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DETECTION OF SURFACE-BREAKING CRACKS IN METALS USING A RADIALLY-POLARIZED MICROWAVE PROBE

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ABSTRACT

A novel microwave and millimeter wave method for the detection of surface-breaking cracks in metals is discussed and demonstrated. This technique utilizes a radially-polarized probe to scan a desired surface that may contain such a crack. When a crack is within the probe aperture, the reflection properties of the probe change and thus indicate the presence and location of the crack. The uniqueness of this method is in the fact that the probe consists of a radially-polarized open-ended waveguide, making detection of a crack independent of its orientation relative to the probe polarization vector direction. This is a significant practical advantage when compared with other prominent existing microwave surface crack detection techniques. This method can also be used to detect cracks covered by dielectric layers such as paint and rust. These efficacy of this method is demonstrated through measurements and electromagnetic simulations.

Keywords: Crack detection, microwave nondestructive testing, radially-polarized probe

1. INTRODUCTION

Detection of cracks in metals is an important issue in many industries and applications such as civil infrastructure, utilities and aerospace. There are a number of standard nondestructive testing (NDT) techniques available for this purpose, each with its own limitations and advantages [1]. Microwave and millimeter wave techniques possess certain advantages compared to other techniques, including the ability to detect cracks through dielectric coating layers (such as paint or rust), filled cracks, metal independence, etc. [2-3]. However, these techniques commonly involve the use of a linearly-polarized probe (e.g., an open-ended waveguide) or a radially-polarized open-ended coaxial probe, which is scanned (mechanically or electronically) over the metal surface [2-3]. Linearly-polarized probes, such as the open-ended rectangular waveguide have been demonstrated to have excellent utility for the detection of cracks [4-5], including through dielectric layers, determining crack ends, crack sizing and shallow scratches [4-6]. However, this type of probe is ineffective at detecting cracks when the length of the crack is aligned with the direction of the electric field polarization [4].

The open-ended coaxial probe is not polarization specific (i.e., radially-polarized), making the detection of cracks independent of their relative orientation. However, the open-ended coaxial probe requires electrical contact with the metal surface, and it is very sensitive to perturbations in geometry of the probe, which can occur due to probe construction or environmental effects such as thermal expansion, and thus this type of probe can become impractical [7-10].

A radially-polarized probe, as described here, combines the polarization independence of the open-ended coaxial probe with the practicality of the rectangular waveguide probe. In this paper, the utility of a radially-polarized waveguide probe for detecting surface-breaking cracks in metals is demonstrated through electromagnetic simulations and several experiments.

2. MATERIALS AND METHODS

The radially-polarized probe used in this paper, shown in Figure 1, is an open-ended circular waveguide excited with a TM mode similar to what was done in [11-12]; however, the feed was optimized and fabricated for use in the 15-26.5 GHz range. The simulation and experiments demonstrated in this paper were performed at a frequency of 20 GHz. The probe inner diameter

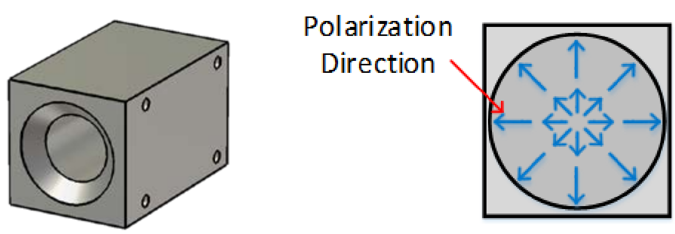

FIGURE 1: FRONT VIEW (LEFT) AND POLARIZATION SCHEMATIC (RIGHT) OF THE DESIGNED RADIALLY POLARIZED PROBE. THE BLUE ARROWS INDICATE THE ELECTRIC FIELD POLARIZATION VECTOR DIRECTION.

is 25 mm. Also shown in Figure 1 is a diagram of the electric field polarization over the probe aperture (i.e., the opening of the probe). Similar to the open-ended coaxial probe, the polarization vector points away from the center of probe. This radial polarization distribution gives the probe its orientation independence.

In order to investigate the utility of this radially-polarized probe for crack detection, it is used to scan across a metal plate with a machined notch in it. Over the course of the scan, the phase of the reflection coefficient seen at the probe aperture is measured. A diagram of the scanning process is shown in Figure 2, in which such a probe is moved in a straight line across the metal plate at a fixed liftoff (distance between the plate and the probe). The scan direction is perpendicular to the length of the crack.

