OPTIMIZATION OF A PORTABLE MICROWAVE INTERFERENCE SCANNING SYSTEM FOR NONDESTRUCTIVE TESTING OF MULTI-LAYERED DIELECTRIC MATERIALS

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ABSTRACT

A portable microwave interference scanning system has been demonstrated to detect damage in composite ceramic armor test specimens including engineered features in specially fabricated surrogates. The system has been optimized for detection of identified features in sample specimens. The system has been optimized for portability and field application flexibility, including miniaturization and wireless interfacing of it components.

Composite ceramic armor is employed in the form of plate inserts in garments and seats; in panels in vehicles, aircraft and vessels; and as an appliqué in armored vehicles. Effectiveness of ceramic armor can be degraded by defects present from production and by operational damage resulting from handling or impact with objects in the environment, other than projectiles. In normal use, ceramic armor is routinely exposed to the possibility of such damage.

The microwave interference scanning technique detects and images internal cracks, internal laminar features such as disbonds and variations in material properties such as density. It requires access to only one surface, and no coupling medium. Other NDE methods, including through-transmission x-ray, x-ray Computed Tomography, and destructive examination, are used to verify defects and other detected anomalies. The development of this portable system will provide a suitable method for in-theatre health monitoring of composite ceramic armor.

The Wireless Hand Held Prototype system is shown in Figure 1. The correlation between the microwave interference scanning image scan of the artificially cracked tile (center) and a through-transmission x-ray image of the same tile (right) is shown in Figure 2. A photograph of the face of the damaged region of the armor panel is shown in Figure 2 on the left. The wide, light gray patterns with dark edges in the microwave image are interference patterns centered on the crack centerlines which are identified with red marker lines.

Work has shown that detected damage level data are not affected by outer covering layers. Test panels used in this work were provided by the US Army Tank-Automotive Research, Development and Engineering Center (TARDEC), by the US Army Research Laboratory, and by the Ballistics Testing Station through Argonne National Laboratory. This paper will describe the system and present current results.

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Figure 1. Prototype Wireless Handheld System.

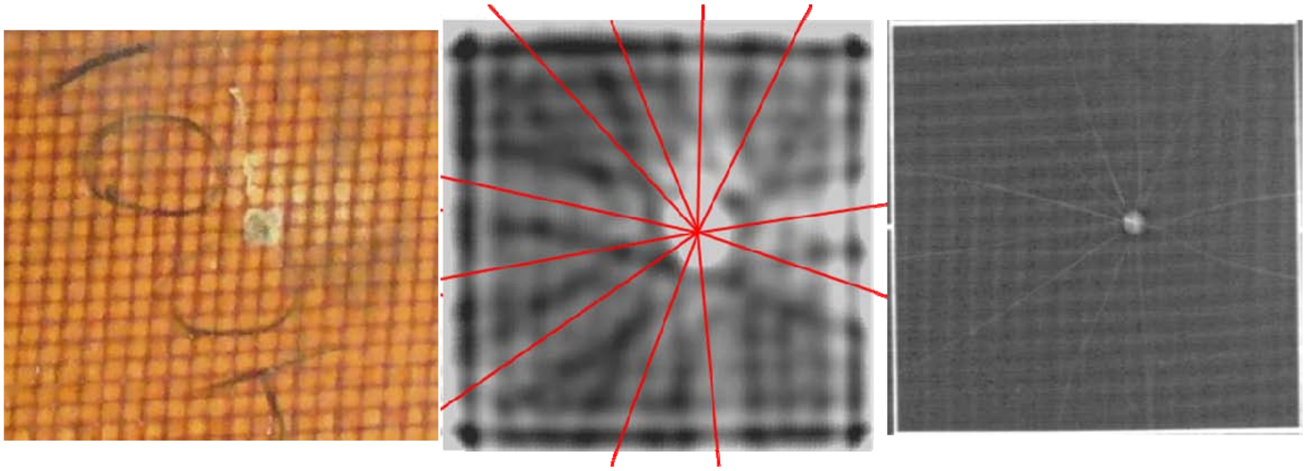


Figure 2. Photograph (left), microwave interference scan image (center) and x-ray image (right) of an artificially cracked tile in an armor panel.

1. INTRODUCTION

The microwave interference scanning technique has been successfully demonstrated on armor panels constructed of high-performance technical ceramics. The ceramic armor is employed in the form of plate inserts in garments and seats; in panels in vehicles, aircraft and vessels; and as an appliqué in armored vehicles. Ceramic armor provides effective and efficient erosion of and defeat of ballistic threats. Effectiveness of ceramic armor can be degraded by defects present from production and by operational damage resulting from handling or impact with objects in the environment, other than projectiles. In normal use, ceramic armor is routinely exposed to the possibility of such damage (Salem et al, 2007).

