AN INTRODUCTION TO ACPD

Martin C Lugg

TECHNICAL SOFTWARE CONSULTANTS LIMITED

Technical Software Consultants Ltd.
6 Mill Square, Featherstone Road,
Wolverton Mill, Milton Keynes, MK12 5RB
UNITED KINGDOM

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1. THE ACPD TECHNIQUE

When an alternating current is passed through a conductor, the so-called "skin effect" forces the current to flow in a thin layer on the outer surface. This means the effective cross-section carrying the current is small, so that currents of less than an Amp can generate relatively high surface voltages. This feature offers benefits compared with the direct current method (DCPD), particularly on large specimens.

The thickness of the current-carrying layer, the so-called "skin depth", δ, is given by:

$$\delta = (\pi\sigma\mu_r\mu_o f)^{-1/2}$$

where σ is the electrical conductivity of the material, μ_r is its relative magnetic permeability, μ_o is the permeability of free space, and f is the frequency of the applied alternating current.

Materials of high permeability or conductivity thus have relatively small skin depths. At a frequency of about 5kHz, for example, ferromagnetic mild steel has a skin depth of order 0.1mm, high conductivity materials such as aluminium, tungsten and zinc have skin depths of 1-2mm, and low conductivity metals such as titanium, stainless steel and Inconel have skin depths of 5-8mm.

The input current produces a surface voltage which is measured by a two point contacting probe. The value of the measured voltage is dependent on the strength of input current, the separation of the two measuring points, the skin depth, the material conductivity and the specimen geometry.

The technique is mainly used for crack sizing because the need for good electrical contact makes it unsuitable for crack detection. Crack detection (as well as crack sizing in cases where surface contact is not possible) is best carried out with a non-contacting technique such as a.c. field measurement (ACFM).

For a given material, keeping the current and the probe gap constant, and ensuring a uniform current distribution makes the measured voltage dependent only on the conductive metal path length between the probe tips. When the probe straddles a surface-breaking crack, this path length is obviously longer than with no crack. A combination of two voltage readings, one across a crack and the other on an adjacent uncracked area, allows separation of the effect of the crack from the other effects. In this way crack depth can be calculated without the need for any calibration on notches.

The conditions necessary for the successful operation of the ACPD technique are fulfilled as follows:

a) The output circuit of the ACPD instrument maintains a constant current amplitude (generally about 1 Amp) for any load up to certain limits (generally a few Ohms).

b) The input circuit of the instrument ensures that only the voltage produced directly by the surface current is measured. Other voltages, such as those induced in pick-up loops, are rejected.

c) The field needs to be of uniform strength over the area of probe deployment which is usually achieved by adequate separation of the current input points, and ensuring a minimal distance between the location of the cross-crack and adjacent reference voltage measurements.

2. PRACTICAL DEPLOYMENT

The ACPD technique requires two connections between the instrument and the specimen under inspection - namely the current output or field connection, and the voltage input (from a single probe for inspection and sizing, or from one of a number of probes during crack growth monitoring). This section describes the general rules for deployment on simple specimens such as flat plates or uniform cylinders. Deployment on more complex geometries is described in the next section.

2.1 FIELD CONNECTION

The field lead is generally used to inject a current into the specimen by direct contact. In this case the two contacts should be placed reasonably far apart, equidistant on either side of the crack site and with the crack lying perpendicular to the line between the contacts (see Figure 1). The contacts should be about 150mm away from the crack, if possible. The further apart the contacts are the more uniform the field is. However, the surface current density (and hence the measured voltage) drops and the load increases as the current contact distance increases, so there is a limit to how far apart the contacts can be (which is dependent on material conductivity). On ferritic steel, the field contacts are most conveniently attached by magnets. On non-ferrous materials they have to be fixed on mechanically (e.g. screwed onto spot-welded studs, spot welded directly to the surface, or attached to suitable points with crocodile clips).

