth increases to 7–8 mm in these materials, which was much larger than the length scale 0.1–1.0 mm of the surface cracks being examined. In such cases a thick-skin model of the field is appropriate and since the thread and crack depths are small compared with the bolt radius it is possible to neglect the bolt curvature. The field in this case is a static field so that Laplace's equation is used to describe the field within the bolt. The periodic thread profile may be treated by conformal mapping techniques using the Schwarz–Christoffel transformation and as a result this problem can be reduced to the well-known potential problem for flow past a normal barrier representing the crack.

Another typical thick-skin application of the system is to the inspection of bored holes (Lugg *et al.* 1986). This work, which commenced with magnetic materials, showed that it was quite possible to detect and size bore cracks, and it has recently been adapted for inspecting bore holes in turbine discs in Inconel. Here the analysis of the recorded voltage distribution is more complex because of the combination of an elliptical crack and thick skin. A semi-automated scanning system was used with a fixed induced-field probe and a computer-driven screw system for rotating the disc around it. A series of twelve fatigue-cracked discs was inspected and a typical trace across a fatigue crack is shown in figure 2. Traces like these were

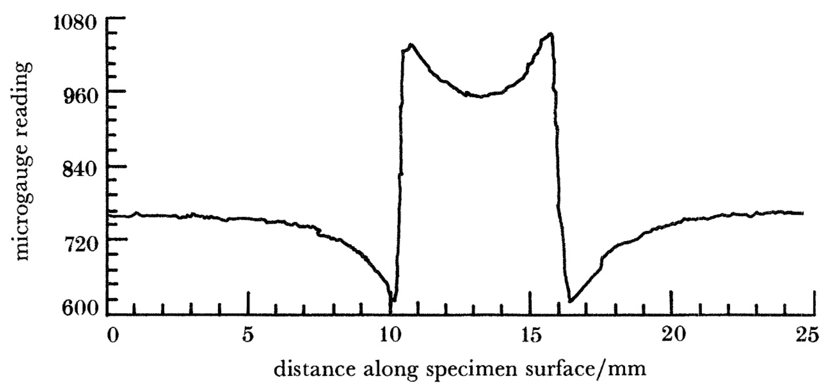

FIGURE 2. Probe readings during traverse across a bore crack for a thick-skin situation.

used to produce the crack shape information shown in figure 3. In this example the disc was subsequently sectioned to give the optical information shown in the same figure. The data have been corrected in this case for the effect of skin depth only (Mirshekar-Syahkal *et al.* 1981). If the skin depth is much larger than the elliptical flaw dimensions, the problem may be shown to reduce to that for the potential flow past an ellipsoid, which may be described in terms of ellipsoidal coordinates and is well known. The solution represents the thick-skin limit of the solution for arbitrary skin depth with an elliptical flaw; the thin-skin limit corresponds with the solution to be described later by the unfolding algorithm. The solution of the Helmholtz

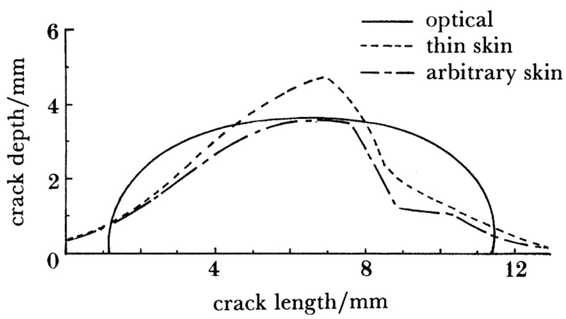

FIGURE 3. Interpretations of crack profile for a bore crack. The ACFM was used.

problem, posed when the skin depth is arbitrary, is under investigation by both analytical and numerical means.

A recent similar application on steels used in the offshore industry, involves taper threads. The work includes a variety of components such as tethers and riser connections and one particular example of the semi-automated system is shown in figure 4. Typical results obtained during a fatigue test on a tether threaded-end are shown in figure 5. This figure includes both AC field and optical measurements, and it can be seen that the crack depth and shape can be accurately measured.