A means to detect damage and manufacturing defects which are not visually apparent is needed to determine the integrity of the ceramic armor so that appropriate replacement can be made. Recently, a microwave-based method, having US and international patents (Little, 2002, 2003, 2005, 2007), has been developed and demonstrated that is as applicable to ceramic armor systems (Schmidt et al 2009). Applications development has included optimization of antenna – material interaction, and miniaturization of the microwave interferometry system. The method permits real time evaluation by inspection from one surface only, through non-contacting encapsulation, with panels hung in place.

2. DESCRIPTION OF THE METHOD

Theinterference scanning method requires access to only one side of a part. The microwave interference pattern is created by bathing the part in microwave energy as illustrated in Figure 3. The probe (transmitter and receiver antenna) is moved over the part, bathing it in microwave energy. Some energy is reflected and transmitted at every interface of changing dielectric constant in the field of the transmitter. This includes the front and back surfaces of the part, and every "feature" in the part that has a discontinuity in dielectric properties. A microwave interference pattern is created when the reflected energy is combined with the transmitted signal to create the measured detector voltage at each of the receivers. The voltage values for both receivers are saved with the associated X-Y position on the object.

The combination of dielectric constants of the engineered ceramic materials and the microwave frequency used in the tests yields wavelengths in the material of about 8 mm (0.33 inches) to 20 mm (0.83 inches). The magnitude of the phase difference between the emitted signal and reflected signal determines the voltage of the signal. This interference pattern is illustrated by the response from a 2.5 mm (0.10 inch) spherical conductive reflector shown in Figure 4.

Hardware Channels A and B are separated by a quarter wavelength ($\lambda/4$) in the wave propagation dimension, Z. In any "image" data, the rate of change of the detected signal value impacts the "clarity" of that image. This is true for detected Z axis features as well. Thus the "image" data of a feature is optimized visually at a Z dimension associated with maximum rate of change of the signal in the Z dimension. This is achieved for each channel by moving the emitter (and receiver) within a quarter wave length in the Z direction. This position is referred to as the "Stand-Off" distance.

3. EQUIPMENT CONFIGURATION

The portable version of the microwave interferometry equipment is shown in Figure 5a. This shows the laptop-computer with the driving electronics and the scan head. The same computer and electronics can be coupled in the laboratory to an XY Positioning Table as shown in Figure 5b. Operating, interface and display software resides on the interface and display computer.

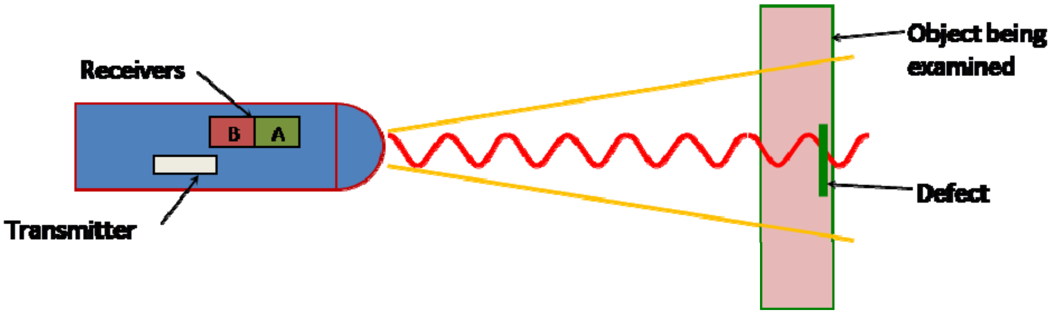


Figure 3. Schematic diagram showing relative position of microwave transmitter and receiver head to the part under examination. One-sided access is shown.