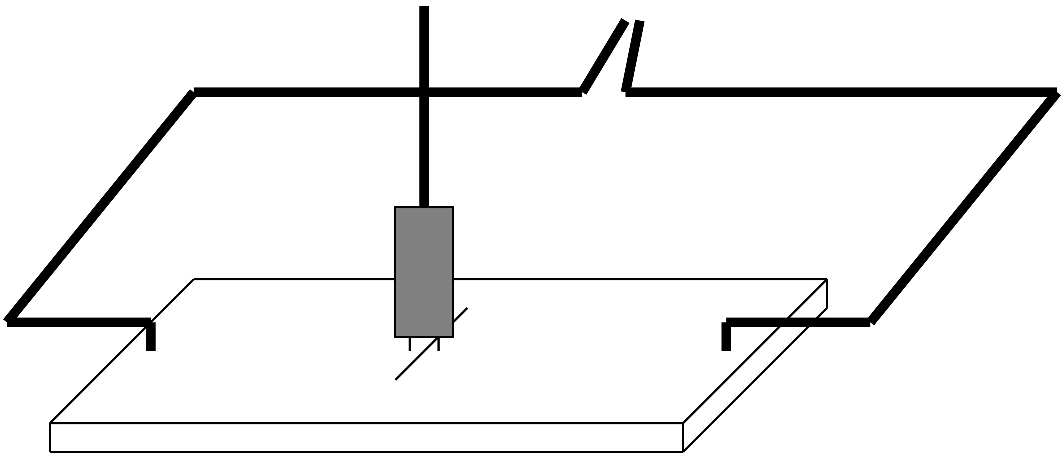

Figure 1 - Injected current input on a flat plate

In order to minimise inductive pick-up, the field leads should be taken away from the contacts at right angles to the injected current as shown, and should be brought together away from the crack site. Any relative movement between the field leads and the specimen should be kept to a minimum, especially when inspecting a non-ferritic specimen.

In certain situations, such as for axial cracks on a cylinder, an injected field is not very practical. In this case it is better to use the field leads to induce a current into the specimen by deploying them above the specimen surface perpendicular to the crack (see Figure 2).

For other situations where it is not possible to inject a current, but where it is also difficult to lay inducing wires, special purpose ACPD voltage probes can be produced which carry a self-contained induction coil.

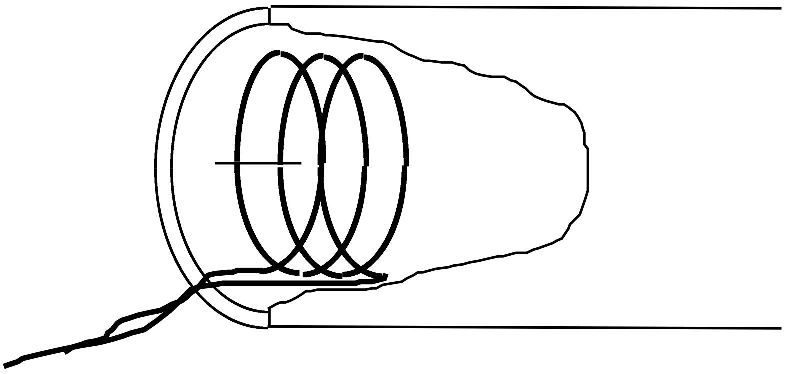

Figure 2 - Induced field input for axial crack in cylinder (cut-away view)

2.2 VOLTAGE PROBE CONNECTION

In order to minimise unnecessary electromagnetic pick-up by the voltage probe leads, they need to be as widely separated from the field leads as practicable. A good way of ensuring they are kept apart during manual inspection is to loop the voltage probe lead behind the neck of the user. It is important to maintain good electrical contact with the sample with both pins for several seconds while the voltage display settles. For this reason, probe pins are often sprung so that contact is maintained even if the probe is moved slightly. Such probes should be held down with the springs fully compressed to minimise the area of loop between the pins.

2.3 TAKING MEASUREMENTS

In its simplest deployment, the ACPD technique requires three parameters in order to produce a crack depth; these are a voltage reading with the probe straddling the crack, a voltage reading with the probe adjacent to but not straddling the crack, and the spacing between the voltage probe contacts. The voltage readings are in arbitrary units because only the ratio of the two is used.

If the position of a crack is not known, the voltage probe should be moved along a line perpendicular to the expected crack edge. The display should be watched for any sudden changes in reading. The reading will jump up from one steady value to another higher value when the leading probe contact crosses a crack, and/or from the higher value back down to a lower value when the trailing contact crosses the crack. Note that these values should be stable, repeatable and non-zero; non-repeatable or very low readings indicate loss of electrical contact by either the voltage probe or the field input.