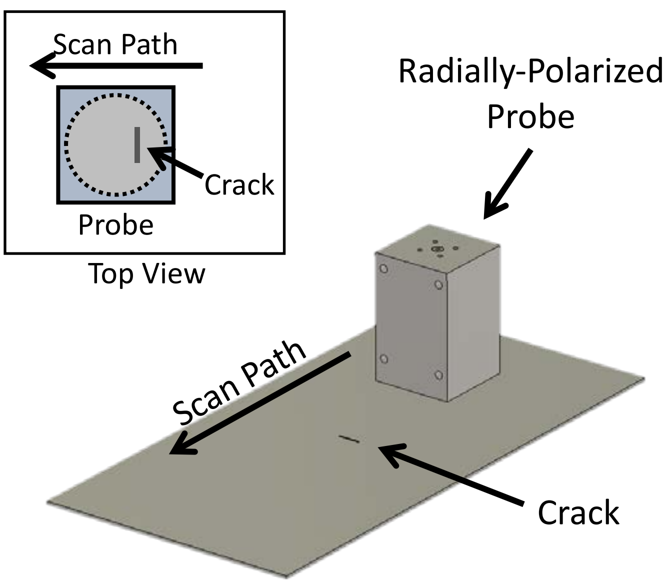

FIGURE 2: DIAGRAM OF THE SCAN PROCESS USED IN SCANS DONE THROUGH SIMULATION.

2.1 Simulations

Scans were performed through electromagnetic simulation using CST Microwave Studio®. A metal plate containing a through notch with a length of 8 mm and a width of 0.5 mm was scanned using the radially-polarized probe at a liftoff of 0.5 mm, and the phase of the reflection coefficient is plotted in Figure 3. The metal plate has a thickness of 3 mm, and thus the notch has a depth of 3 mm. This simulation was repeated with the probe rotated by 90 degrees in order to demonstrate the independence of the probe to the relative orientation of probe and crack. The simulation gives a good idea of what characteristic signal is to be expected in measurement.

2.2 Measurements

The measurements were set up to replicate the simulation as much as possible so that the results could be compared. A metal plate (thickness of 3 mm) containing a through notch with a length of 8 mm and a width of 0.5 mm was scanned using the radially polarized probe. A 60 mm by 60 mm area of the metal plate containing the crack was raster scanned at a liftoff of 0.5 mm to create a 2D image, using an automated scanning platform, using a step size of 2 mm (in both directions) . This process was repeated with the crack rotated 90 degrees to demonstrate polarization independence. The surface of the metal plate was then covered with masking tape, and the scan was repeated.

3. RESULTS AND DISCUSSIONS

3.1 Simulations

Figure 3 shows the simulation results, where the phase of the reflection coefficient calculated at the probe aperture is plotted at each probe location during the 1D scan. The center of the crack is located at the relative position of zero. The vertical dotted lines show the relative positions when the crack enters and leaves the probe aperture (i.e., the opening of the probe). It can be seen that the characteristic signal of the crack consists of two sharp phase peaks that occur when the crack is near either edge of the probe aperture. The characteristic signal is also independent of the probe orientation relative to the crack, as only very small differences between the two plots can be observed. The small variations in phase when the crack is not within the probe aperture is likely due to numerical errors/uncertainties in simulation.

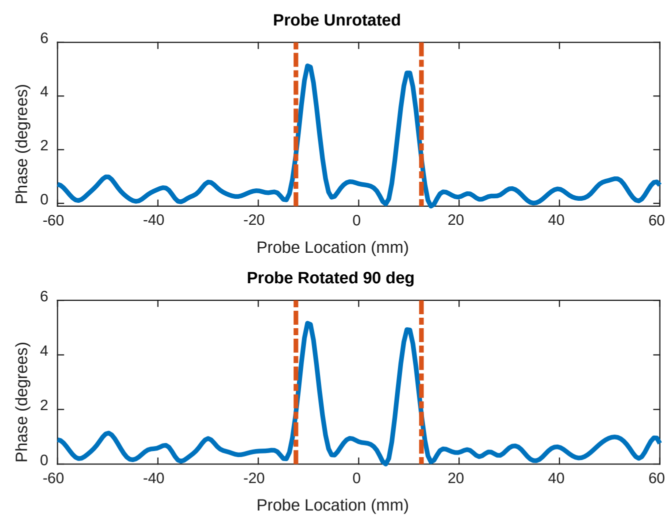

FIGURE 3: SCANS OF THE CRACK MADE THROUGH SIMULATION WITH TWO DIFFERENT PROBE ORIENTATIONS.

