SIGNIFICANCE OF EDDY CURRENT CRACK/SLOT RESPONSE TO AIRPLANE INSPECTION

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INTRODUCTION

From the early 1960's, a small narrow slot has been used to calibrate eddy current instrument sensitivity for surface crack inspection of airplane structure. Recently, the difference in the eddy current response of an electrodischarge machined (EDM) slot and a fatigue crack has received considerable attention. A conclusion that may be drawn from this reported difference is that the present practice of using an EDM slot for eddy current instrument sensitivity calibration could result in a failure to detect a required crack. [redacted] It is a conclusion drawn from a too general application of the eddy current crack/slot response difference reported by researchers in quantitative nondestructive evaluation.[1-7] The objective of quantitative nondestructive evaluation is to analyze eddy current signals to identify a crack and determine its length, depth, orientation, etc. Research in this area has shown that a significant difference can exist between the eddy current signal from a fatigue crack and an EDM slot of comparable size. For the purpose of quantifying a crack from its eddy current signal, comparison with the eddy current signal of an EDM slot may not be useful.

EDM Slots and "Detectable Cracks"

[redacted] For crack detection, the EDM slot serves two principal functions. Most important, an EDM slot of sufficiently small size is used to set the sensitivity level of an eddy current surface crack inspection. The eddy current calibration standard commonly used for this purpose is a 0.020 inch (0.5 mm) deep EDM slot, Figure 1.

Secondly, the eddy current response of an EDM slot is sufficiently crack-like so that the rapid signal change produced when an eddy current probe is scanned across an EDM slot can be compared to the signal obtained when an eddy current probe is scanned across a crack, Figure 2. This visual similarity between the eddy current response of a crack and EDM slot helps to identify a crack signal.

It is important to emphasize that in airplane structural inspection the principal use of the EDM slot is to set eddy current instrument sensitivity. The calibration slot is not necessarily intended to represent the size of the detectable crack. A "detectable crack" is one that is detectable using specified eddy current inspection guidelines. Detectable crack size takes into consideration the difference in test results that can be expected from eddy current inspections performed with a variety of instruments and range in inspector skill. These differences have led to a conservative position being taken with respect to the calibration slot size and detectable crack size.

Under Boeing Damage Tolerance Methods and Allowables criteria, the eddy current detectable crack length for general surface crack inspection is 0.2 inch (5 mm), and 0.1 inch (2.5 mm) for closely controlled inspections, for example around fastener ends. Under general inspection guidelines, eddy current test system sensitivity for detecting these cracks is established using an 0.02 inch (0.5 mm) deep EDM slot. Selecting a conservative crack length-to-depth ratio of 4:1, the depth of the detectable crack is 0.05 inch (1.25 mm), two and one-half times the depth of the calibration slot. A crack of this depth would produce a significantly larger eddy current response than the 0.02 inch (0.5 mm) calibration slot. For example, using a 200 KHz test frequency and a 0.12 inch (3.0 mm) diameter shielded pencil probe, the response of an eddy current meter signal display instrument to an 0.04 inch (1.0 mm) deep EDM slot in aluminum is nearly twice that of an 0.02 inch (0.5 mm) deep EDM slot, Figure 2. Similar results are obtained from fatigue cracks when using a meter signal display eddy current instrument.

From damage tolerance criteria, the reliability of detecting a specified detectable crack for a one time eddy current inspection is taken as 0.63. In practice, repeat inspections are used. The interval between repeat inspections is based on crack growth rates determined from fatigue tests and stress analysis. Inspection intervals allow for two or three repeat eddy current inspections before a crack reaches limit length. At each re-inspection interval, crack growth has further increased the possibility of its eddy current detection.

Eddy current test sensitivity, multiple inspections, and a conservative detectable crack length ensure eddy current detection of a required crack before limit length is reached.

Comparison of Crack and EDM Slot Response

The conservative approach that has been taken to eddy current crack detection is still open to the question: If an eddy current test system is calibrated with an EDM slot, will the required fatigue crack be detected?