Having determined the crack location, the two required voltages should be obtained as shown in Figure 3. The probe should be edged slowly towards the crack until the voltage reading jumps up. This value should be recorded as the cross-crack voltage, V_c. Readings should be observed on the instrument front panel for stability. A reading should be stable within ± 1 digit for several seconds before being captured. The captured value should be checked to ensure it matches the value observed on the instrument before capture. The probe should then be slowly backed off until the voltage reading drops down again. This value should be recorded as the reference voltage, V_r. The purpose of this procedure is to obtain voltage readings as close together as possible to minimise the effect of any variation in input field strength. Such variations occur, even with a nominally uniform input field, around short cracks or cracks in materials with a large skin depth.

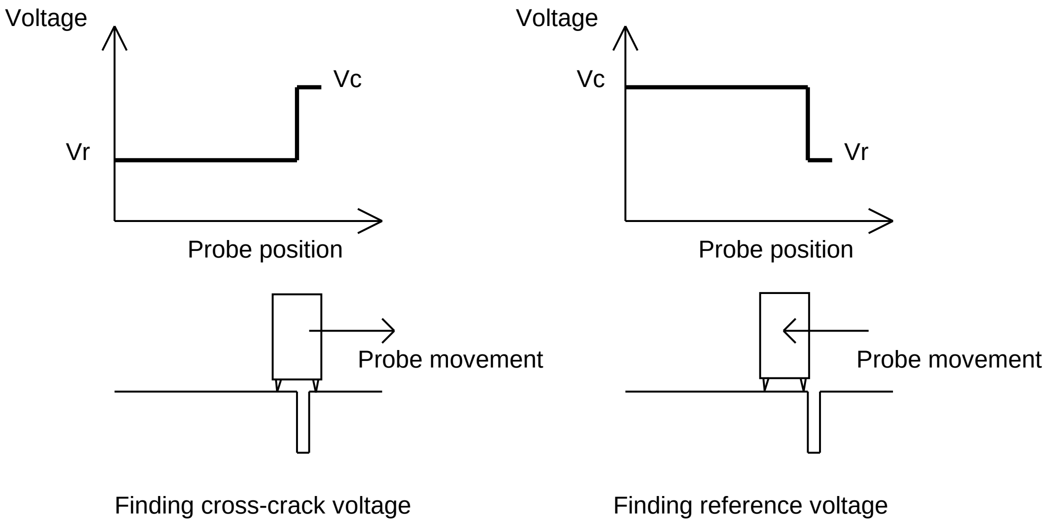

Figure 3 - Accurate measurement of ACPD voltages

When used on a flat plate, the spacing between the voltage probe contacts along the metal surface will be the same as the straight-line separation in air. This can then be measured with a ruler. On any other surface, the separation along the metal surface will be longer and should be measured directly, using a flexible tape, for example, at the site where the readings are taken.

The voltage changes shown in Figure 3 apply for a long uniform depth crack in a thin-skin material. If the crack is short compared to its depth (i.e. length ≤ 10 x depth), or is in a thick-skin material, the voltage is not constant either side of a crack - instead the distribution contains sharp cusps (as shown in Figure 4). In such cases, it is important to measure the voltages at the cusp points (as close to the crack edge as possible) otherwise the crack depth will be underestimated. In cases where it is not possible to measure the cusp voltages (such as when monitoring crack growth with fixed probes) it is possible to correct for this underestimate if the separation between the crack and the nearest voltage contact is known (refer to TSC for details).

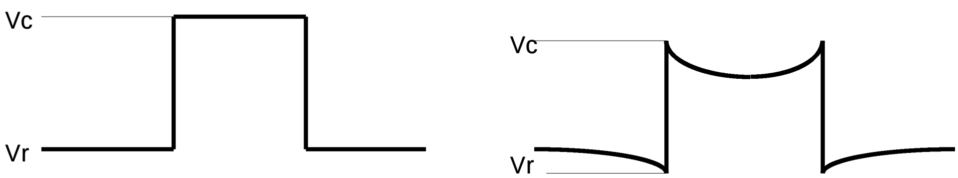

Figure 4 - Comparison of ACPD voltages from a probe crossing (left) a long and (right) a short crack

3. FURTHER DEPLOYMENT CONSIDERATIONS

3.1 CT - SPECIMENS

Access on a standard compact tension (CT) specimen obviously prohibits the field wire and probe contact arrangement used on a flat plate. Experience has shown that the best positions for the current inputs are on the edge faces either side of the notch as shown in Figure 5. This gives a good, linear dependence of voltage on crack length over a large length range. The current input points may conveniently be combined with the fittings for a clip gauge, if used. The relatively small size of CT specimen means that there is an inevitable redistribution of current when the crack approaches through-wall. This process then gives a non-linear variation in voltage with crack length.