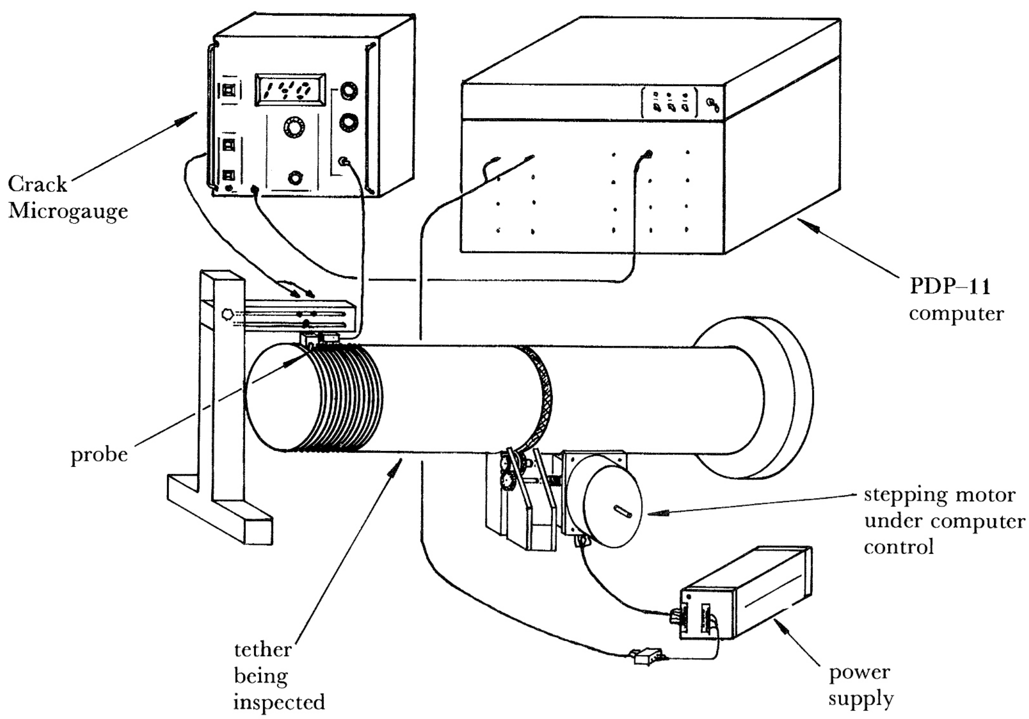

FIGURE 4. Automated inspection for crack profile in a high-strength threaded member designed for offshore use.

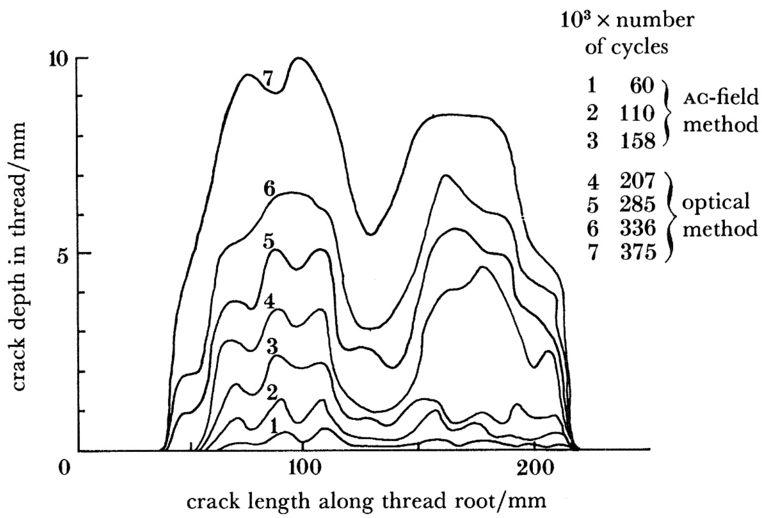

FIGURE 5. Fatigue-crack shape-evolution results obtained during a laboratory test on a high-strength steel threaded member (tether type connector).

