SAW-CUT SCANNING PATTERNS

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INTRODUCTION

The scanning of surface saw cuts can yield clues both about the interaction of nondestructive evaluation (NDE) devices with samples and the ability to detect and characterize flaws of other shapes. In this case, the device is a modified AC magnetic bridge (the bridge) which has been described elsewhere [1,2,3]. Electrical bridges can be operated in two modes: Off-null operation occurs when the bridge output is minimized (nulled) and the reaction of the bridge to various samples is judged by changes in the output voltage. Off-null operation is principally used for control. Renull operation occurs when the bridge is nulled for each sample and the physical parameters required to null the bridge (usually resistance and/or resistance and capacitance) can be used to determine physical differences in the samples.

Woodward, et. al. [4] used the bridge in the off-null mode to scan surface saw cuts and developed formulae which predicted the width and depth of the saw cuts from the resulting patterns. Schmidt, et. al.[5] modified this technique using the bridge in a renull mode and in an *ad hoc* manner predicted the variation in depth of a fatigue crack along the course of the crack.

Preliminary results from a more thorough investigation on surface saw cuts are presented here. The complete investigation will examine both surface and hidden saw cuts under a range of frequencies.

THE EXPERIMENT

The experiment was conducted exactly in the manner described previously [4], i.e., it was carried out with the same experimental setup, and with the same samples. The samples were plates of 6061-T6 aluminum and approximately 10 cm x 10 cm and 6.35-mm thick. The single saw cut in each plate was perpendicular to one side and divided the plate into equal areas.

The plane of the pole face is shown in Fig. 1 where the hatched areas are two ferrite poles separated by a 0.51-mm thick piece of copper. In scanning, this plane is parallel to the plane of the sample and separated from the sample plane by lift off. In the Woodward experiment, the lift off was immeasurably small. Here, the effect of lift off is first examined, and for most of the data, a lift off of 1.27 mm was used. This value was chosen because most eddy-current work uses values of this sort. Work done with the bridge [6] on aluminum indicates that lift-off values up to 4 or 5 mm can be used for various types of flaw detection.

Scanning was carried out in 0.254-mm increments over a range of 24 mm symmetrically scanning the saw cut. The orientation of the bridge face was such that the 13.7-mm dimension in Fig. 1 was parallel to the cut. At each displacement position, the bridge, which was run at 10 kHz, was renulled and the values of resistance and capacitance were recorded. Real and imaginary reluctances were calculated [2,7] for each position. For each scan, these values were subtracted from the initial values of the scan. Thus, *the real and imaginary reluctances presented here are with respect to the values which would be obtained with an unflawded plate*. Because the bridge used is asymmetric as assumed in the bridge theory [2], the values of real and imaginary reluctance are probably off. However, the ratio of one to the other is probably correct.

A typical renull scan obtained here is shown in Fig. 2, where both the real and imaginary reluctances are plotted. The icon at the bottom accurately represents the pole face in the scanning (displacement) direction. Note that both the real and imaginary reluctances have peaks immediately over the center of each pole face. The actual pole-face positions with respect to the saw cuts for the peaks a,b, and c on Fig. 2 are shown in

RESULTS

Woodward's results for off-null scans at 10 kHz are shown in Figs. 4 and 5. The scanning orientation of the bridge face with respect to the "crack" (the saw cut) is indicated by icons on both figures. Off-null voltage versus displacement is shown in Fig. 2

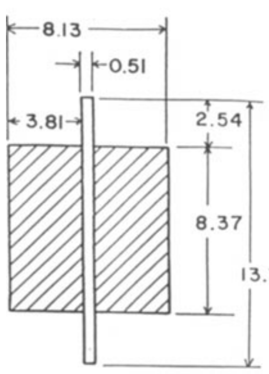

Figure 1. Face of the bridge pole which intersects the sample

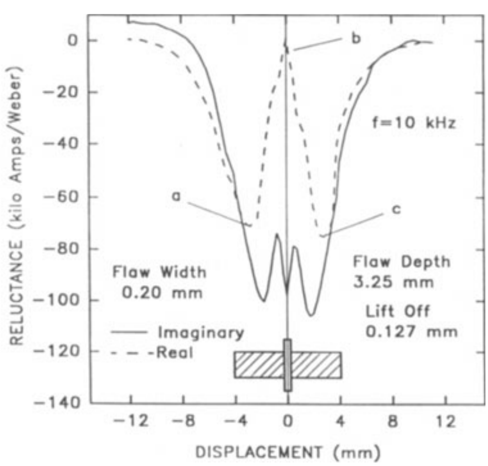

Figure 2. Positions of the bridge pole with respect to the saw cuts to produce the satellite peaks (a,c) and the central peak (b).