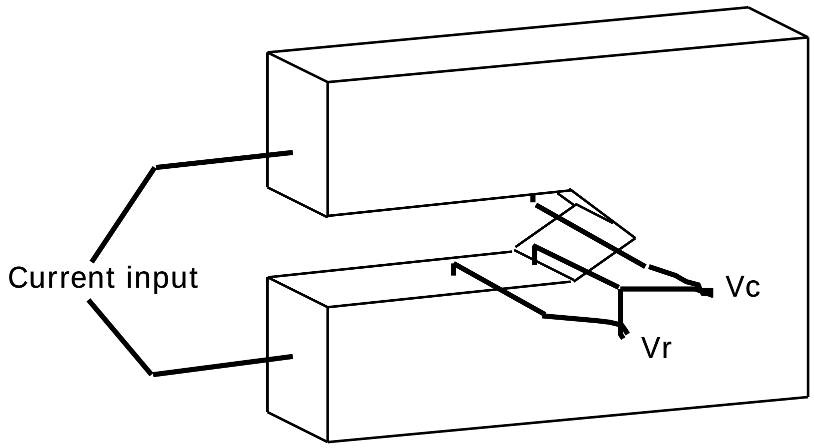

Figure 5 - ACPD connections for a CT specimen

The voltage contacts are best placed in a three-point arrangement along the centre-line of the notch as shown in Figure 5. The middle contact is then common to both probes. The cross-crack probe points should be symmetrically placed on the top and bottom notch faces close to the start of the 'V'. The third contact making up the reference probe should be placed 10mm or so further away from the 'V' on one notch face. Note that the measurement of the cross-crack probe spacing must be made around the 'V'.

If the CT specimen material is thin-skin and the crack front is fairly straight (as is usual in CT specimens cracking) then no account need be taken of the fact that the voltage readings are not taken at the crack edge. If, on the other hand, the material as thick skin then a modifier must be used to take account of the stand-off distance between the centre contact and the crack. Modifiers are discussed further in Section 4.

3.2 LARGE SPECIMENS

When inspecting or monitoring on large specimens such as tubular joints, there is a limit to the region over which the field strength is uniform and large enough to measure. The usable width of field is considered to be roughly equal to half the separation between the current input points, centred on the line between these points as shown in Figure 6. If it is required to inspect an area outside this range, the field input points should be moved (either by physical disconnection and reconnection, or by switching between an array of inputs).

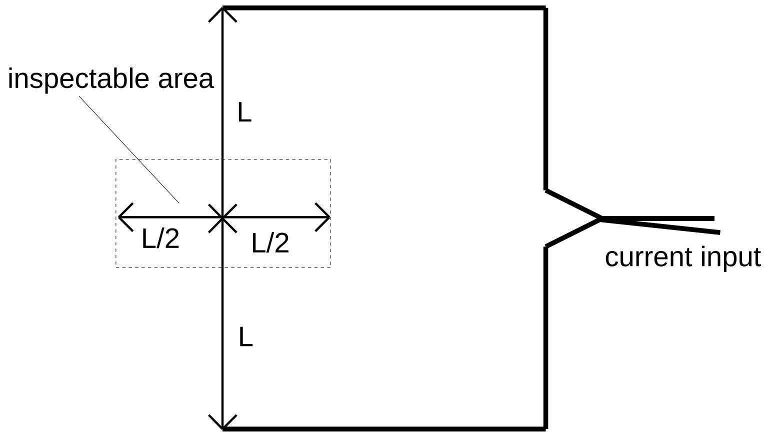

Figure 6 - Extent of usable injected field

3.3 THREADS

Most cracks in threads occur along the thread roots but the position around the root radius is not generally known. For small to medium threads (up to say 10mm pitch) it is generally best to make the voltage probes contact across adjacent crowns as shown in Figure 7, using a purpose-built probe spacing. If the thread is on a solid component, such as a bolt, the field is best injected along the axis. This gives a uniform distribution around the thread circumference. If this arrangement is not possible it may be better to induce the field using a coil that moves with the voltage probe as shown in Figure 7.

