Alternating current flow in internally flawed conductors: A tomographic analysis

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The alternating current potential drop technique is a nondestructive testing method that is mostly applied to estimate the depth of surface breaking flaws (e.g., cracks) in metallic conductors. When the flaw is hidden (internal or bottom cracks), other techniques (e.g., radiographic) must be used, which may only provide limited information on the location and dimensions of the hidden flaw. This work presents a detailed numerical analysis of ac flow in internally flawed conductors. The results can be used to reveal and estimate the dimensions and location of hidden flaws. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2338655]

The depth of surface breaking flaws (e.g., cracks) can be assessed using the alternating current potential drop (ACPD) technique. The presence of a crack increases the local electrical resistance and the measured electrical potential across the crack flanks. Therefore, one may measure the surface voltages far and adjacent to the crack, for a given injected ac.[1–3] These measurements are then converted into crack depth by a theoretical approximation or by means of experimental calibrations.

When applying a high frequency current to an electrical conductor (metal), the current flows in a thin superficial layer of the conductor. This phenomenon is known as the skin effect.[4] The skin thickness δ depends on the metal properties and the current frequency f and is given by

$$\delta = \frac{1}{(\pi \mu_r \mu_0 \sigma f)^{1/2}}, \tag{1}$$

where μ_r is the relative magnetic permeability, μ_0 is the magnetic permeability of free space measured, and σ is the electrical conductivity.

Figure 1 is a schematic representation of the uniform current flow within a skin of thickness δ, in a conductor that contains three distinct types of discontinuities: surface breaking, internal, and bottom cracks, all of uniform depth d. The current is injected at point 1, flows along the metal surface, and exits at point 2. The voltage drop is measured by a probe whose contacts form a constant gap Δ. When placing the probe far away from the crack, a voltage V_1 is measured (reference voltage). A voltage V_2 is measured when placing the probe across the *surface breaking crack*.

Provided a surface breaking flaw is identified, the ACPD technique may be applied to estimate its depth. Two distinct cases are to be considered: *thin* and *thick* skin modes.[5–7] The thin skin approximation for crack depth estimation is well established and supported experimentally. It gives an excellent prediction of the crack depth provided all the requirements for thin skin are met. The thick skin solution is a modification (or rather an adjustment) of the thin skin solution that requires cumbersome experimental calibrations.[8–10] This approximation gives a lower limit of the crack depth with limited accuracy. Saguy and Rittel[11] proposed a global solution which bridges the thin and thick skin solutions in a seamless manner. This solution provides an excellent approximation of the crack depth irrespective of the skin thickness.

The internal flow of ac in the presence of internal discontinuities has not been investigated so far. Therefore, this letter reports results on this subject, namely, a universal relationship between V_2/V_1 and $\delta/(t-d)$ that indicates unambiguously the presence of a hidden flaw and its dimensions. The systematic variation of the current's frequency (and skin depth) is analogous to ac tomography.

Three-dimensional models of flawed conductors were analyzed using ANSYS (electromagnetic toolbox) simulation tool.[12] The analyzed problems consisted of a metal conductor, with a rectangular cross section area, containing a bottom or internal crack of uniform depth. A uniform sinusoidal current was applied remotely from the crack, along the surface direction. The current frequency was systematically varied to simulate different skin depths. Due to the symmetry of the problem, only one-half of the specimen was analyzed.

A solution is sought for the potential which satisfies the following equation:

$$\nabla^2 \mathbf{A} + \sigma\mu \frac{\partial \mathbf{A}}{\partial t} + \mu \mathbf{J}_{\text{source}} = 0, \tag{2}$$

where $\mathbf{A}$ is the magnetic vector potential, $\mu = \mu_0 \mu_r$, and $\mathbf{J}_{\text{source}}$ is the current density of the source. The boundary conditions are as follows (Fig. 2): At the crack surfaces and

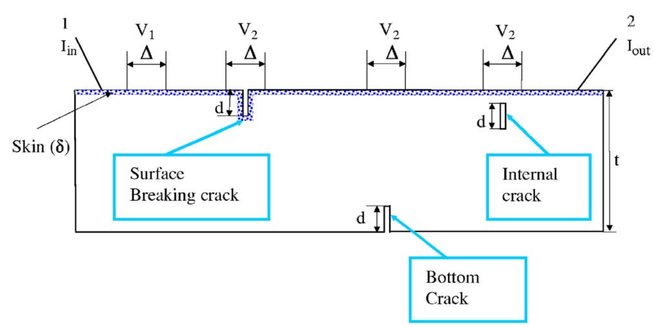

FIG. 1. Three distinct crack configurations: surface breaking, internal, and bottom cracks. Current density distribution in a cracked specimen for the thin skin case.