To answer this, it is necessary to review the eddy current response of a crack and an EDM slot. Consider first a large crack. A large crack is defined as a crack with a length and depth greater than the extent of the eddy current field induced in a conductor. Such a crack can be characterized as a nonconducting plane perpendicular to the surface of the conductor. A very tight crack can be represented by an infinitely thin nonconducting plane. An eddy current test probe centered over this infinitely thin crack or nonconducting plane would see no loss in conducting material. However, the induced eddy current field would be interrupted throughout its extension into the conductor by the nonconducting plane. Test coil response to this condition is approximately the same as that produced by a decrease in conductivity. Essentially, the eddy current impedance plane response of a large tight crack would be expected to occur along the conductivity curve in the direction of reduced conductivity.

The opposite extreme to a large infinitely tight crack is a large infinitely wide crack. This condition can be represented by the edge of a conductor. The eddy current response to a large infinitely wide crack is the same as that produced by edge-effect, the change in test coil impedance experienced as the coil crosses the edge of a conductor.

The approximate limit conditions identified for a large tight crack and a large wide crack are the eddy current test coil's conductivity curve and edge effect curve. Figure 3 describes these limit conditions relative to the eddy current test guidelines recommended for surface crack inspection of aluminum airplane structure: shielded pencil probe, 0.12 inch (3.0 mm) in diameter, operating at 200 KHz.

The eddy current detection of a shallow crack presents a different set of conditions. A shallow crack is defined as a crack with a depth less than the depth of eddy current penetration. As the depth of a shallow crack decreases, it interrupts less and less of an induced eddy current.

The strength of an eddy current is greatest at the surface of a conductor, decreasing rapidly with depth. Also, phase angle lag, the delay in the time of eddy current initiation relative to its initiation at the surface of a conductor, increases with eddy current depth below the surface. These two conditions, decreasing eddy current strength and increasing phase angle lag with depth, are described in Figure 4.

A large crack has been identified as a crack that interrupts the combined amplitude and phase of all the components making up an induced eddy current. A very shallow crack interrupts only those eddy current components at or near the surface of a conductor where eddy current strength is greatest and phase angle lag is small.

It has been found experimentally that a shallow crack or slot, with a depth one-third or less that of eddy current standard depth of penetration, generates an impedance plane signal in the direction of the test probe's lift-off signal. As the depth of a shallow crack or slot increases, the angle between the test probes lift-off signal and the crack or slot signal also increases. This angle increases until crack or slot depth is greater than the depth of eddy current penetration. In which case, test conditions are those of a large crack or slot as described in Figure 3.

The approximate response limit of an eddy current signal from a shallow crack or slot is the test probe's lift-off signal as described in Figure 5. In this example, both the EDM slot and the fatigue crack have an estimated depth of 0.020 inch (0.5 mm). Crack and slot depth are approximately one-third of the standard depth of penetration for the 5 KHz test frequency and 29.5 percent IACS test conductor conductivity. The difference in the length of the impedance plane signal between the EDM slot and fatigue crack is the result of crack width. The width of the fatigue crack is estimated at 0.0005 inch (0.013 mm). The EDM slot width is 0.0045 inch (0.11 mm). The eddy current signal from the EDM slot contains a component of edge effect which increased its size.

Limit conditions for the eddy current impedance plane response of deep and shallow cracks that are very tight or very wide have been described. Figure 6 demonstrates these limits using cracks and EDM slots with a range of depths and widths. Test conditions are those commonly used for the eddy current inspection of aluminum airplane structure: shielded pencil probe, 0.12 inch (3.0 mm) in diameter, operating at 200 KHz.

As the width of the large cracks of Figure 6 decrease, their impedance plane signals approach the conductivity curve limit condition for a very tight crack. The signals from the large wide EDM slots closely follow the edge-effect signal limit condition. As the depth of the shallow slots and crack decrease, the closer their eddy current signal is to the lift-off curve.

Use of the EDM Slot for Instrument Calibration

The range in impedance plane crack and slot response described in Figure 6 provides little support for the use of EDM slots to calibrate an eddy current instrument for surface crack inspection. However, before passing judgement, it is necessary to review the eddy current surface crack inspection practice used in airplane structural inspection.

Currently, the impedance plane signal display is not commonly used for eddy current crack inspection of airplane structure. Into the mid-1980's the meter signal display eddy current instrument was used almost exclusively for this purpose.

Today it is estimated that more than 80 percent of eddy current airplane surface crack inspection is performed using meter signal display instruments. It was crack detection experience gained with the meter signal display eddy current instrument that led to acceptance of the EDM slot for instrument calibration.

