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Measurement Parameter Optimization for Surface Crack Detection in Metals Using an Open-Ended Waveguide Probe

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Abstract - *Fatigue and stress induced surface crack detection in metals is an important practical issue. A newly developed microwave inspection approach, using an open-ended rectangular waveguide, has proved to be an effective tool for detecting such cracks. This novel microwave approach overcomes some of the limitations associated with the standard detection methods for surface crack detection. In addition, this approach is applicable to exposed, filled (with a dielectric such as dirt, rust, etc.) and cracks under dielectric coatings such as paint. This paper presents the basic foundation of this surface crack detection methodology along with the ways by which measurement parameters may be optimized for increased detection sensitivity.*

I. INTRODUCTION

Metal fatigue or failure usually begins from the surface. Aircraft fuselage, turbine blades and steel bridges are examples of environments in which this type of metal failure occurs. Hence, surface crack detection on metallic structures is of utmost importance to the on-line and in-service inspections of metallic components. There are many conventional nondestructive testing (NDT) methods used for interrogating metal surfaces, however, each method possesses certain limitations and disadvantages (such as acoustic emission, dye penetrant, eddy current, ultrasonics, radiography techniques, using x- or gamma radiation, and magnetic particle testing) [1].

There have been several researchers who have attempted using microwaves for surface crack detection in metals, achieving modest success [2]. None of these techniques, however, have dealt with filled and covered cracks. In addition, these techniques have not shown crack characterization capabilities such as dimension determination, tip location identification, etc.

Recent discoveries in using open-ended rectangular waveguides for microwave surface crack detection and sizing have generated much renewed interest in this area [3-7]. Microwave techniques offer certain advantages over the standard techniques, namely:

- the method is fast, reliable and relatively inexpensive,
- the sensor may or may not be in contact with the surface under examination offering the possibility of remote inspection,
- cracks may be filled or covered with dielectric materials such as paint, dirt, rust, etc.,
- cracks may be on non-ferromagnetic as well as ferromagnetic metals or alloys,
- microwave techniques work with coarse-grained materials,
- the detected signal is only due to surface defects and not to interior flaws (i.e. easier signal interpretation),
- the dimensions of a crack as well as orientation, edge and tip locations can be evaluated,
- no special operator skills or surface preparation are required,
- the technique is environmentally compliant and operator friendly and safe (low microwave power),
- such a system may be battery operated and portable and the results are obtained in real-time,
- theoretical modeling provides for prior-to-detection measurement parameter(s) optimization.

II. BASIC APPROACH

Fig. 1 shows the geometry of a crack with a width of w, a depth of d and a length of L and a waveguide aperture when the crack length is parallel to the broad dimension of the waveguide. δ, the scanning distance, is a dimension indicating the position of the crack relative to an arbitrary location

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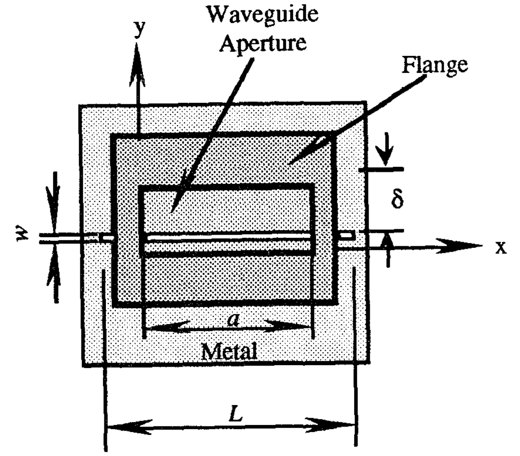

Fig. 1. The relative geometry of a surface crack and an open-ended waveguide aperture.

on the small dimension of the waveguide aperture.

"Crack characteristic signal" is referred to the detector voltage variations as a function of scanning distance, *δ*, when a waveguide aperture is scanned over a crack. The detector is located at some distance away from the waveguide aperture probing the standing wave pattern inside the waveguide. Fig. 2 shows the characteristic signals for two long (length greater than the broad dimension of the waveguide aperture) cracks milled on an aluminum surface with a width of 0.28 mm and two different depths of 0.96 mm and 1.49 mm, respectively, at 24 GHz. Different attributes of this approach have been published elsewhere, in addition to two electromagnetic models that have been developed for this inspection methodology [3,5]. Fig. 3 shows the comparison between the modeling and experimental results for a crack with a width of 0.55 mm and a depth of 2.5 mm at 24 GHz. One of the most important issues associated with this inspection method is the optimization of measurement parameters. These parameters include the frequency of operation, location of the detector on the standing wave pattern, dielectric fillers and coatings filling and covering the crack and the incident power.

