NEAR-FIELD MICROWAVE DETECTION OF CORROSION PRECURSOR PITTING UNDER THIN DIELECTRIC COATINGS IN METALLIC SUBSTRATE

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ABSTRACT. Detection of corrosion precursor pitting on metallic surfaces under various coatings and on bare metal is of keen interest in evaluation of aircraft fuselage. Near-field microwave nondestructive testing methods, utilizing open-ended rectangular waveguides and coaxial probes, have been used extensively for detection of surface flaws in metals, both on bare metal and under a dielectric coating. This paper presents the preliminary results of using microwave techniques to detect corrosion precursor pitting under paint and primer, applique and on bare metal. Machined pits of 500 µm diameter were detected using open-ended rectangular waveguides at V-Band under paint and primer and applique, and on bare metal. Using coaxial probes, machined pits with diameters down to 150 µm on bare metal were also detected. Relative pit size and density were shown on a corrosion-pitted sample using open-ended rectangular waveguides at frequencies of 35 GHz to 70 GHz. The use of Boeing’s MAUS™ scanning systems provided improved results by alleviating standoff variation and scanning artifact. Typical results of this investigation are also presented.

INTRODUCTION & BACKGROUND

Detection of corrosion is a critical issue in determining the lifetime of metallic aircraft components exposed to environmental degradation. Often, the detection of corrosion is further complicated by the presence of paint and primer, where the presence of corrosion cannot be visibly determined until bubbling begins to form under the paint. The generation of corrosion is preceded by the presence of corrosion precursor pitting. If this pitting can be detected before significant corrosion occurs, the extent of corrosion and area which requires repair will be greatly reduced. Thus, early detection of the presence of corrosion precursor pitting under paint and primer is of great importance in the aircraft industry. The objective of this investigation is to determine the feasibility of using near-field microwave nondestructive testing (NDT) techniques for the detection of corrosion precursor pitting, and to investigate the minimum detectable size of pitting for a given range of frequencies.

Near-field microwave NDT techniques, utilizing open-ended rectangular waveguide

1 MAUS is a registered trademark of The Boeing Company.
probes, have been shown to detect the presence of corrosion under paint and primer in both steel and aluminum substrate, including the spatial extent of the corrosion [1-4]. Furthermore, the presence of corrosion pitting has been seen under paint and primer in aluminum substrates [4]. There are several advantages that make the use of microwave NDT techniques suitable for the detection of corrosion precursor pitting under paint and primer. Near-field microwave techniques have been shown to be sensitive to small surface indentations in metals, such as scratches, cracks, pitting and dents [5-9]. Microwave signals are sensitive to changes in material properties, such as the presence of corrosion. Microwave signals are capable of penetrating dielectric materials, such as paint and primer, and measurements can be made in a one-sided and non-contact fashion. Furthermore, high spatial resolution can be obtained, and the spatial extent of damage can be determined with no or minimal use of signal processing. Finally, since microwave signals are totally reflected of the metallic substrate, the type of metal on which corrosion is being detected is of no consequence.

SAMPLE PREPARATION

For this investigation, two 12” x 12” aluminum samples were prepared. Figure 1 shows the first sample which contains three identical sets of machined pits, ranging from 500 μm in diameter to 100 μm in diameter, and 500 μm in depth to 25 μm in depth. This sample contained one set of pitting under paint and primer, one set under applique, and one set on exposed metal. The second sample was allowed to corrode in a salt fog chamber until the presence of precursor pitting was seen. The corrosion product was then removed, and one side of the sample was painted, while the other side remained exposed. This resulted in actual precursor pitting ranging in diameter up to approximately 1 mm, with negligible corrosion product.

MEASUREMENT APPROACH

Laboratory-designed microwave reflectometers operating at Ka-Band (26.5 - 40 GHz) and V-Band (50 - 75 GHz) were primarily utilized for this investigation. These correspond to aperture dimensions of (7.11 mm x 3.56 mm) and (3.8 mm x 1.9 mm) for Ka-Band and V-Band, respectively. In addition, the use of two waveguide transitions were investigated, namely Ka-Band to U-Band (40 - 60 GHz), and V-Band to W-Band (75 - 110 GHz), which corresponds to smaller apertures of dimension (4.8 mm x 2.4 mm) and (2.54 mm x 1.27 mm), respectively. While the frequencies used were not in the range of the
higher bands, they were still above the cutoff frequency of the transitions. The use of these transitions allowed for the decrease in the aperture dimensions, while maintaining a relatively low frequency. This allowed for increase in spatial resolution, while keeping sensitivity to variations in standoff distance relatively minimal. This setup provided the capability of changing several parameters for increasing the detection of pitting, primarily the frequency of operation, the standoff distance, aperture dimensions and angle of incidence.