A characteristic of the meter signal display eddy current instrument is its response to a single component of the test probe's impedance plane signal, usually the vertical component. This characteristic is used to advantage in the calibration of the meter signal display instrument to suppress interference signals caused by test probe lift-off.

Lift-off signals are produced when an eddy current probe is angled or lifted from the surface of a conductor. These signals interfere with crack detection. In practice, lift-off signal suppression is accomplished by adjusting the eddy current instrument's "phase" or "lift-off" control so that little change in meter movement is experienced between test probe in contact with the surface of a calibration standard and when the probe is spaced approximately 0.003 inch (0.075 mm) from the surface. When an eddy current meter signal display instrument is adjusted for lift-off suppression, the corresponding impedance plane signal display will be rotated so the lift-off signal deflects horizontally to the left.

Figure 7 is a the phase rotation of the Figure 6 impedance plane display. The lift-off signal is rotated so that it deflects horizontally to the left. The same lift-off direction that is established when the phase of a meter signal display eddy current instrument is adjusted to obtain lift-off suppression. With this signal orientation, the meter signal display instrument only responds to the vertical component of the related impedance plane display as represented by Figure 7.

The graph of Figure 8 plots the response of an eddy current meter signal display instrument against crack and EDM slot depth. Test samples are the same as those of Figure 7. Test conditions are shielded pencil probe, 0.12 inch (3.0 mm) in diameter, 200 KHz test frequency, and meter instrument phase adjustment for 0.003 inch (0.075 mm) of lift-off suppression. Meter response to the shallow 0.020 inch (0.5 mm) deep crack and slots is similar. Large cracks produce a greater eddy current meter response than large EDM slots. For aluminum alloys, this approximate relationship has been found to exist for eddy current frequencies commonly used in airplane structural inspection, between 100 KHz to 500 KHz, and for shielded and unshielded pencil probes.

The described change in eddy current impedance plane signal with crack or slot width applies to aluminum alloys with conductivity between 25 and 45 percent IACS. Similar eddy current signal change with crack width occurs with the low conductivity alloys and the ferromagnetic steel alloys. Using the calibration guidelines of Figure 9, the response of a meter signal display eddy current instrument with sensitivity calibrated to an EDM slot provides for titanium and steel crack detection comparable to that described for the aluminum alloys.

CONCLUSION

Eddy current surface crack inspection of airplane structure is controlled through test sensitivity established using an EDM slot, and through reference standard alloy selection, test frequency selection, and detailed calibration and inspection procedures. These controls and the conservative position taken on the reliability of eddy current surface crack detection ensure the detection of a required crack before limit length is reached.

In support of crack detection assurance using an EDM slot for sensitivity calibration is a Boeing study on the reliability of airplane lap-splice eddy current inspection.[8] For this inspection, the required detectable crack is 0.1 inch (2.5 mm) long, extending from a lap-splice fastener hole, Figure 10. The Boeing study showed that for the specified eddy current lap splice inspection procedure, using meter signal display eddy current instruments, cracks 0.096 inch and longer were detected with a 90 percent probability of detection (POD) and a 95 percent confidence, Figure 11. For purposes of establishing initial inspection and repeat inspection intervals, the assigned detection probability for the 0.1 inch "required crack" is 0.63. This assigned detection probability does not include the improved crack detection probability that results from multiple cracks in an inspection area.

This discussion has dealt principally with eddy current surface crack inspection using meter display of eddy current signals. Impedance plane display of eddy current signals is finding increased use in airplane structural inspection. Impedance plane signal display has both advantages and disadvantages. There is a definite advantage in having both signal length and direction to identify and evaluate a crack indication. Additionally, the direction and extent of base signal movement permits identification of test variables which can influence test results.

Disadvantages are the eddy current impedance plane response of an EDM slot and a fatigue crack can be significantly different in length and direction. The difference in the impedance plane response by outwardly similar eddy current test probes complexes the problem of establishing reference signal displays and interpretation guidelines. These concerns are being addressed through preparation of detailed eddy current impedance plane inspection procedures and the identification of test probe performance guidelines. The objective is for the same crack detection assurance when using either impedance plane or meter display of eddy current signals.

