MEASUREMENT OF CRACK DEPTH IN A TRANSITION WELD USING ACPD

R. Collins, D.H. Michael and R. Clark*

University College London NDE Centre
Torrington Place, London WC1E 7JE, U.K
* Rolls-Royce & Associates, Derby, U.K.

INTRODUCTION

This paper is concerned with the application of the ACPD method to the measurement of surface-breaking cracks at the interface between an austenitic and a ferritic steel in a transition weld. The ACPD method, shown schematically in figure 1, involves the establishment of a uniform thin-skin field which is used to interrogate a surface-breaking crack. Measurements of surface potential difference made before and across a crack are then used to infer its depth through a simple one-dimensional formula derived on the assumption that the material is homogeneous and that the field remains uniform on the metal surface and the crack faces [1]. The question of how to interpret readings from an ACPD gauge used on a transition weld arose after preliminary measurements had been made on specimens with spark-eroded rectangular notches of different depths and of aspect ratio 2 at a range of frequencies [2]. The one-dimensional interpretation of voltage readings was found to be inadequate, but sensible estimates of depth were nevertheless obtained on the basis of a very simple theoretical model of the effect of the discontinuity in material properties on the surface field measurements, coupled with the application of a single correction factor for the effect of the aspect ratio of the flaw. In reality the aspect ratio correction, which is known as a Multiplier [1], can be expected to depend on the size of the probe relative to the size of the flaw, but the value used in those tests was certainly of the right order of size. The encouraging results of these tests, which were performed at Rolls-Royce & Associates, Derby, U.K., indicated overall that the method may have important application in this study. In furthering this work a specimen with a weld-induced surface-breaking crack of higher aspect ratio was manufactured and the

![Fig. 1 Arrangement of an ACPD system for crack measurement.](image-url)
construction of a more detailed model of the surface field which is being explored in the measurements was put in hand in order that a rational procedure for the correct interpretation of instrument readings could be formulated. This paper compares test data obtained on the manufactured crack with predictions of crack depth obtained from both the simple theory and from the more elaborate models. Details of the theoretical developments will be published separately [3]. This initial work considers only defects of large aspect ratio.

DESCRIPTION OF THE STUDY

(a) Results from simple model

Figure 2a shows a section across a crack of uniform depth at a junction between two materials whose properties will be distinguished by suffixes a for austenitic and f for ferritic. The electrical skin depths are denoted by \( \delta_a \) and \( \delta_f \) respectively. The material properties relevant to this work which determine these values are given in Table 1. The likely range of instrument frequencies is 250 Hz to 10 kHz so that the operating conditions are such that \( 0.2 \text{ mm} < \delta_f < 1.5 \text{ mm} \), while \( 4 \text{ mm} < \delta_a < 25 \text{ mm} \). In contrast the approximate crack depths to be studied are \( 2 \text{ mm} < d < 20 \text{ mm} \). The theoretical field problem to be considered, therefore, is the combination of a thin or not-so-thin skin on the ferritic side where \( \delta_f/d < 1 \) or \( \delta_f/d < 1 \), with a thick or not-so-thick skin on the austenitic side where \( \delta_a/d > 1 \) or \( \delta_a/d = 1 \). This combination, which is potentially the most awkward from a mathematical point of view, is that considered in the companion paper [3]; here we discuss the problem only at the thin-thin limit where \( \delta_f/d << 1 \) and \( \delta_a/d << 1 \). The aspect ratio of interest is high so that a model with uniform crack depth is appropriate.

**Table 1** Data on material properties for the transition weld

<table>
<thead>
<tr>
<th>Material</th>
<th>( \mu_r )</th>
<th>( \sigma_f )</th>
<th>( \delta_f )</th>
<th>( \delta_a )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>100</td>
<td>4.45x10^6 S/m</td>
<td>1.56x10^6 S/m</td>
<td>2.85</td>
<td>5.92</td>
</tr>
<tr>
<td>Stainless</td>
<td>1</td>
<td>1.56x10^6 S/m</td>
<td>2.85</td>
<td>5.92</td>
<td></td>
</tr>
</tbody>
</table>

Hence \( S = \sigma_f/\sigma_a = 2.85 \)  
\( R = (\sigma_a \mu_f/\sigma_f \mu_a)^{1/2} = 5.92 \)

At frequency 10 kHz: \( \delta_f = 0.238 \text{ mm} \) and \( \delta_a = 4.02 \text{ mm} \)