AN UNFOLDING ALGORITHM FOR SURFACE FIELDS

Perhaps the most important modification of (2) occurs in applications to fatigue in the large-scale steel structures already referred to where effect (i) becomes very important. It has been shown that failure to allow for the finite aspect ratio of surface breaking cracks in equation (2) could lead to underestimates of the centre-line depth of cracks of the order of 20–30% if the aspect ratio is small. To model this effect, an unfolding algorithm of wide utility has been formulated. Good practice in the AC field method of crack sizing requires that the crack should be interrogated by a uniform current which may be injected or induced. It has been found that the perturbations to the surface field produced by a crack in such a case is given by a plane Laplacian-field distribution in a domain which is obtained by unfolding one face of the crack up into the incident plane. This construction is illustrated in figure 6 in which the surface distribution required is to be obtained by unfolding the crack face BCD into the surface plane, and seeking a plane Laplacian potential ϕ with $\phi = 0$ on the symmetry line ABCDE. A solution of this problem for the case of a crack of circular-arc form can be obtained by adaptation of the known solution of the analogous hydrodynamic problem to describe the flow of an infinite irrotational stream past an indentation in a plane (Dover *et al.* 1980, 1981). The circular-arc problem can be treated by conformal mapping techniques; when the crack shape is elliptical the problem has been treated by a Fourier analysis using elliptical coordinates with numerical evaluation of the coefficients in the series (Collins *et al.* 1985). The modified interpretations of instrument readings of voltage obtained through these solutions lead to agreement between theory and experiment for finite aspect ratio cracks to within 10%.

This algorithm can be exploited to provide information on surface-field distributions in many interesting situations. It has already been used by Dover & Dharmavasan (1984) to calculate the effect of line contacts across the face of a crack, which occur in practice when two different cracks grow towards each other until they are separated only by a thin line of the metal. Work is also in progress on the unfolding of corner cracks and edge cracks in plates, overlapping cracks and on the leakage fields produced by through cracks. Of more general interest still is

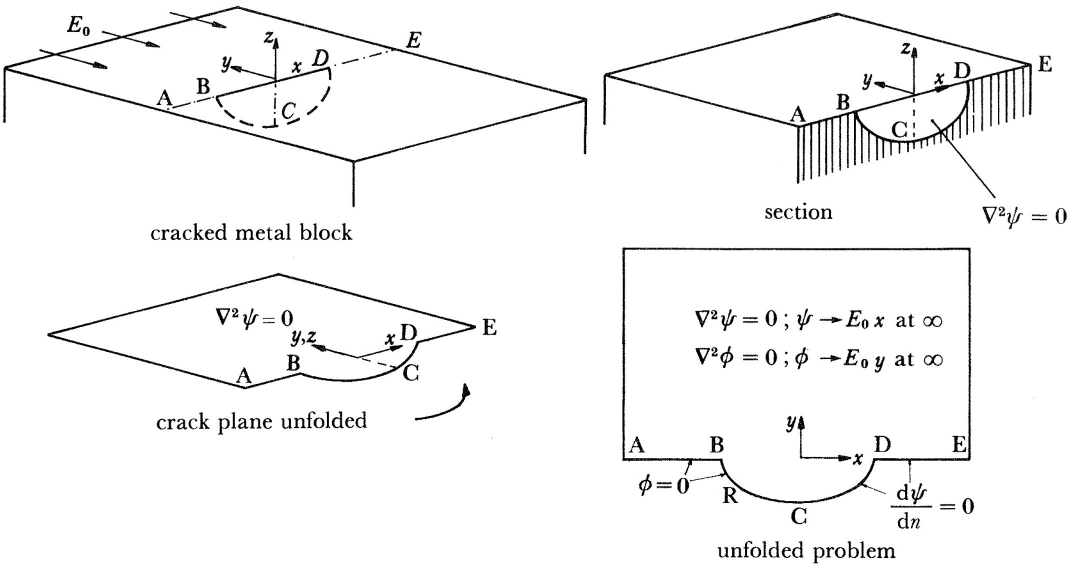

FIGURE 6. Theoretical interpretation of the use of the AC-field method for the surface-crack problem.

the fact that the unfolding algorithm can be applied in problems which arise with the eddy-current method where surface flaws are exposed by inducing a surface field from a stand-off probe. Such interrogating fields are in general much more complicated distributions than a uniform surface current, and they are not surface Laplacian fields. Nevertheless, it is now clear that the perturbation produced by a surface flaw does have a surface Laplacian distribution, which can be found by the same construction although it is only piecewise analytic in the unfolded domain. An example of this has recently been given by Michael *et al.* (1986) for a stand off dipole field interrogating a semi-elliptical crack.