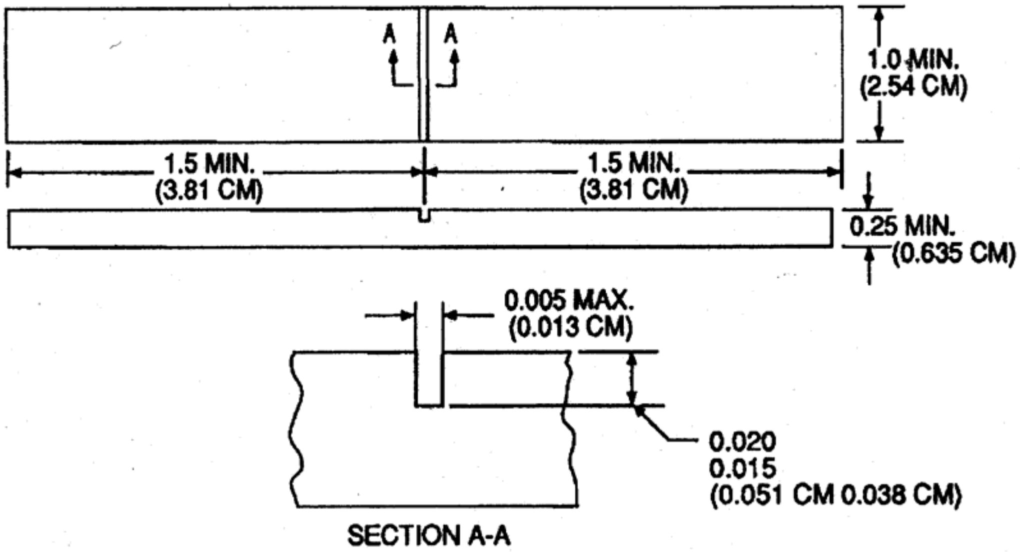

FIGURE 1. EDDY CURRENT SURFACE CRACK REFERENCE STANDARD

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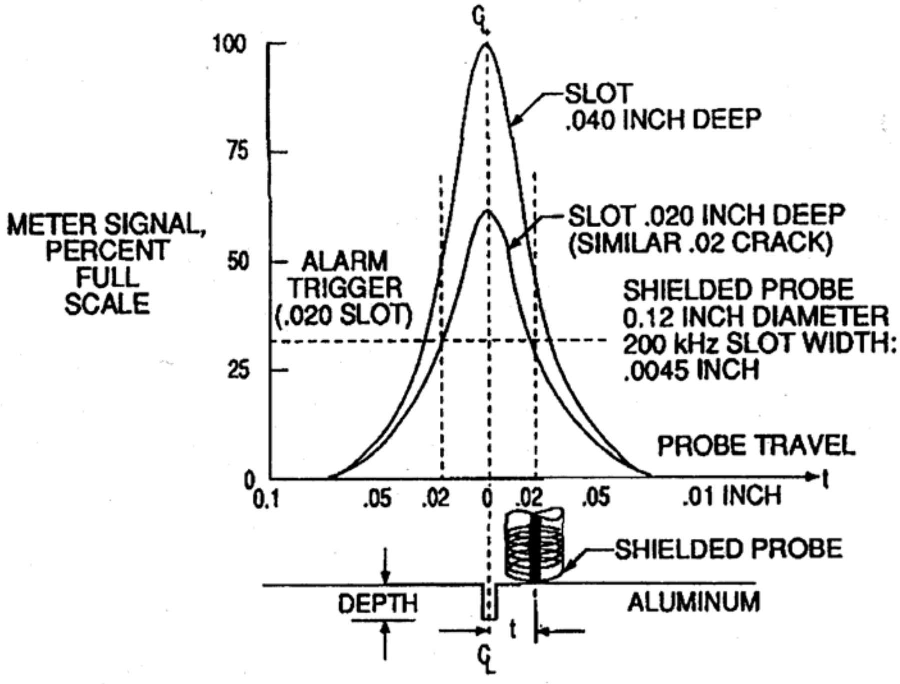