Consider the conditions across the junction \( J \) shown in figure 2b in which a surface current flows in the y direction and meets a discontinuity in material properties at the plane \( Ox \) with no crack present. With an input current of angular frequency \( \omega \), the skin parameters on either side of the discontinuity are

\[
k_f^2 = i\mu_f\sigma_f\omega; \quad \delta_f = \sqrt{2/\mu_f\sigma_f\omega} \quad \text{and} \quad k_a^2 = i\mu_a\sigma_a\omega; \quad \delta_a = \sqrt{2/\mu_a\sigma_a\omega}
\]

where \( \sigma \) is the electrical conductivity and \( \mu \) the magnetic permeability. We are not concerned with the transition regions in which the current flows from one material to the other. The changes in these regions occur on length scales of the order of the skin depths \( \delta_f \) and \( \delta_a \) in the neighbourhood of \( O \) and, as in the homogenous model at the thin-skin limit, these are assumed to be small compared with crack depth \( d \) and probe size \( \Delta \). We thus assume that

\[
\delta_f/d << 1; \quad \delta_a/d << 1 \quad \text{and} \quad \delta_f/\Delta << 1; \quad \delta_a/\Delta << 1
\]

On either side of the discontinuity the streams will be of the forms

\[
E_f = E_f \exp(-k_fx), \quad (\text{Re} k_f > 0) \quad \text{and} \quad E_x = E_x \exp(-k_xx), \quad (\text{Re} k_x > 0)
\]
Fig. 2  (a) Section across a crack of uniform depth d at a junction between a ferritic and austenitic material, (b) current flow across a junction between two materials with no crack, (c) probe signal on crossing the junction in (b).

where $E_f$ and $E_a$ denote the respective surface values of $E_y$. Since the total current flow I must be conserved, we have

$$I = \sigma_f E_f \int_0^\infty \exp(-k_f x) dx = \sigma_a E_a \int_0^\infty \exp(-k_a x) dx$$

from which

$$I = \sigma_f E_f / k_f = \sigma_a E_a / k_a$$

On using equations (1) and (5), the ratio of the surface values is given by

$$R = E_f / E_a = \sqrt{\sigma_a \mu_f / \sigma_f \mu_a}$$

The surface values determine the magnitudes of the voltage readings which would be obtained with a probe contacting the surface and they are seen here to be permanently rescaled when the current traverses a discontinuity in material properties. For example if the probe in figure 2b is moved across the junction there will be a linear transition with distance while the probe is straddling the discontinuity, with constant signals $E_f \Delta$ and $E_a \Delta$ on either side once the traverse is completed, as shown in figure 2c.
Fig. 3 (a) Procedure for folding the field in fig. 2b, (b) refolded field with crack at the junction, (c) probe signal seen on crossing the crack.

Since we are considering thin-skin fields in this case, the unfolding theory may be applied [1] and it follows that figure 2b shows the fields on the unfolded metal and crack faces when a crack of uniform depth \( d \) is situated at the interface. If we fold the crack back into place, as in figures 3a and b, then the probe signals may be deduced for this circumstance from the relationship between the locations of the probe contacts on the physical surface and the unfolded plane. On denoting the readings obtained when off the crack and when straddling the crack with suffixes 1 and 2 respectively we have

\[
V_{1f} = E_f \Delta; \quad V_{2f} = E_f \Delta + (E_f + E_s)d
\]

and

\[
V_{1s} = E_s \Delta; \quad V_{2s} = E_s \Delta + (E_f + E_s)d
\]

It follows that

\[
(V_2 - V_1)_f = (V_2 - V_1)_s = V_2 - V_1
\]
showing that the discontinuity in voltage registered by the probe on crossing the crack is independent of the side from which readings are taken, and further that

\[ d = \frac{\Delta(V_2 - V_1)}{(V_{1f} + V_{1a})} = \frac{1}{2}\Delta(V_2 - V_1)/V_{1m} \]  

(10)

where \( V_{1m} = (V_{1f} + V_{1a})/2 \) is the mean of the two off-crack readings. If there were no discontinuity in material properties, then \( V_{1f} = V_{1a} = V_1 \) and equation (10) would then reduce to

\[ d^* = \frac{1}{2}\Delta(V_2 - V_1)/V_1 \]  

(11)

which is the one-dimensional interpretation of instrument readings used in the homogeneous problem [1]. Interestingly, equation (10) retains the one-dimensional form for the material junction, provided that the mean of the two values of \( V_1 \) on either side of the crack is employed. If it is the case, however, that access to the crack can be obtained from one side only, then in terms of measurements \( V_1 \) and \( V_2 \) made from the ferritic side, we have from equations (6), (7) and (11)

\[ d = \frac{R}{1 + R}\Delta(V_2/V_1 - 1) = d^* \frac{2R}{1 + R} \]  