THICK-SKIN FIELDS

It is evident that an AC field can only signal the presence of flaws in a metal which are within the surface layer of depth δ. To interrogate subsurface flaws it is thus necessary to ensure that the skin depth extends beyond the depth of the flaw. This can be done be suitable adjustment of the AC frequency. To make wider use of the Crack Microgauge for subsurface detection, a laboratory version of the instrument was developed to operate at frequencies of both 6 kHz and 600 Hz. The lower frequency increases the skin depth by a factor of approximately three. To enhance this capability even further, another model is currently being built at a frequency of about 30 Hz.

Apart from the investigations of cracks in threads and disc bores mentioned earlier we have used fields with deep penetration in two other investigations. The first was designed to test the capability of this technique for blind side detection, that is, to detect the presence of a flaw on one face of a plate by measurements on the other face. This was done successfully in stainless steel plates by Mirshekar-Syahkal *et al.* (1985) using 6 kHz and 600 Hz frequencies. The other application of current interest is the investigation of the integrity of diffusion bonded interfaces in nickel-based alloys. In a project currently proposed it is intended to use an AC field of deep penetration to inspect the interface for cavities produced by local failure of the bonding. The specimen consists of an annulus diffusion bonded on to a central disc which was treated before bonding so that a series of defects would be present around the interface. The bond line was subsequently inspected with an induced-field probe linked to the Crack Microgauge. The probe was connected to a computer-controlled stepping motor so that the probe contacts straddling the crack could be driven along the bond line. A typical set of results is shown in figure 7 and the twelve defects at equispaced intervals are clearly visible. This work has just commenced and the next stage will see an assessment of changes in both amplitude and phase of the surface voltage. It is anticipated that this additional information may allow theoretical interpretation

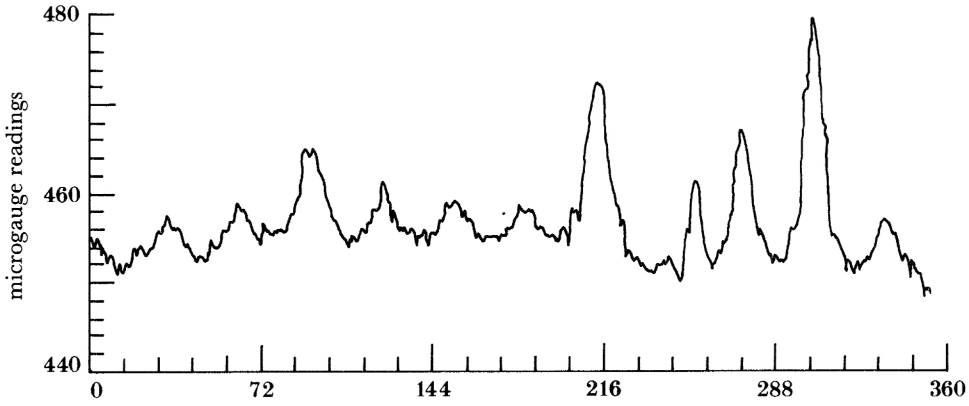

FIGURE 7. Inspection by the AC-field method of a diffusion bonded disc containing twelve subsurface flaws. (Each peak corresponds to a flaw.)

of the defect size and location. The theoretical problems posed here in the general case when skin depth, flaw sizes and locations are arbitrary are no longer the Laplace problems encountered at the thin-skin and thick-skin limits. Solutions of the Helmholtz equation are now involved and are the subjects of current studies by both analytical and numerical means.

STRESS EFFECT

The application of stress to a specimen which is being monitored by the AC-field technique causes changes in the measured value of potential drop. The magnitude of the effect varies with the material under test but in some cases it has proved to be sufficiently large to influence the accuracy of crack measurement. For this reason the physical cause of the effect has been investigated and the magnitude measured for several materials. As described earlier, the principle of operation of the Crack Microgauge is that the instrument is used to measure the surface voltage both adjacent to and across a crack. The measurements are very close to each other so that only the path length differs in these two measurements and this fact can be used to determine the crack depth. A basic assumption here is that the skin depth is constant. It has been assumed in this work on the stress effect that the skin depth may be a function of the applied stress. Since the skin depth is given by (1), it follows that the surface voltage varies as $(\mu/\sigma)^{\frac{1}{2}}$ for a given total current flow.