III. MEASUREMENT OPTIMIZATION RESULTS

The results of optimization of the measurement parameters are given in this section.

A. Detector Position

The diode detector that probes the standing wave properties inside the waveguide is usually located exactly in the middle of the standing wave maximum and minimum [3]. However, this location may be changed for increased detection sensitivity. This feature is illustrated in Fig. 4 which shows the normalized (with respect to the short circuit value) crack characteristic signals for a crack, in a steel plate, with a width of 0.15 mm, a depth of 1.55 mm, recorded at 34.8 GHz, for two diode locations. One location coincides with the minimum of the standing wave pattern (indicated as "0" in the Fig.) and the other with a location at which the standing wave voltage is 25% of its maximum value (indicated as "0.25" in the Fig.). Therefore, we may conclude that the diode position is not only an important parameter for increasing crack detection sensitivity, but also that there may be more than one location that may be considered optimal.

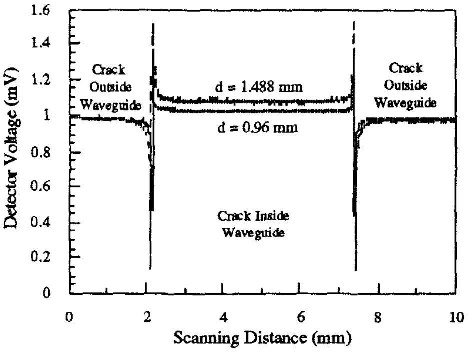

Fig. 2. Crack characteristic signals for two cracks with different depths at 24 GHz.

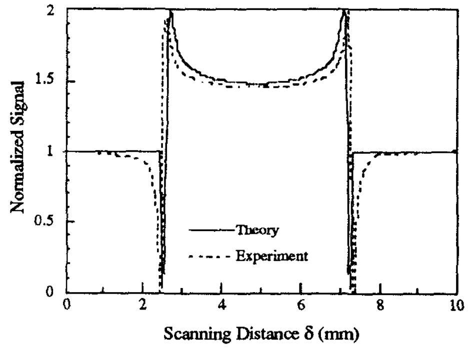

Fig. 3. Comparison between the theoretical and experimental results.

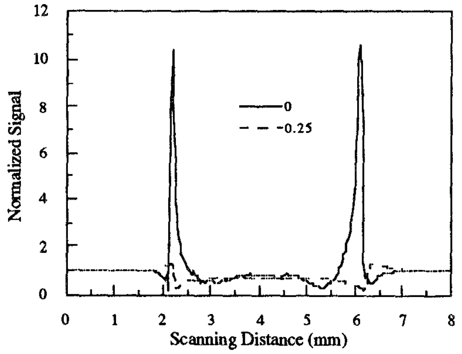

Fig. 4. Influence of detector position on the crack characteristics signal.

B. Filled Cracks

As shown in Fig. 2, the signal level in the middle of the crack characteristic signal is primarily a function of crack depth. This means that for cracks of certain depths it is possible that the short circuit signal level and the signal level in the middle of the crack characteristic signal be very similar. In such cases the crack is rendered not detected. However, if the crack is filled with some dielectric material, its electrical depth is changed and the difference between the two signal levels mentioned earlier increases which makes the crack detectable. Fig. 5 shows the crack characteristic signals for an empty and a rust filled crack with a width of 0.51 mm and a depth of 6 mm at 24 GHz. Clearly, once the crack is filled its detection becomes easier. This approach may be used in complement to the dye penetrant method.

C. Operating Frequency

Frequency of operation is another important optimization parameter. Given specific waveguide dimensions, the choice of frequency may be important for detecting surface cracks. If a crack is considered to be a cavity, it is expected that depending on the dimensions of cavity its resonant characteristics change as a function of frequency. Therefore, even within a given waveguide band a particular frequency may be more important than all others. Fig. 6 shows the crack characteristic signals for a crack with a width of 0.2 mm and a depth of 2.5 mm at three different frequencies in X-band region. The results clearly show that at a frequency of 12 GHz the crack characteristic signal renders the crack much easier detectable.