(12)

In this form the quantity \( 2R/(1 + R) \) plays the part of a Multiplier for the ferritic side of the material junction, \( d/d^* = M_{jf} \) say, which operates on the simple one-dimensional result \( d^* \) so as to modify it to the correct depth \( d \). Although accurate knowledge of \( \mu_f \) is difficult, the likely value of \( R \) for the ferritic-austenitic junction is large. The property values in Table 1 suggest \( R = 5.92 \) for example, and equation (12) would then give \( M_{jf} = 1.71 \) implying that the one-dimensional interpretation would underestimate the true depth by 42%. If \( R >> 1 \), as would be the case when \( \mu_f >> \mu_a \), then

\[ d = 2d^* \]  

(13)

so that \( M_{jf} = 2 \) in that extreme and a one-dimensional interpretation from measurements on the ferritic side would then underestimate the true depth by 50%. This result may be interpreted as showing that the contribution to the cross-crack voltage associated with the austenitic crack face in this thin-thin limit is then negligible compared with the contribution from the ferritic face, and this is in fact the simple assumption adopted by Charlesworth and Clark [2] in interpreting their earlier measurements.

The profile of probe signal to be expected on crossing the crack in this case is shown in figure 3c. The essential features which distinguish it from the conventional top-hat profile seen with no material discontinuity are (i) the linear variation in probe reading as the probe traverses the crack and (ii) the rescaling of the off-crack signal. In fact, if both sides are accessible to the probe these two off-crack readings allow an experimental measurement of \( R \) since

\[ R = E_f/E_a = V_{1f}/V_{1a} \]  

(14)

Note that the values in Table 1 give \( R = 5.92 \) and the off-crack signal on the ferritic side is thus the larger of the two signals in this thin-thin limit.

(b) Results from further theory

The unfolding model on which the results in the previous section are based, is valid
for vanishingly small skin depths $\delta/d << 1$ and in formulating that model it was argued that the disturbances to the field in the neighbourhood of the corners $P, J$ and $Q$ depicted in figure 3b would occur on the length scale of the skin depth. They would thus contribute negligibly to the surface values and as a result, the unfolded field is insensitive to the crack inclination to the surface, the details of fields at the corners being ignored. The corner solutions have been studied however [4] and their influence has been included in a development of this thin-thin theory [3] to show that the junction Multiplier for the ferritic side, correct to the first order in skin thickness is given by

$$d/d^* = \frac{2R}{1 + R} \left\{ 1 - \frac{\delta_f d^*}{\pi d^* \Delta} + \frac{4 - \pi \delta_f (1 + S)}{8\pi d^*} \right\}$$

(15)

where $S = \sigma_f/\sigma_a$ with value $S = 2.85$ from Table 1. In the limit of negligible skin depths, that is $\delta_f/d^* << 1$ and $\delta_d/d^* << 1$, equation (15) of course reproduces the result in equation (12). For the case when $R$ is large (15) gives

$$d/d^* = 2\left\{ 1 - \frac{\delta_f d^*}{\pi d^* \Delta} + \frac{4 - \pi \delta_f (1 + S)}{8\pi d^*} \right\}$$

(16)

to be compared with the thin-skin result in (13) which was interpreted there as showing the austenitic contribution to the cross crack signal to be negligibly small compared with the ferritic. In contrast, when the first order effects of skin thickness are included, (16) still contains a contribution from the austenitic side in the limit of large $R$ through the ratio of conductivities $S = \sigma_f/\sigma_a$. When plotted as functions of $d^*/\Delta$, it is observed that the junction Multipliers for the thin-thin model fall rapidly to values which are sensibly constant for $d^*/\Delta$ above about 0.2 - 0.3, and that the result $M_{jf} = 2R/(1 + R)$ is a good first approximation to those values [3].

The second theoretical model developed in reference [3] considers a situation in which the skin depth on the austenitic side is large. It involves a mixture of the thin-skin theory with corner corrections in the ferritic material and a solution at the static limit in the austenitic which describes a line source at the crack tip fed from the current flow on the ferritic face of the crack. No explicit expression for the ferritic side Multiplier arises from this model but it gives

$$d - (S\delta_f/\pi \sqrt{2}) \ln [\delta_f/d] = 2d^* \left\{ 1 - \frac{\delta_f d^*}{\pi d^* \Delta} + \frac{4 - \pi \delta_f (1 + S)}{8\pi d^*} \right\}$$