Limited measurements were also performed utilizing an open-ended coaxial probe. Previous investigations have shown that open-ended coaxial probes are capable of detecting thin cracks on exposed metal surface [9]. This portion of the investigation is by no means complete, and was only performed to determine the potential of using these probes.

RESULTS

The results of this investigation are shown as 2-D raster scan images, obtained using either a 2-D scan table or the MAUS™. In some cases, simple mathematical processing of the data was performed to partially eliminate the adverse effect of standoff variation.

Ka-Band Results

Most measurements performed at Ka-Band were conducted at 35 GHz. At this band, the machined pitting could not be adequately detected under paint, applique, or on bare metal. Thus, measurements were performed on the corroded-pitted sample at this frequency. These measurements were conducted using the U-Band waveguide transition.

Figure 2 shows the result of a scan made of an individual pit on the corrosion-pitted sample. As can be seen, the presence of the pit can be easily detected, and the scan produces a distinct image associated with the pit. As shown in the image, two small points surrounded by partial circular rings represent the presence of the pit. It is assumed that the two small points correspond to the edges of the pit, and the spacing of which may increase or decrease (to a single point) as a function of the pit diameter, the frequency of operation and the transition aperture dimensions. The rings are not complete circles because of the linear polarization of the waveguide. As can be seen, the signal produced, including the rings, is larger than the physical size of the pitting. This is advantageous, since the scans produced a signal due of pitting which is larger than the physical size of the pit.

![FIGURE 2. Scan of an individual corrosion pit at 35 GHz with a U-Band waveguide transition.](image-url)
FIGURE 3. Scan of a lightly pitted area (a) and heavily pitted area (b) of the corrosion-pitted sample, scanned at 35 GHz using the U-Band waveguide transition.

Figure 3a shows a 50 mm x 50 mm, lightly pitted area located on the corrosion-pitted sample. As can be seen, individual pits can be easily detected, and the relative size and location of these can be inferred. Figure 3b shows a more heavily pitted area on the same sample. This image shows that relative size and density of heavily pitted areas can be seen. As can be seen in both of the images, the signal characteristic of pitting from Figure 2 is present for each individual pit.

Figure 4a shows a scan performed on the corrosion-pitted sample using the MAUS™ scanning system, at 35 GHz with the U-Band adapter. As can be seen, similar results were obtained using this scanning system to those obtained using the laboratory scan tables. Scanning artifacts, which were present as small vertical ripples in the images produced using the scan table above, are not seen in the images produced using the MAUS™. Thus, smaller pits and features, which were masked from scanning artifacts, can be detected using this setup. For comparison, Figure 4b shows a scan of roughly the same area using a typical eddy current probe. As can be seen, the microwave probe could detect surface pitting comparably well with eddy current techniques.

FIGURE 4. Scan of the corrosion-pitting sample scanned using the MAUS™ with a 35 GHz waveguide probe with U-Band waveguide transition (a), and using a typical eddy current probe (b).
**V-Band Results**

Measurements were performed on the machine-pitted sample at 65 GHz and 70 GHz, utilizing the W-Band waveguide transition. These measurements showed that, at these frequencies, 500 μm-diameter pits and with depths of 500, 200 and 150 μm could be detected on bare metal, under paint and primer, and under applique. Figure 5 shows a scan of the 500 μm-diameter pits under paint, scanned at 70 GHz with the waveguide transition, and at near contact. Figure 6 shows the results of the same row of pits under a layer of applique, scanned using the same parameters. In both figures, the indication of the 500, 200 and 150 μm-deep pits can be seen from left to right in the image, respectively. While the pitting can be distinguished in the scans, variations in paint thickness, surface roughness, scratches in the metal, standoff variation and scanning artifacts provide clutter which may mask the indication of smaller pits, making detection of these difficult or impossible. As seen with the Ka-Band results, the use of the MAUS™ may alleviate some of these problems.