Thus the effect of stress leading to changes in voltage could be due to changes in conductivity or permeability. Preliminary theoretical calculations show that for magnetic materials it is the change in permeability that gives the larger effect. This effect is closely related to magnetostriction where a change in the magnetic field produces a mechanical strain.

In magnetic materials there are uncompensated electron spins in each atom which give each a magnetic dipole moment. Alignment of these dipoles is a preferred state except that a large amount of energy would be associated with the magnetic field lines outside the material. Instead, domains, that is regions where the electron spins are all aligned, are produced within the metal with the net effect that the external magnetic field is reduced. The domain boundaries, or 'Bloch Walls' are associated with a surface energy and, with the presence of internal strains, impurities, dislocations, etc. they require energy to move. Mechanical stress can cause movement of domain boundaries giving rise to reversible, irreversible or discontinuous changes depending on the material, magnetic field and stress. These changes in domains influence the permeability.

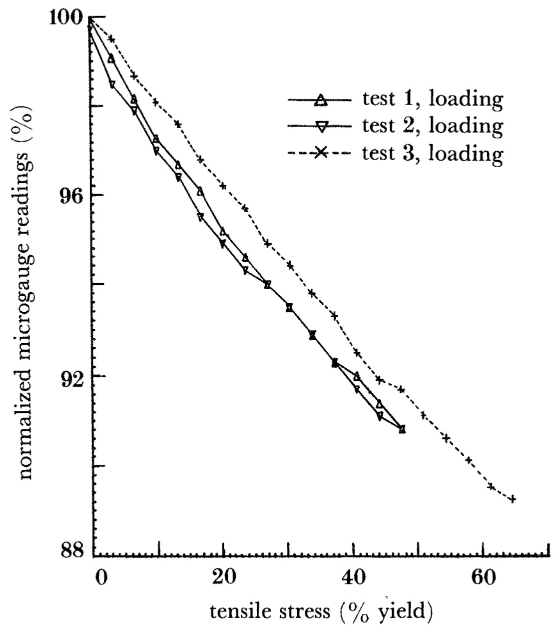

FIGURE 8. Measured changes in AC reading for a steel specimen (HY100) subjected to an increasing stress.

With the use of the Crack Microgauge, elastic stress was found to cause measurable, almost linear changes in the surface voltage for materials such as HY80, HY100 and HY130, and figure 8 shows some of the results of this work. Both tensile and compression stresses have been applied parallel and perpendicular to the impressed current direction. Some theoretical models based on the movement of Bloch walls have been developed to explain the effect of stress on measured AC signals (Lugg *et al.* 1985*a*). Certain materials could have much larger changes in permeability and it is possible that, given a linear change with stress, these could be used as the sensor in a transducer. Alternatively the effect might be used to measure residual stress. Here it would be necessary to maintain a uniform field strength and measure a reference value on a stress-free portion of the material. It should even be possible to measure the distribution of residual stress in welded joints and a study of this possibility is in progress.

Applications to underwater NDE

Monitoring fatigue-crack growth with the use of AC fields has proved to be relatively easy and has been found to be possible with seawater corrosion fatigue tests. In these tests a computer driven tracking system is used to drive the probe along the weld toe, or alternatively permanent spot welded connections are made. This gives an elementary array which will again allow computer controlled monitoring when connected to a switch unit. A diagram of a typical test system is shown in figure 9 and an example of the high-quality data that can be produced is shown in figure 10.