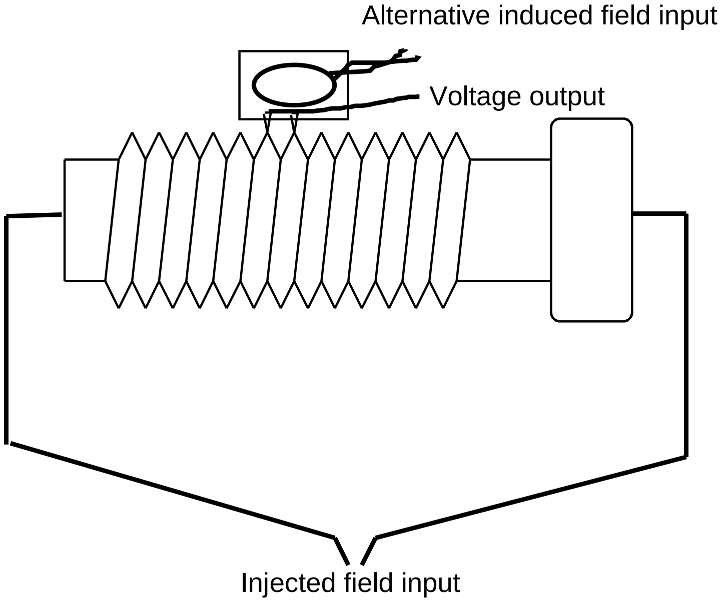

Figure 7 - ACPD connections for bolt inspection

The reference voltage should be taken further around the same thread as the crack voltage at a point where the voltage is seen to return to a steady value. Voltage readings taken across the thread immediately adjacent to a crack often show a satellite signal (especially on thick skin material). This is a drop in voltage below the normal background level caused by a diversion of current away from the nearby crack. Examples of the voltage traces expected are shown in Figure 8.

When sizing, modifiers should be used if the crack is short or the material is thick skin to take account of the stand-off distance between the thread crown and the crack.

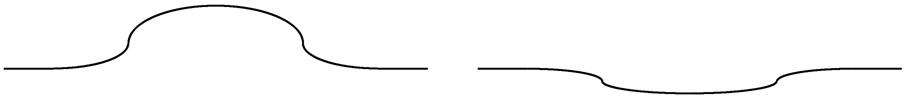

Figure 8 - Typical voltage traces from (left) a thread containing a crack, and (right) a thread adjacent to a crack.

3.4 UNDERWATER

ACPD can also be used underwater using specialised subsea instruments. The same principles apply as described above but obviously cleaning of the inspection site down to bright metal is very important for successful operation.

Underwater probes are generally bulkier than topside ones to allow deployment by gloved hand. The technique is made safe for underwater use by the use of low currents, low drive impedances and RCD trips.

Underwater inspection is often carried out on tubular welded joints, where the principles described in section 3.2 should be applied. The current injection points should be placed on lines intersecting the weld toe at right angles as shown in Figure 9.

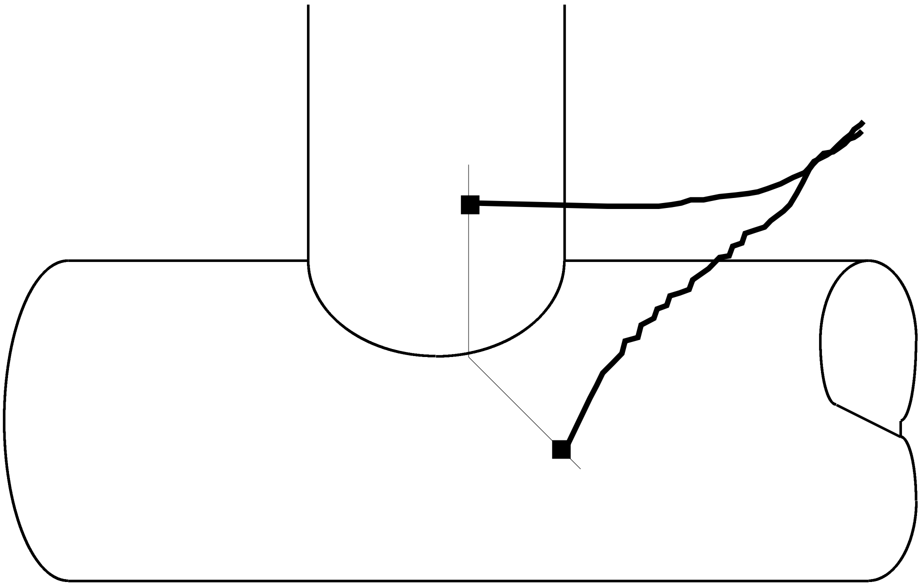

Figure 9 - Injected current input on a tubular intersection

4. CRACK SIZING

Crack sizing using the ACPD technique is best carried out using theoretically-derived results applicable to real fatigue cracks. Use of notches in calibration blocks should be avoided if at all possible. The number of variable parameters that can arise in an ACPD inspection is quite large and theoretical results do not exist for all combinations. The inspection should therefore be carried out so as to fit one of the parameter sets for which theoretical results do exist.