Tests were performed on the corrosion-pitted sample using a 65 GHz probe with the waveguide transition. Figure 7 shows the results of a scan of a small pit on the corrosion-pitted sample, scanned at a standoff distance of 2.5 millimeters. Figure 8 shows a scan of a small pit located on a scratch in the metal. As can be seen in both cases, the characteristic pit image distinctly gives an indication of the pit and, in the case of Figure 8, the presence of a scratch does not significantly mask this signal.

**Coaxial Results**

Limited investigations were performed utilizing an open-ended coaxial probe for the detection of pitting on exposed metal surfaces. Scans were performed on the machined-pitted sample at 35 GHz, with the coaxial probe in contact with the surface of the plate. The frequency and standoff were by no means optimized, and this investigation was only performed to determine the potential of this type of probe.

Figure 9a shows a scan of the 500 μm-diameter, 150 μm-deep pit on exposed metal. The pit can be seen clearly in the center of the image. The spot in the top-left of the image may have been due to a scratch on the surface of the metal. Figure 9b shows a scan of the

![Figure 5](image1.png)  **FIGURE 5.** Raster scan of three 500 μm machined pits with depths of 500, 200 and 150 μm from left to right under paint and primer, scanned at 70 GHz with the W-Band waveguide transition.

![Figure 6](image2.png)  **FIGURE 6.** Raster scan of three 500 μm machined pits with depths of 500, 200 and 150 μm from left to right under applique, scanned at 70 GHz with the W-Band waveguide transition.
200 μm-diameter, 150 μm-deep pit. Again, the pit can be easily detected at the center of the scan. Figure 9c shows a scan of the 150 μm-diameter, 150 μm-deep pit. The spot in the center shows the presence of the pit, and the two spots on the lower right are due to a scratch near the vicinity of the pit. Smaller diameter pits were also scanned, however, the results did not distinctly show the presence of a pit.

FIGURE 7. Scan of a corrosion pit at 65 GHz using a W-Band waveguide transition.

FIGURE 8. Scan of a corrosion pit located on a scratch on the plate, scanned at 65 GHz using a W-Band waveguide transition.

FIGURE 9. Scan of a 500 μm diameter (a), 200 μm diameter (b) and 150 μm diameter (c), 150 μm deep machined pit on bare metal, scanned at 35 GHz using a coaxial probe.
CONCLUSION

The results of this investigation have shown that, using near-field microwave techniques, pitting can be detected on bare metal, under paint and primer, and under applique. However, there is a limit to the size of pit that can be detected, based upon the frequency of operation and the probe used. Using open-ended rectangular waveguides, with a waveguide transition, it was possible to detect machined pits with a diameter of 500 μm, and as shallow as 150 μm. These pits could be detected on bare metal and under both types of coating at 70 GHz with a W-Band waveguide transition. However, at 35 GHz with a U-band transition, the indication of these pits could not be seen. Using an open-ended coaxial probe operating at 35 GHz, pits could be detected with diameters of 500, 200 and 150 μm, and depths as shallow as 150 μm. However, using a coaxial probe, pitting was shown to be detected on bare metal, and the probe needs to be very near-contact with the surface of the plate.

The results from the corrosion-pitted sample showed promising results at 35 GHz with a U-Band waveguide transition. It was shown that relative pit location, pitting density, and size can be determined from raster scans. Furthermore, the presence of scratches and slight corrosion product did not obscure or mask the pitting signals. The results obtained for surface pitting using the microwave probes compared well with those obtained using a standard eddy current probe.

Standoff variation and scanning artifacts cluttered many of the scans performed using the laboratory 2-D scanning table. These effects may obscure or completely mask the signals generated from pitting, and may render detectable pits undetectable. The use of Boeing’s MAUS™ scanner alleviated both of these problems quite well. This is reflected in the scans performed using the MAUS™ when compared with the 2-D scanning table.

Overall, the results are very encouraging. The use of near-field microwave techniques, utilizing open-ended rectangular waveguides, can be used to detect the presence of surface pitting in metal under paint and primer, under applique, or on bare metal. The images generated from 2-D raster scans can show relative pit size, density and spatial location. A further application may involve using this technique to determine if removal of surface pitting is complete during repair.

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REFERENCES


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