3.2 Measurements

Figure 4 shows the images made through the measurements of the metal plate with two orthogonal crack orientations. The images show the phase of the reflection coefficient measured at the probe aperture for each probe location. The center of the crack is located at the origin of each image. The two images are very similar to each other except for rotation, thus illustrating the lack of dependence on polarization direction using this method, unlike a rectangular waveguide probe. The black dotted lines show the scan paths for the plots made through the simulations.

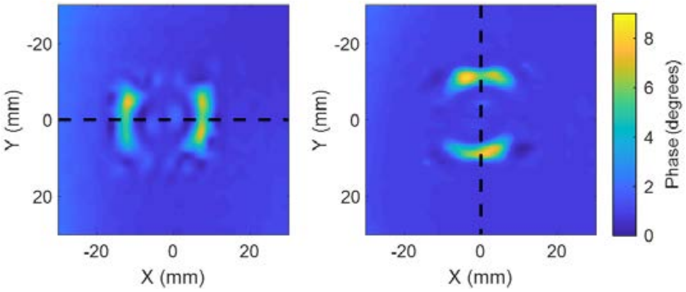

FIGURE 4: IMAGES MADE THROUGH MEASUREMENT WITH THE RADIALLY POLARIZED PROBE OF A VERTICAL CRACK (LEFT) AND A HORIZANTAL CRACK (RIGHT).

Figure 5 shows a line scan along the horizontal dotted line in Figure 4 (left). When compared to the simulation response in Figure 3, the results are very close to what is expected. The two phase peaks are in the same relative location as in simulation. The difference between the phase values in the two peaks is due to an unintended tilt of the probe relative to the metal surface, which causes one edge of the probe to be slightly closer to the crack than the other edge. Additionally, the gradual slope of the measured signal is caused by the slight curvature of the metal plate. In Figure 6, a scan of the crack covered with masking tape (similar in dielectric properties to common paint) can be seen, in which the crack indication is very similar to the uncovered crack shown in Figure 5. This demonstrates the feasibility of this method for detecting cracks through other dielectric layers such as paint or rust.

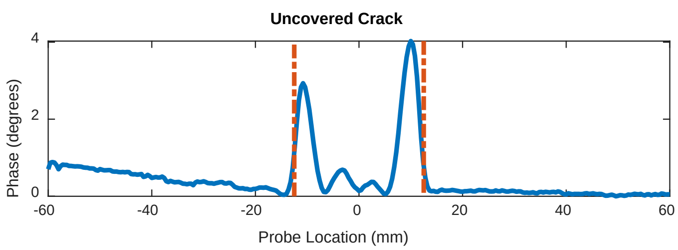

FIGURE 5: SCAN OF THE CRACK MADE THROUGH MEASUREMENT.

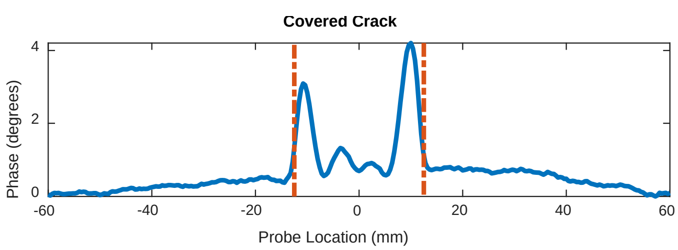

FIGURE 6: SCANS OF THE CRACK COVERED WITH MASKING TAPE MADE THROUGH MEASUREMENT.

4. CONCLUSION

The utility of a radially-polarized probe to detect cracks in metal was demonstrated. Measurements were presented to show the independence of the radially polarized probe to crack orientation, as well as the ability of the probe to detect cracks through dielectric layers. Simulations were also presented to that corroborated the measured crack characteristic signals.

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