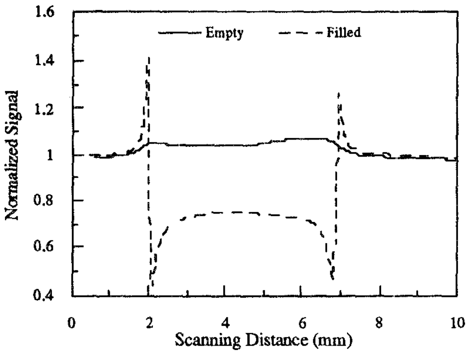

Fig. 5. Crack characteristic signals for a crack when empty and when filled with rust powder.

D. Covered Cracks

When a crack is covered with a dielectric coating such as paint, this microwave approach is still able to detect the crack since microwave signals penetrate inside dielectric coatings. Furthermore, when a crack is covered with a dielectric coating the incident microwave signal interacts with the crack edges before the aperture edges coincide with the crack edges (i.e. the crack edges are detected before the waveguide comes over the crack). This results in the widening of the crack characteristic signal's sharp transitions. Therefore, one may not need a high resolution scanner when detecting covered cracks. This also means that a thin layer of a dielectric material may be used to cover the probing waveguide aperture for enhancing crack detection. Fig. 7 shows the crack characteristic signals for a crack with a width of 0.51 mm and a depth of 2 mm at 24

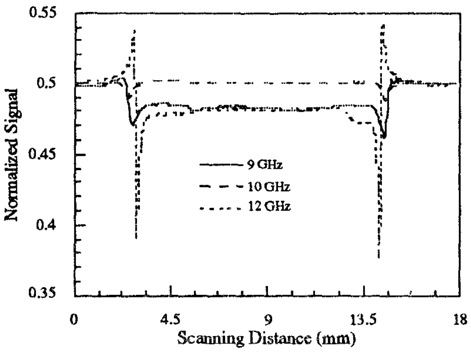

Fig. 6. The influence of operating frequency on crack characteristic signal.

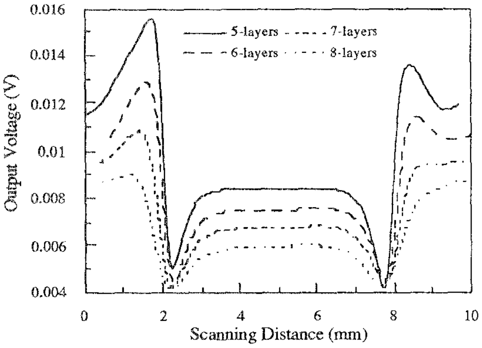

Fig. 7. Crack Characteristic signals for a crack covered with four different layers of wrapping paper (0.12 - 0.24 mm-thick).

GHz when covered with multiple layers of wrapping paper whose dielectric properties are similar to common paint.

E. Incident Power Level

When detecting cracks under coatings and depending on the coating thickness and its dielectric properties (i.e. electrical thickness) the magnitude of the reflected signal from the crack may be in the order of system noise, thus rendering the crack undetectable. However, this problem may be alleviated by increasing the incident power level. Since, the foundation of this approach is based on the properties of the reflection coefficient at the waveguide aperture, increasing the incident power level increases the reflected signal level while the reflection coefficient remains constant. To illustrate the utility of increased incident power, a crack in steel with a width of 0.2 mm and a depth of 1.5 mm was covered with 1.36 mm-thick of wrapping paper. The crack characteristic signal for this case was obtained at 17 GHz for four different incident power levels, as shown in Fig. 8. Clearly, the typical crack characteristic signal begins to appear once the incident power level has exceeded 8 dBm. Therefore, incident power may be used as an optimization parameter for enhanced crack detection. It is very important to note that all four power levels used in this case are very low.

IV. CONCLUSIONS

The basic attributes of a novel microwave approach for detection and characterization of surface cracks in metals were discussed. There are several measurement parameters that may be used as optimization parameters for increased crack detection sensitivity. The influence of these parameters on crack detection sensitivity on various cracks milled in aluminum and steel specimens was demonstrated.

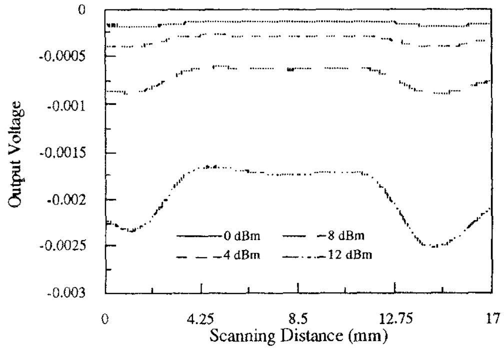

Fig. 8. Crack characteristic signals for a crack in steel covered with 1.36 mm-thick wrapping paper for four different incident power levels.

ACKNOWLEDGMENT

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