for samples of constant saw-cut width, 0.2 mm, but differing depth. All the scans show three peaks, a central peak surrounded symmetrically by satellite peaks. The satellite peaks occur over the pole faces as in Fig. 2. Note that the central peak remains constant

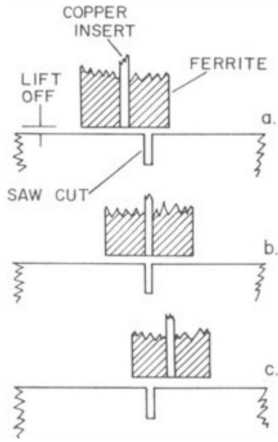

Figure 3. Typical reluctances from a renull bridge scan using an AC magnetic bridge showing the pole configuration when pole is centered on the saw cut.

Fig. 3. Note that when the peaks a and c occur, the saw cut is centered over one pole face while the other pole face looks at an unflawed aluminum surface. In position b, the pole face is positioned as shown in Fig. 2.

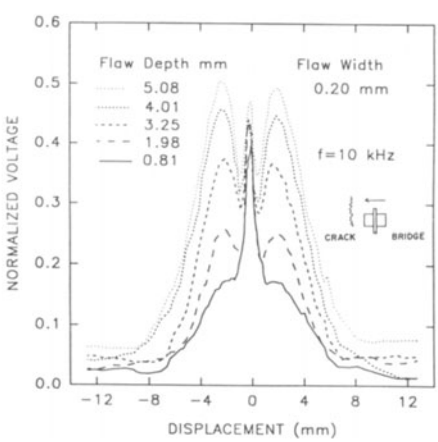

Figure 4. Normalized voltages from an off-null bridge scan showing variations of the height of the satellite peaks with variation of depth of the saw cut.

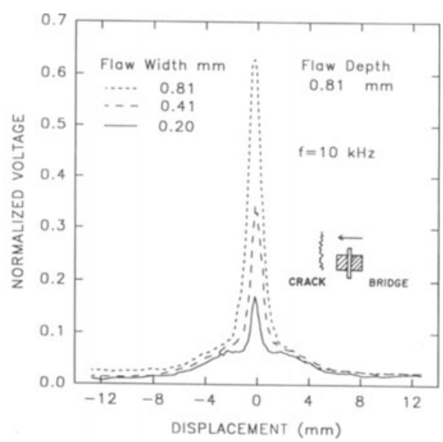

Figure 5. Normalized voltages from an off-null bridge scan showing variations of the height of the central peak with variation of width of the saw cut.

with saw-cut depth while the height of the satellite peak changes. For these data (i.e., at 10 kHz with a saw- cut width of 0.2 mm), the depth D_V of the crack in millimeters is related to the normalized voltages of the satellite peak V_h by

$$D_V = -0.277+0.619V+0.084V_h^2 \quad (1)$$

with a mean square deviation of 0.075 mm. The off-null voltages on Fig. 5 are for the minimum crack depth (to minimize the effects of the satellite peaks) at 10 kHz, and demonstrate the effect of changing saw-cut width. Here, the height of the satellite peak remains essentially constant while the height of the central peak varies with width. The width W_V is related to the voltage height of the central peak V_w by the expression

$$W_V = -0.034+0.135V_w \quad (2)$$

with a mean square deviation of 0.004 mm.

Of the three peaks observed, the satellite peaks are the most important since they remain as the width of the saw cut goes to values of less than 0.1 mm. The central peak essentially disappears. For example, the fatigue crack examined in Ref. [5] had no central peak. Therefore, of the above two equations, Eq. 1 will find the widest application.

The experiment which produced Fig. 4 was reproduced in the renull mode. The resulting real and imaginary reluctances are displayed in Figs. 6 and 7. In Fig. 6, the real reluctance is seen to decrease as the scan approaches the saw cut. It is interesting, however, that the reluctance approaches the unflawed reluctance where the poles straddle the saw cut (the configuration of Fig. 3b. Thus, the central peak is absent and only the satellite peaks remain. The depth D_R of the saw cut with respect to the real reluctances R_D of the satellite peaks is given by

$$D_R = -1.349-0.062R_D \quad (3)$$

where the mean square deviation is 0.062. The imaginary reluctance is proportional to the conductivity of the sample. Since the conductivity should be greatly decreased by the saw cuts, the imaginary reluctance should decrease as the scan approaches the saw cut. The

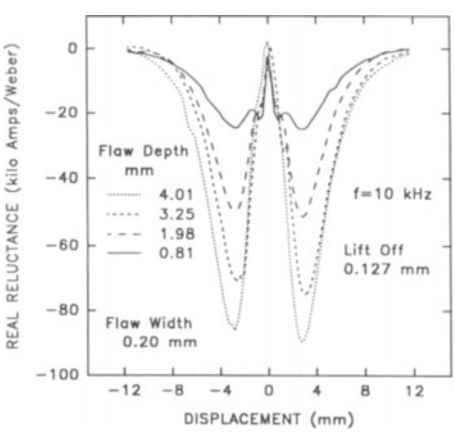

Figure 6. Real reluctances from a renull bridge scan showing variations of the height of the satellite peaks with variations of depth of the saw cut.