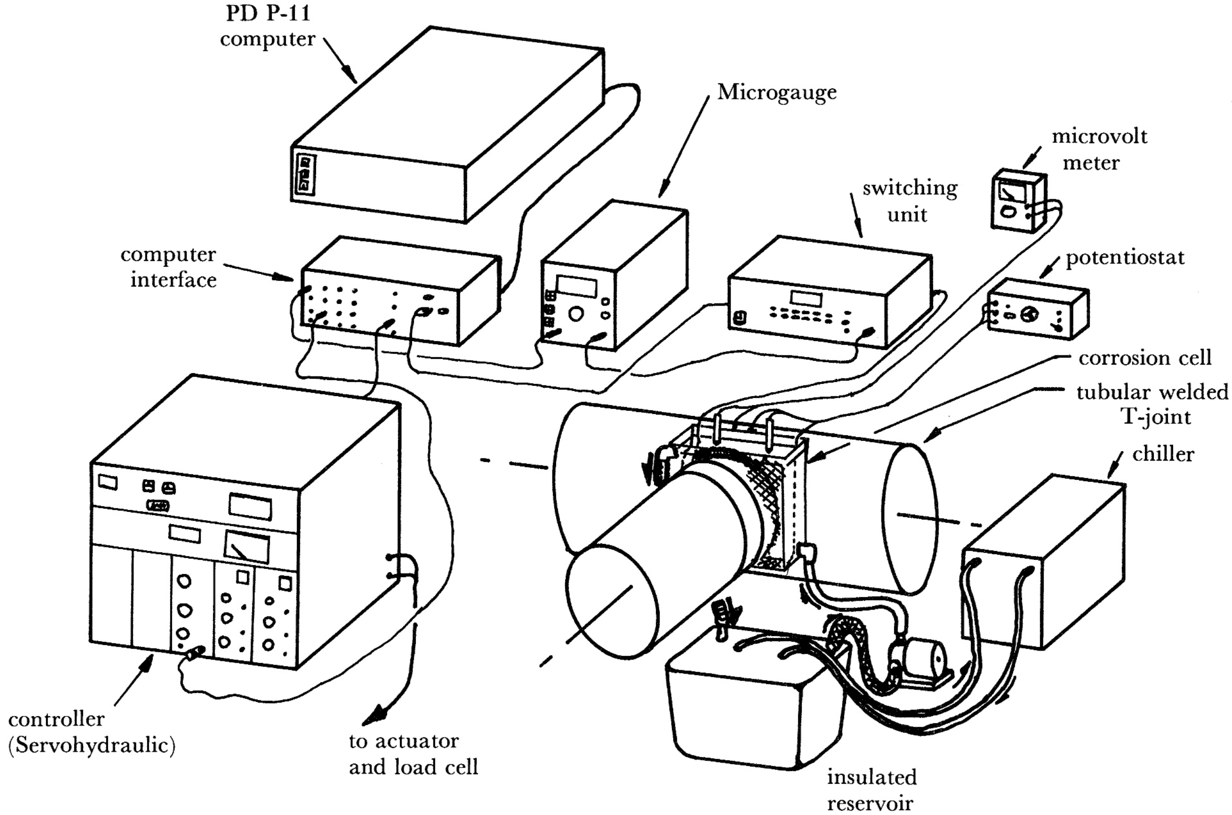

FIGURE 9. Automated crack-shape measurement for a tubular welded T-joint during a corrosion-fatigue test.

The problem of surface-crack sizing in steel is effectively solved with this system and recently an underwater version of the instrument has been developed for use offshore (Collins *et al.* 1985). There still remains, however, the need to determine the reliability of these measurements. In the nuclear and aerospace industries it has proved to be necessary to conduct carefully controlled validation trials for individual inspection systems. The offshore industry is no exception in this respect and the Underwater NDE Centre has been set up at University College London to fulfil this need. Reliability of NDT systems is assessed from the use of probability of detection curves, derived as a function of crack length or depth. The theoretical POD curve for a simple specimen is seldom achieved in practice partly because of what might be termed crack visibility in complex geometries. Whatever physical phenomenon is chosen as the basis for an NDT system there exists a combination of factors which could make the crack flaw difficult