(17)

which can be used to evaluate $M_{jf}$ by assigning values to $d/\Delta$ and evaluating $d^*/\Delta$. It may be observed that for vanishingly small skin depth $\delta_f$, this equation reduces to equation (13) showing a Multiplier of $M_{jf} = 2$. Multipliers have been evaluated from equation (17) using the property values in Table 1 and the results are plotted in reference [3] for three values of $\Delta/\delta_f$. For $\Delta/\delta_f = 10$, $M_{jf}$ has a minimum value of 1.6 at $d^*/\Delta \approx 0.3$ but subsequently rises slowly to achieve the same level as given by the thin-thin model at high $d^*/\Delta$. There is found to be a stronger dependence of $M_{jf}$ on $\Delta/\delta_f$ in the thin-thick model than in the thin-thin and an increase in $\Delta/\delta_f$ is seen to push the minimum in $M_{jf}$ towards lower values of $d^*/\Delta$. The overall level of $M_{jf}$ is not greatly affected however.

EXPERIMENTATION

A jig was designed to enable the technique to be applied to a tubular transition weld specimen. It consisted of a perspex frame which held a pad of twelve equally-spaced inducing wires so that they were positioned 1mm above the metal surface when the jig was held in place on the tubular specimen by two electromagnets. The spacing between the wires was 7.5 mm and the overall pad size was 140 mm x 80 mm. A standard spring-loaded probe of gap 10 mm was used in conjunction with a U8 Crack Microgauge instrument operating at 6 KHz to take readings by hand at measurement positions which were always arranged to be in the centre of the jig. Figure 4 shows the experimental arrangement.
Fig. 4 Experimental set-up for measurements on a tubular transition weld specimen
The tubular specimen comprised a tube of 316 stainless steel joined by an austenitic stainless steel weld to a tube of low alloy CrMo steel. A crack present at the CrMo/stainless steel bond line extended around the entire circumference of the weld and hence could be considered to be long and of essentially constant depth as assumed in the models. In order to obtain repeatable results the surface of the CrMo was cleaned so as to remove the oxide and to allow good probe contact to be made.

Table 2

<table>
<thead>
<tr>
<th>No</th>
<th>d*</th>
<th>d</th>
<th>Mjf = 2</th>
<th>d</th>
<th>Mjf</th>
<th>Mjf = 2 for thin-thin model</th>
<th>Mjf = 2 for thin-thick model</th>
<th>d</th>
<th>real</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>7.53</td>
<td>15.07</td>
<td>1.70</td>
<td>12.79</td>
<td>1.87</td>
<td>14.10</td>
<td>14.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2:</td>
<td>8.54</td>
<td>17.09</td>
<td>1.70</td>
<td>14.51</td>
<td>1.88</td>
<td>16.10</td>
<td>16.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3:</td>
<td>7.15</td>
<td>14.30</td>
<td>1.70</td>
<td>12.20</td>
<td>1.87</td>
<td>13.40</td>
<td>12.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4:</td>
<td>6.70</td>
<td>13.40</td>
<td>1.70</td>
<td>11.39</td>
<td>1.87</td>
<td>12.50</td>
<td>12.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean error</td>
<td>+9.2%</td>
<td>-7.1%</td>
<td>+2.3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 gives values of crack depth obtained at four positions along the crack. The values calculated are the one-dimensional depth d*, the depth obtained from the simple theory assuming Mjf = 2 (equation 13), that for the thin-thin model with corner corrections (equation 15) and the result obtained by applying the thin-thick model (equation 17). In all cases measurements were made from the ferritic side. The property values given in Table 1 give δf = 0.34 mm at 6kHz. The values calculated from the electrical measurements are compared in Table 2 with the real depths obtained from destructive examination at these four positions after core samples were taken. The values given by Mjf = 2 are seen to overestimate the true depths slightly in all cases, but only by +9.2% on average. This is remarkable given the simplicity of that model. With corner corrections, the thin-thin model produces improved agreement in that the Multiplier predicted is constant at 1.70, correct to two decimal places, this giving underestimates of true depth in all cases, but with the mean error reduced to -7.1%. Best agreement is obtained with the thin-thick model which gives a Multiplier value essentially constant at 1.87 for the conditions of the test, showing one underestimate and three overestimates but with a mean error of only +2.3%. The results from all models in Table 2 are in fact very satisfactory.

ACKNOWLEDGMENTS

We are grateful to Rolls-Royce & Associates, Derby, United Kingdom for initiating this work and for agreeing to its publication. R. Clark is now with the British Railways Board at the Railway Technical Centre in Derby.

REFERENCES

2. F.D.W. Charlesworth & R. Clark. Private communication