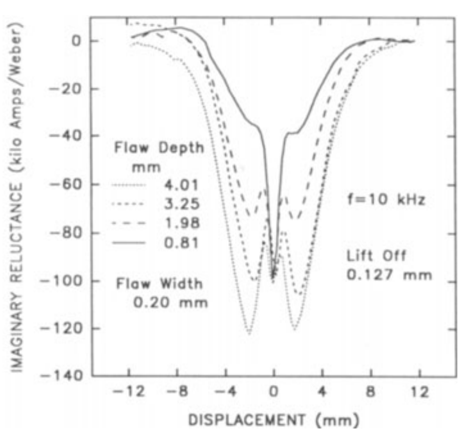

Figure 7. Imaginary reluctances from a renull bridge scan showing variations of the height of the satellite peaks with variations of depth of the saw cut.

behavior of the imaginary reluctance in Fig. 7 has an appearance very similar to that of the voltage in Fig. 4, i.e., a central peak unchanging with depth of saw cut with satellite peaks that do change. The variation of the depth D_I with the height of the imaginary reluctance I_D at the peaks of the satellites is given by

$$D_I = -1.601 - 0.047 I_D \tag{4}$$

with a mean square deviation of 0.031.

The renull scan thus produces a double check on the depth of saw cuts or cracks. Since fatigue cracks are rarely well-defined, it will be interesting to study the renull scanning patterns to determine what characteristics of the crack might cause a disagreement between these two measures of crack depth.

Real and imaginary reluctances were obtained for changing flaw width at constant flaw depth, the experiment which produced Fig. 5. The real reluctance behavior is shown in Fig 8. Both the central peak and the satellite peaks remain unchanged with flaw width, but a new feature appears. New satellite peaks appear symmetrically to the central peak between the central peak and the previous satellite peaks. These new satellite peaks appear to be formed when the 0.51-cm thick copper insert seen in Fig.1 is less than the width of the saw cut. Probably what is happening here is that Lenz's Law is restricting the electromagnetic field to the small gap between the edges of the insert and the saw cut. It is clear that in real NDE situations, this new satellite peak would not occur. The imaginary-reluctance scan of Fig. 9 displays an appearance identical to that of the voltage scan of Fig. 5. The satellite peaks remain essentially unchanged while the central peak produces a relation between width W_I and height I_W given by

$$W_I = 0.062 - 0.00175 I_W \tag{5}$$

with a mean square deviation of 0.079 millimeters. In NDE situations, the central peak would probably be absent.

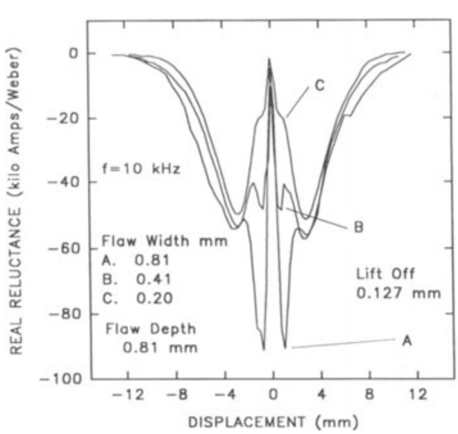

Figure 8. Real reluctances from a renull scan showing no variations in either the central or the satellite peaks with variations of width of the saw cut.

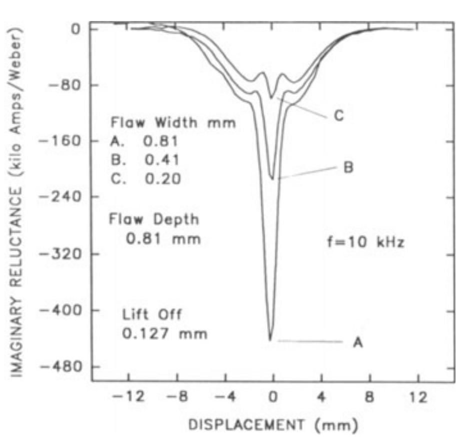

Figure 9. Imaginary reluctances from a renull scan showing variations of height of the central peak with variations of width of the saw cut.