FIGURE 2. EDDY CURRENT METER SIGNAL AS SHIELDED PROBE CROSSES A SLOT OR CRACK OF SIMILAR DEPTH

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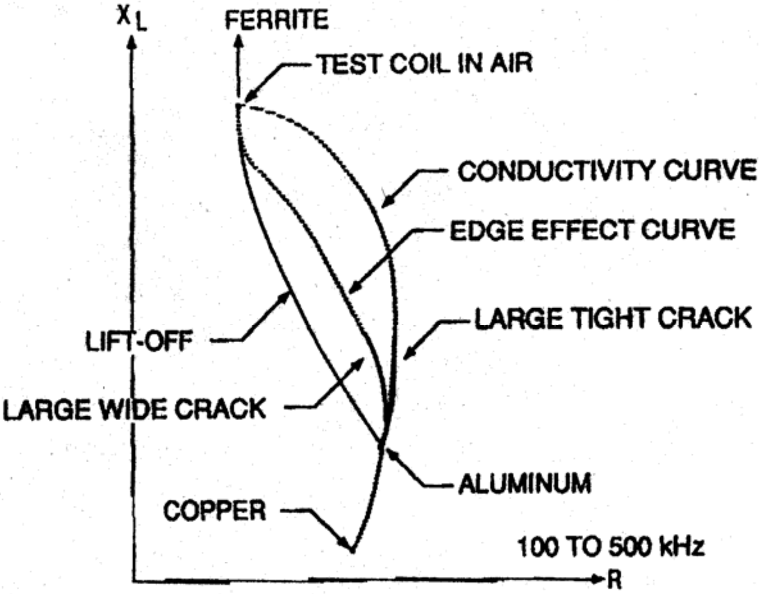

FIGURE 3. LIMIT CONDITIONS, EDDY CURRENT CRACK SIGNALS.

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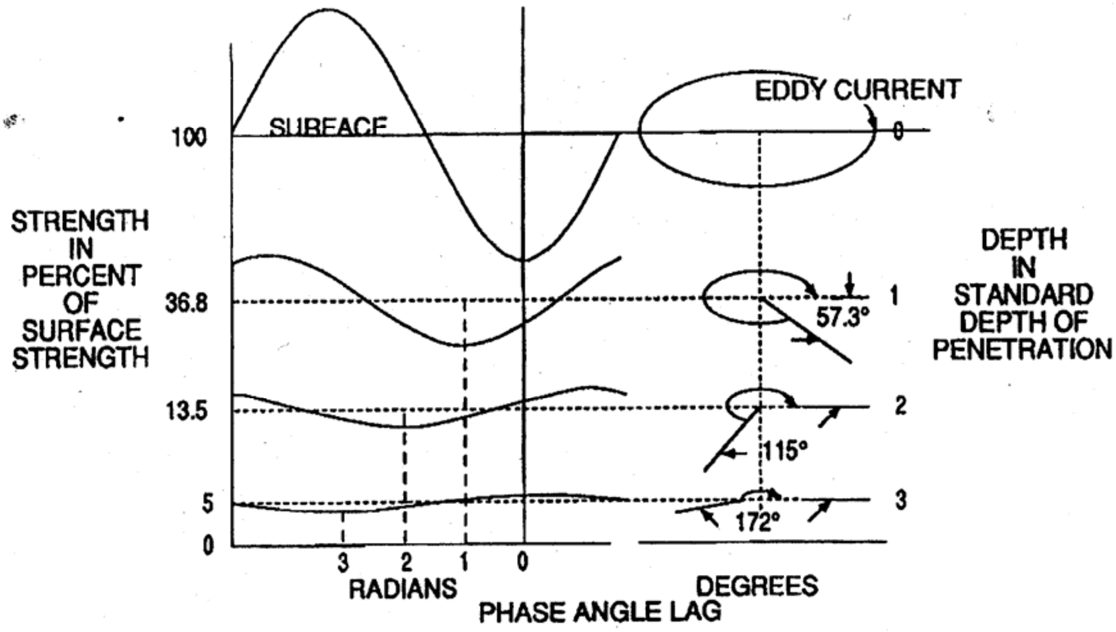