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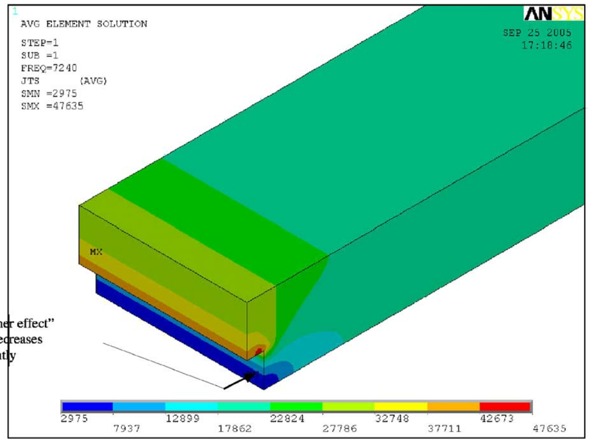

FIG. 2. Current density distribution: $\delta/(t-d)<0.5$. Thick skin: $t/\delta=50/5$, $d/\delta=10/5$.

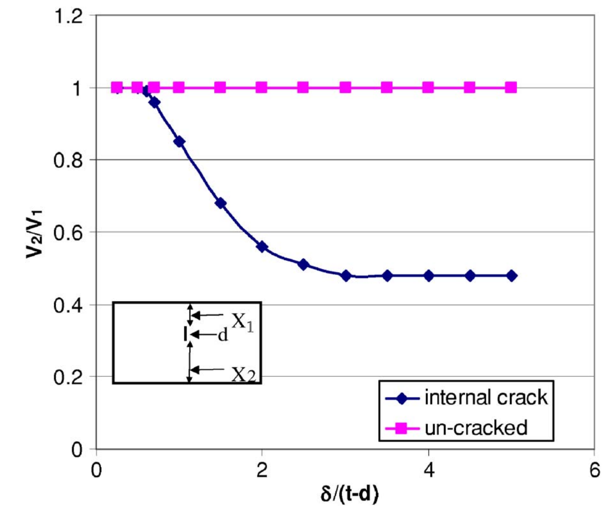

FIG. 4. V_2/V_1 vs $\delta/(t-d)$. Probe distance=5 mm-bottom cracks.

in the upper surface (where the current flows), the flux lines are parallel (Dirichlet boundary condition).

The solution of a bottom crack problem in which the skin thickness δ is small compared to the uncracked thickness $t-d$, ($\delta/(t-d)<0.5$), is shown in Fig. 2. In this case, the current distribution is not affected by the crack and the voltage ratio is constant ($V_2/V_1=1$).

Figure 3 shows the current density distribution for a δ that is large enough to interact with the tip of the bottom crack d. In that case, the current density is observed to vary in the vicinity of the crack tip. The *corner effect* phenomenon[12] is noticeable here, and the current decreases significantly close to the corner.

Moreover, the analyses show that as $\Delta/2$ decreases, the voltage ratio change is increasingly larger, as observed in Ref. 11. One can select a specific Δ e.g., $\Delta=5$ mm, and in this case, the V_2/V_1 vs $\delta/(t-d)$ relationship is plotted in Fig. 4.

A very interesting result is that, as long as $\delta/(t-d)\leq 0.5$, the electrical field is not affected by the presence of the crack and the V_2/V_1 remains constant and equal to 1. However, when $\delta/(t-d)>0.5$, a *significant drop* in the voltages ratio can be observed, so that the flaw depth can be found in a *straightforward manner* from

$$\frac{\delta}{(t-d)}=0.5. \tag{3}$$

The practicality of this result is obvious. Indeed, a simple measurement can indicate in a straightforward manner whether the investigated component is cracked and, in the affirmative case, provide a measure of the crack depth.