A single saw cut was scanned in the renull mode at various values of lift off. The resulting real and imaginary reluctances are shown in Figs. 10 and 11. The lift off was changed by over a factor of 6. What is interesting about both of these curves is that the central peak changed with a slope magnitude of 228 kilo Amps/Weber millimeter for the real reluctance and 811 kilo Amps/Weber/millimeter for the imaginary reluctance while the satellite peaks, which are indicative of crack depth, changed only about 53 kilo Amps/Weber/millimeter for both reluctances. In normal NDE applications, the central peak would not be there because of small crack width. The relative insensitivity of the satellite peaks to changes in lift off has been seen before [6], and indications are that at lower frequencies even these small changes will become insignificant.

CONCLUSIONS

The real and imaginary reluctances produced by renull scanning with AC magnetic bridges seem to be indicative of the manner in which these parameters change with the sample. Renull scanning produces simultaneously two sets of data about scanning flaws. Both sets of data can be used to predict the width and depth of saw cuts. While for saw cuts, the interpretation of these data agree, for the more complicated flaws usually found in NDE, disagreement between these data may produce additional information about the flaws.

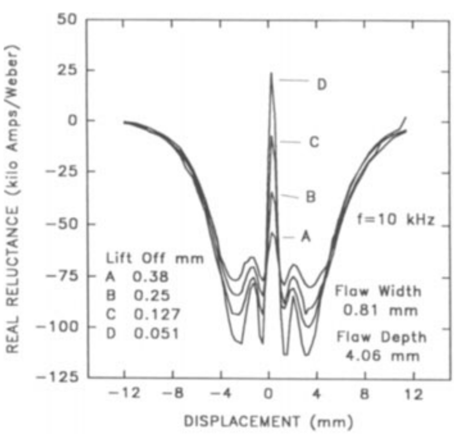

Figure 10. Variations of real reluctances in renull scans of saw cuts at various values of lift off showing large changes in the height of the central peaks and small changes in the height of the satellite peaks.

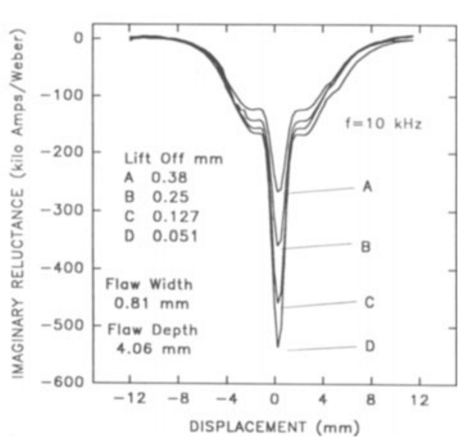

Figure 11. Variations of imaginary reluctances in renull scans of saw cuts at various values of lift off showing large changes in the height of the central peaks and small changes in the height of the satellite peaks.

REFERENCES

1. W.F. Schmidt and O.H. Zinke, *Review of Progress in QNDE*, Vol 12, eds. by D.O.Thompson and D.E. Chimenti, (Plenum Press, New York, 1993), p. 1885.
2. W.F. Schmidt and O.H. Zinke, *Review of Progress in QNDE,* Vol 13, eds. by D.O.Thompson and D.E. Chimenti, (Plenum Press, New York, 1994), p. 1825.

3. O.H. Zinke, U.S. Patent #4,901,017 (February 13, 1990), Canadian Patent #1296061 (February 18, 1992), European Common Market Patent #0329781, (March 29, 1995).
4. M.R. Woodward, H.A. Sreshta, O.H. Zinke, and W.F. Schmidt, "Surface Flaws Using a Modified AC Magnetic Bridge", *Experimental Mechanics*, Vol. 35, Society of Experimental Mechanics, December, 1995, p. 367.
5. W.F. Schmidt, O.H. Zinke, and S. Nasrazadani,"Characterization of a Crack in an Aluminum Bar Using an AC Magnetic Bridge", 147-163, *Special Technical Paper 1251*, American Society of Testing and Materials, ASTM, Philadelphia, PA, April, 1995.
6. W.F. Schmidt and O.H. Zinke, *Review of Progress in QNDE,* Vol 14, eds. by D.O.Thompson and D.E. Chimenti, (Plenum Press, New York, 1995), p. 1725.
7. O.H. Zinke and W.F. Schmidt, "Linear AC Magnetic Circuit Theory", *IEEE Transactions on Magnetics,* Vol. 29, 1993, p. 2207.