FIGURE 4. EDDY CURRENT DECREASE IN STRENGTH AND INCREASE IN PHASE ANGLE LAG WITH DEPTH

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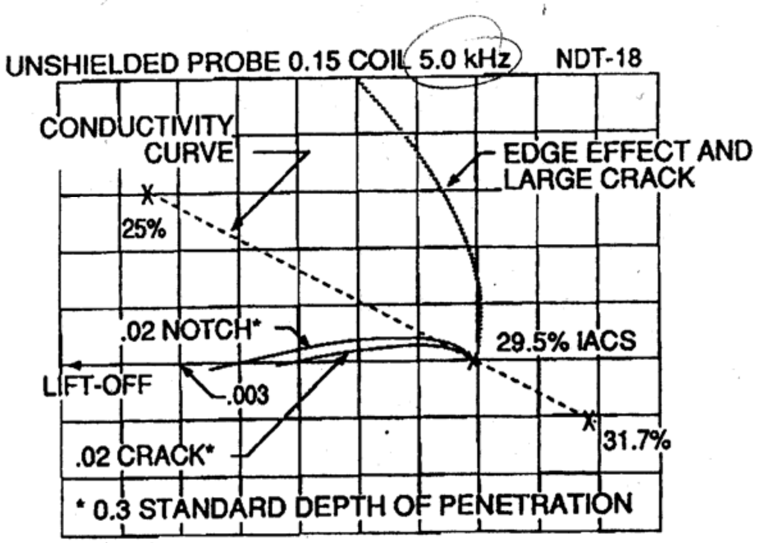

FIGURE 5. EDDY CURRENT SIGNAL FROM A SHALLOW NOTCH AND FATIGUE CRACK

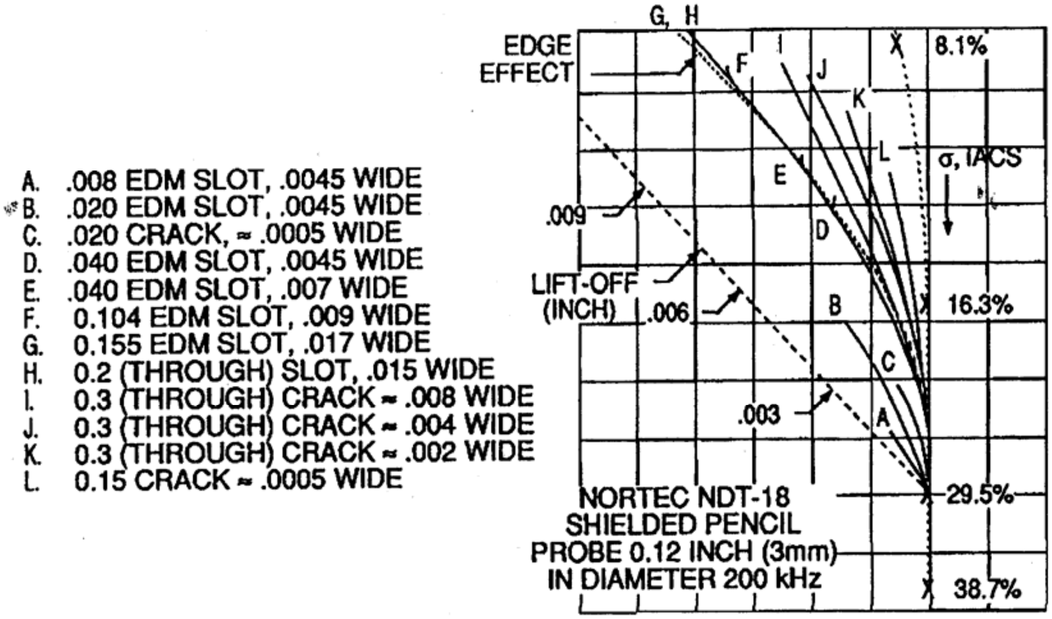

FIGURE 6. EDDY CURRENT IMPEDANCE PLANE RESPONSE OF SLOTS AND CRACKS WITH VARIOUS WIDTHS AND DEPTHS

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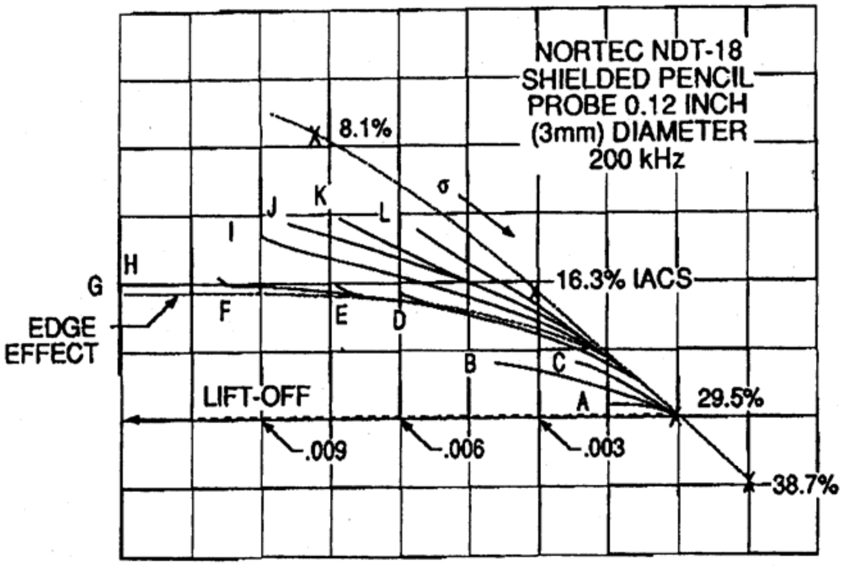