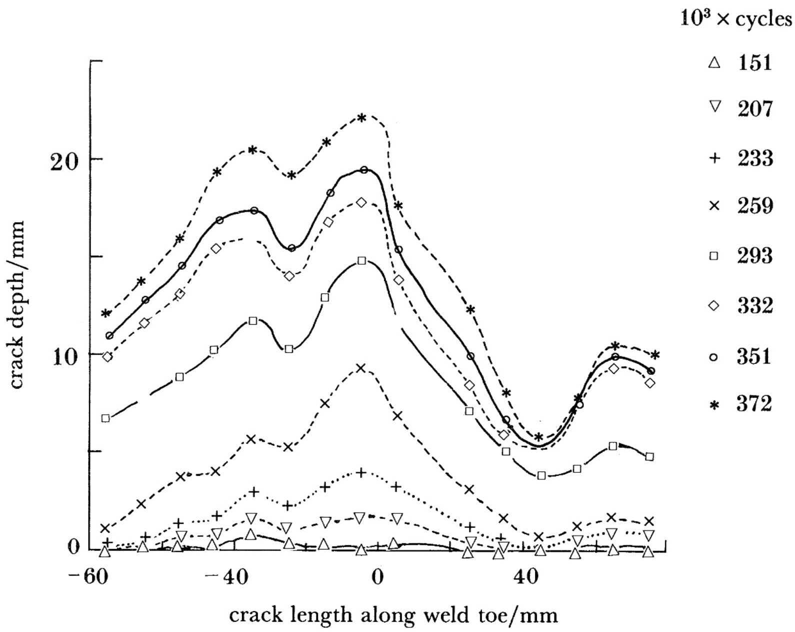

FIGURE 10. Fatigue-test results obtained during the corrosion-fatigue test shown in figure 9.

to detect (or have low visibility). Thus it is always advisable to determine the likely in-service POD curve and, if possible, to use two techniques dependent on quite different physical principles to assess a flawed component. Having established the theoretical and in-service POD curve it is also advisable to determine the reasons for the difference in threshold crack detection in case the operational procedure can be modified to improve the NDT performance.

The POD curve will depend on the likely specimen geometry, the nature of the flaw, the NDT system, the number of specimens tested, etc. and, for a particular industrial application, it is necessary to reproduce these features in order to make the trial realistic. In the case of the offshore industry the specimens required are welded tubular connections of varying size and angle that need to be precracked under loading to give the variety of cracks likely to be met in service. It is, of course, the in-service POD curve that is required.

The nature of the flaw, or in this case fatigue crack, can have a considerable influence on crack visibility and ease of sizing. One would expect that crack-face roughness, aspect ratio, crack closure, crack profile and the presence of deposits on the crack faces could all influence crack visibility. One of the key factors in determining detectability is crack closure. Closure may be partial, as in the case of a crack with a periodic overload, or complete as with inspection under zero or compressive load conditions. This feature is felt to be so important that attempts will be made to detect and size cracks under various conditions of crack opening in the Underwater Centre trials. A related problem, which can make crack sizing very difficult, is produced by material periodically linking across the crack. These features arise because of multiple initiation with cracks on different planes, or irregular stress distribution such as in the weld-toe region. Thus it can be seen that the nature of a sample in any trial is a key factor in controlling the curve of POD against the crack length a.

The number of defective specimens included in the sample is also important as this governs whether realistic confidence limits can be applied to the data. Large numbers of specimens and hence costly trials are often necessary. This problem has been avoided by suggesting that a library of specimens should be produced and revised for trials taking place over a number of years. This suggestion assumes that very accurate assessments of crack size and location can be made in air, during the production of the library. Before assembling the library, the assumption is being verified by using the best techniques currently available to size cracks in a small number of specimens. The specimens in this small calibration trial will then be sectioned to ascertain the accuracy of the technique. The library will then be produced, made available for trials, and slowly modified to reassess accuracy and slightly adjust the population. The first trials are scheduled for late 1986 and will involve MPI and eddy-current detection. During 1987 the crack sizing trial will be undertaken using the AC field measurement technique.

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Discussion

R. B. Thompson (*Ames Laboratory, Iowa State University, Ames, Iowa, U.S.A.*). Professor Dover mentioned that the suppression of artefact signals by his technique was much superior to that which was obtained previously. To what features of his implementation does he attribute the improved suppression of parasites?

W. D. Dover. The improvement has come mainly from the use of a new front-end amplifier; which has almost eliminated the common mode signal. A consequence of this change is that the phase-sensitive detector can now be fully used to eliminate the parasitic signals.