Based on the bottom crack results, it is now interesting to investigate *internal cracks*, with edge coordinates X_1, X_2 (Fig. 5). Following the same logic, we begin with the thin skin (high frequency) and measure (numerically) the voltage ratio. The current frequency is systematically varied until a change in the voltage ratio is noted. Such a change indicates the upper crack-tip location X_1. When the skin depth is increased so that $\delta=X_2$, the observed changes in V_2/V_1 are negligible. However, by flipping the specimen upside down, the above-described procedure can be repeated to assess X_2. It should be noted that the crack depth d cannot be assessed without flipping the specimen.

For example, consider the following problem: stainless steel conductor with rectangular cross sectional area (10×5 mm^2), upper uncracked thickness $X_1=1$ mm, crack depth $d=1$ mm, and lower uncracked thickness $X_2=3$ mm (small figure in Fig. 5).

The analysis results show that $V_2/V_1<1$ occurs first when $\delta=0.5$ mm, and from thereon this ratio decreases no-

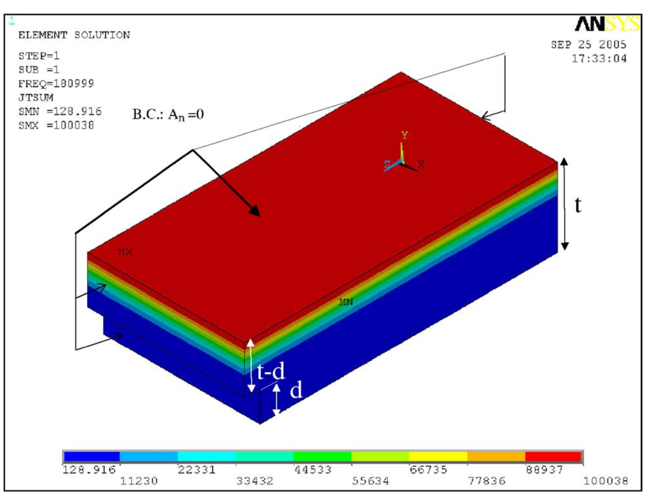

FIG. 3. Bottom crack current density distribution: $\delta=t$.

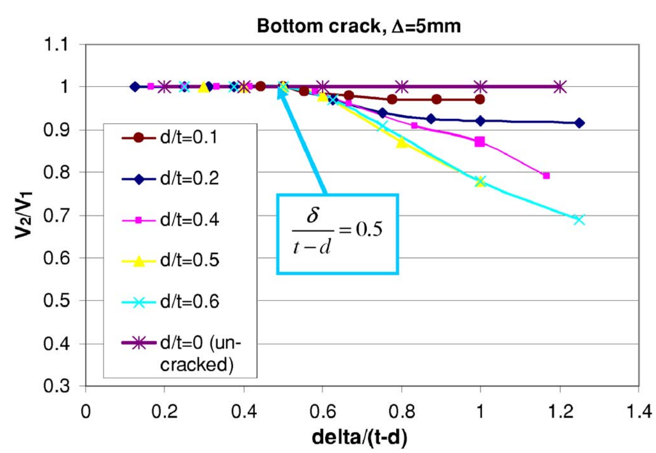

FIG. 5. V_2/V_1 vs $\delta/(t-d)$. Upper uncracked thickness $X_1=1$ mm.

ticeably. From Eq. (3) the upper crack tip is located at $X_1 = 1$ mm. Figure 5 shows the V_2/V_1 vs $\delta/(t-d)$ relationship for $\Delta = 5$ mm, $t = 5$ mm, and $X_1 = 1$ mm. When $\delta/(t-d) > 0.5$, V_2/V_1 decreases noticeably, thus indicating the *presence* of an internal flaw, in contrast with uncracked components for which the voltage ratio remains unaffected by variations in the frequency of the current, i.e., $V_2/V_1 = 1$.

To estimate the lower uncracked thickness, the part is flipped upside down (so $t-d = X_2 = 3$ mm) and repeat the previous exercise. Here, $V_2/V_1 < 1$ occurs first at $\delta = 1.5$ mm. From Eq. (3), X_2 is rightly identified as $X_2 = 3$ mm.

At this stage, one may conclude that a simple method is available to detect internal cracks. This method is a slight variation of that used for the bottom-breaking crack. From these results it can be concluded that the proposed criterion [Eq. (3)] provides a general and accurate methodology to reveal the presence and the size of internal discontinuities.

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