FIGURE 7. IMPEDANCE PLANE SIGNAL DISPLAY OF FIGURE 6 ROTATED FOR HORIZONTAL LIFT-OFF SIGNAL

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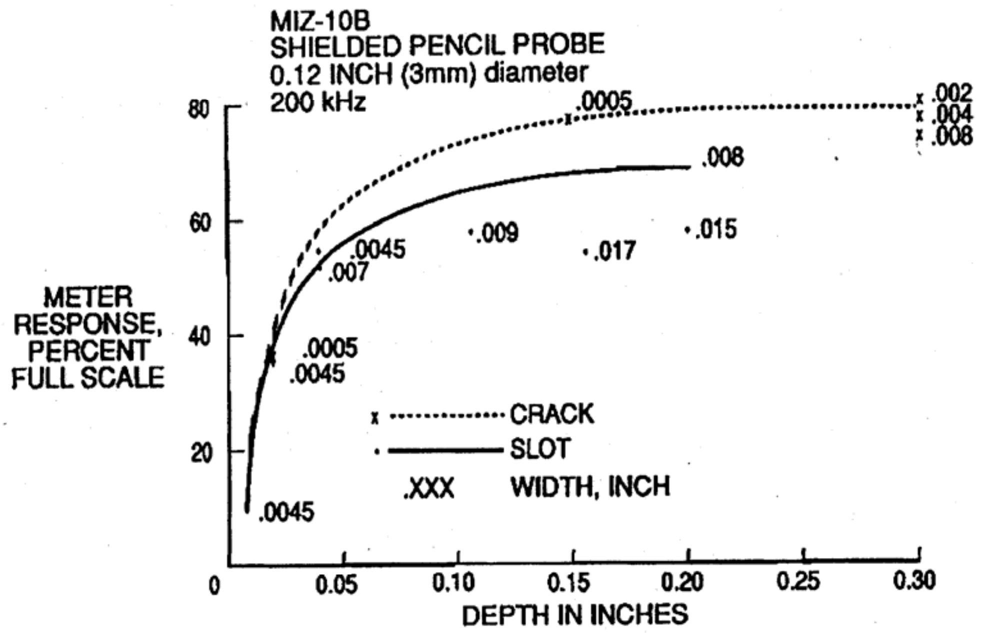

FIGURE 8. EDDY CURRENT METER INSTRUMENT RESPONSE TO SLOTS AND CRACKS IN ALUMINUM ALLOY

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TEST MATERIAL	STANDARD	SLOT DIMENSIONS (INCH)	TEST FREQUENCY
LOW CONDUCTIVITY (0.8 TO 3.5% IACS) TITANIUM ALLOYS	APPROXIMATELY 1% IACS Ti-6AL-4V	DEPTH .025 WIDTH .006 MAX. LENGTH 0.5 MIN.	1 TO 2 MHz
MEDIAN CONDUCTIVITY (25 TO 50% IACS) ALUMINUM ALLOYS	ALUMINUM 30 - 35% IACS	DEPTH .020 WIDTH .006 MAX. LENGTH 0.5 MIN.	100 kHz TO 500 kHz
STEEL ALLOYS FERROMAGNETIC HIGH PERMEABILITY (UNPLATED)	4130 ANNEALED 4340 ANNEALED 4140 ANNEALED	DEPTH .020 WIDTH .006 MAX. LENGTH 0.5 MIN.	100 kHz TO 500 kHz
CROSSION RESISTANT STEEL ALLOYS FERROMAGNETIC LOW PERMEABILITY (UNPLATED)	301 1/2 H	DEPTH .020 WIDTH .006 MAX. LENGTH 0.5 MIN.	100 kHz TO 500 kHz