The main parameter to consider is the skin depth. The case where the skin depth is small compared to the anticipated crack depth has been extensively modelled and crack sizing is usually straight forward using simple formulae or computed look-up tables. It is therefore worthwhile choosing the input current frequency to give a thin skin if possible. A lot of modelling has also been carried out at the opposite extreme where the skin depth is large compared to the crack depth, and if a thin skin cannot be produced it is usually better to reduce the current frequency to produce a thick skin instead. The main disadvantage of increasing the skin depth is that the surface voltage readings and the sensitivity to changes in crack depth are both reduced.

4.1 THIN-SKIN SIZING

The simplest sizing procedure of all applies in the thin-skin case when the crack length is long compared to both the crack depth and the voltage probe spacing. Long in this case means more than 10 times greater. In this case the electric field strength, E, is constant so that the reference voltage is given by:

$$V_r = E\Delta_r$$

where Δ_r is the voltage probe spacing when measuring the reference voltage. The cross-crack voltage is given by:

$$V_c = E\,(\Delta_c + 2d)$$

where Δ_c is the voltage probe spacing when measuring the cross-crack voltage, and 2d represents the extra current path length introduced by a crack of depth d.

Eliminating E from these two equations, the crack depth is thus given by the following simple formula:

$$d_1 = \frac{\Delta r}{2}\left(\frac{Vc}{Vr} - \frac{\Delta c}{\Delta r}\right)$$

The crack depth will be given in the dimensions used for the probe spacings. In most cases the two probe spacings will be equal ($\Delta_r = \Delta_c = \Delta$) so that the equation simplifies to:

$$d_1 = \frac{\Delta}{2}\left(\frac{Vc}{Vr} - 1\right)$$

For example, for a probe of spacing 10mm, a cross-crack voltage of 800 and a reference voltage of 400 indicates a crack of depth 5mm.

The subscript 1 indicates that this is the so-called 1-demensional depth estimate. This first estimate of depth is only strictly true for the conditions of long cracks in a thin skin, but it is also used as the starting point for all defects. In these cases, this initial estimate is modified to take account of the pertaining conditions, such that the true depth d is given by:

$$d = Md_1$$

The modifier, M, is in general a function of probe spacing, probe position relative to the crack, surface breaking crack length, 1-dimensional depth estimate, skin depth etc.

The most often used thin-skin modifiers are those for sizing short cracks. It is generally assumed that such cracks are semi-elliptical in shape, although circular arc or rectangular cracks can also be treated. Theoretical modelling has produced a series of graphs and look-up tables of the shape modifier M. Other modifiers are also available to take account of corner cracks, crack bridging etc.

4.2 THICK-SKIN SIZING

A similarly simple equation for crack depth applies at the thick skin limit when the crack is long compared to the depth and the probe spacing, and the skin depth is large compared to the crack depth. In this case:

$$d = \frac{\Delta}{2}\left(\frac{Vc}{Vr} - 1\right)\left(\frac{Vr}{Vc}\right)^{\frac{1}{2}}$$

For example, for a probe of spacing 10mm, a cross-crack voltage of 800 and a reference voltage of 400 indicates a crack of depth 3.5mm.

The above depth estimate can be related to the 1-dimensional thin-skin depth estimate by $d = Md_1$ in which $M = (1 + 2d_1/\Delta)^{-½}$

In a similar way to the thin-skin case, modifiers have also been computed to take account of short cracks, inclined cracks etc.

Note that ACPD is normally restricted to surface-breaking defects, however in a thick-skin situation it is possible to measure changes in the surface voltage distribution caused by sub-surface defects. In this case, the voltage changes are gradual (i.e. there is no sudden jump as for a surface-breaking crack) and the amplitude is generally inversely proportional to the remaining ligament between the top surface and the crack front. A limited amount of modelling of this situation has been carried out - refer to TSC for more information.

5. CLOSING COMMENTS

As long as care is taken over field input placement and probe deployment as described above, ACPD is a very easy technique to use to obtain accurate crack sizing in a wide range of applications. Over the last twenty years, staff at Technical Software Consultants and University College London have built up a wealth of experience in the successful use of ACPD, and will be pleased to help with any applications not covered in this document.