FIGURE 9. CALIBRATION GUIDELINES FOR EDDY CURRENT SURFACE CRACK NSPECTION

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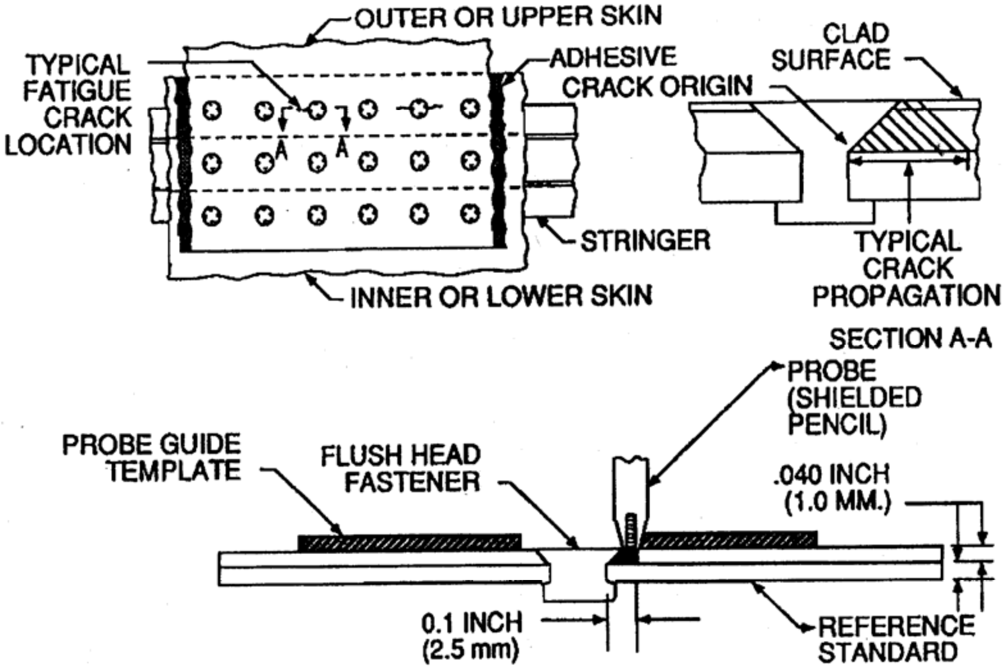

FIGURE 10. LAP-JOINT EDDY CURRENT INSPECTION

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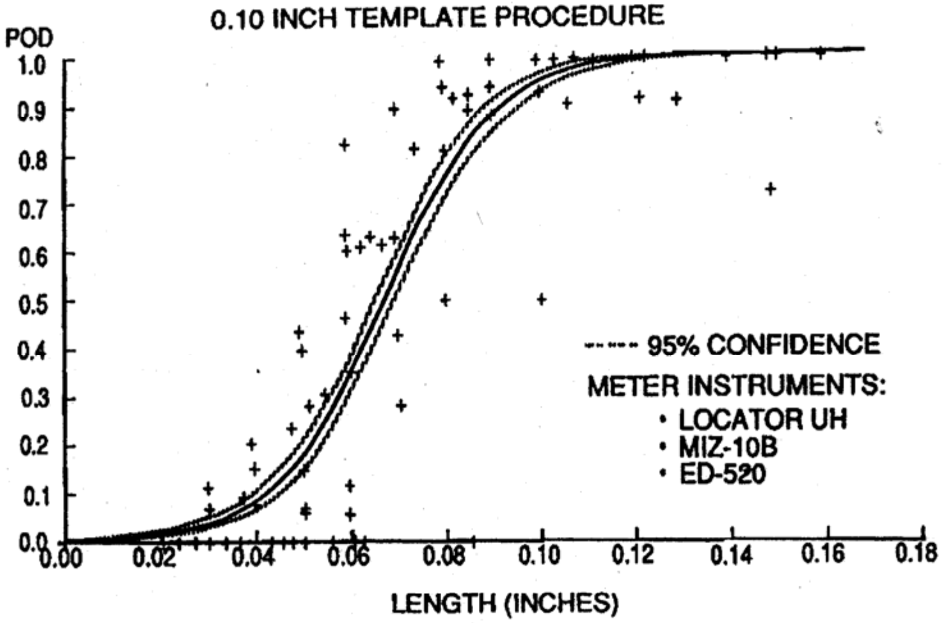

FIGURE 10. DETECTION PROBABILITY AS A FUNCTION OF CRACK LENGTH

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