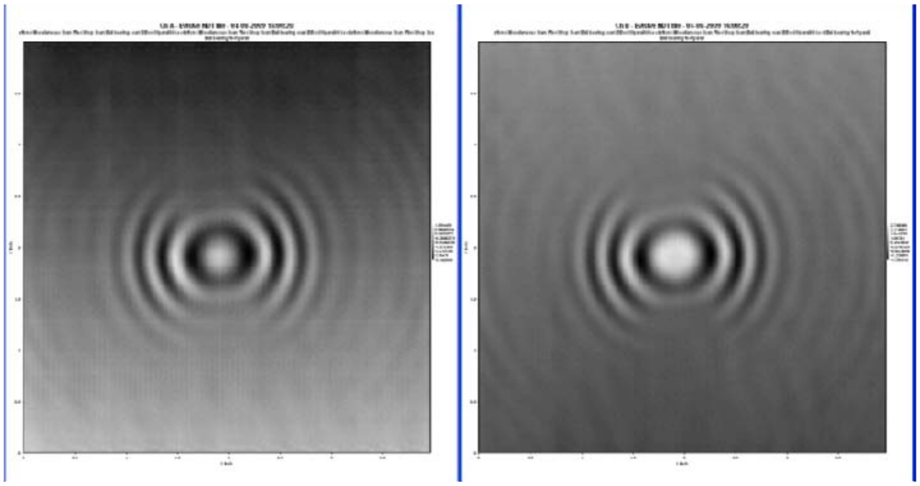
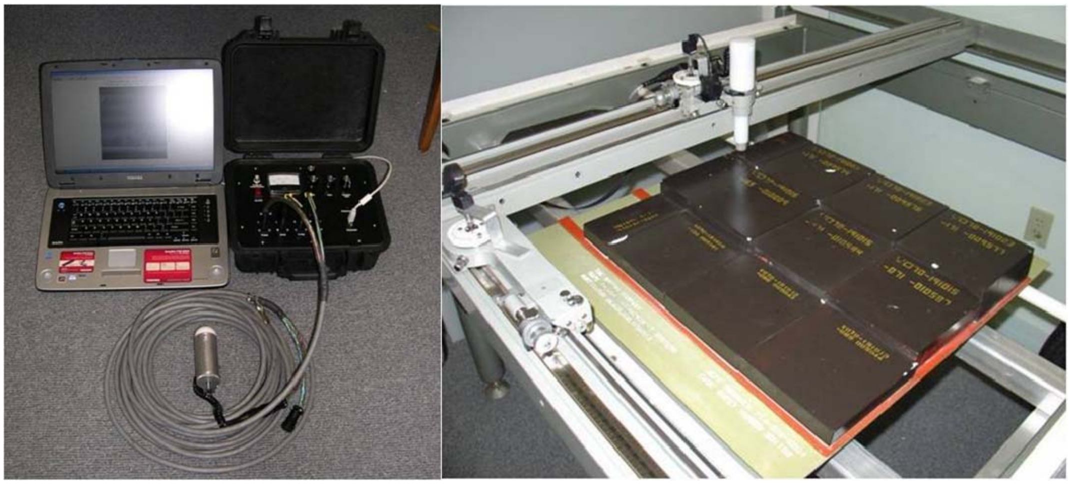


Figure 4. Comparison of phase difference between channels. Channel A is on left and B on right for a flanged wave guide, with aperture dimensions of 3.96 x 10.67 mm (0.156 x 0.420 inches). Target is a 2.54 mm (0.10 inch) conductive sphere located 19 mm below the surface of a glass plate.



(a) (b)

Figure 5. Photographs of portable scanning microwave system
a—computer, electronics and head
b—X-Y positioning table with head attached

Data are collected via an X-Y raster scan over the surface of the part. The data rate is sufficiently high that mechanical positioning or position feedback for manual positioning is the only limitation in scan speed. The scan data are available in near real time. This scanning technology has been applied in the laboratory, with X-Y planar, X-Y cylindrical and r-θ positioning, and in the field with surface X-Y and multi-degree of freedom positioning devices.

With the exception of the infrared tracking position system, the images presented here were acquired on the X-Y positioning table. Datum spacing in the scan direction was 0.003 inches and raster increment was 0.05 inches unless otherwise stated. Scan speed on the X-Y positioning table reach 3 inches per second and ramp to start and stop. Scan speed with the hand held infrared tracking system varies and may exceed 10 inches per second.

4. PORTABLE FIELD CONFIGURATION AND WIRELESS HAND-HELD DEVICE:

A number of portable configurations have been applied to field use: The instrument and control system has been interfaced to mechanized pipe scanners and with a multi-axis position system for free-form manual positioning, and with a variety of manual position encoders.

A portable system has been interfaced to an infrared camera for correlation in other related studies. The equipment is shown in the field in Figure 6. The probe is manipulated manually, position tracked and presented in real-time (the position tracking display is shown in Figure 7). The tracking display facilitates control of coverage and scan density. Before and after images are automatically saved with each scan.

The system electronics have been incorporated into the hand held probe housing and a wireless interface of the probe and control computer has been developed. This required miniaturization of the signal processing components, and development of an additional communications protocol. Bluetooth was used for its efficient application. The self contained power system benefitted from the low power requirements of the Gunn diode, receivers and signal processing components.

This significantly reduces the system size, as well as improving field applicability. The Wireless Hand Held Evisive Scan system is shown in Figures 1 and 8.

Figure 6. Portable microwave interfeometry equipment configured with infrared position tracking

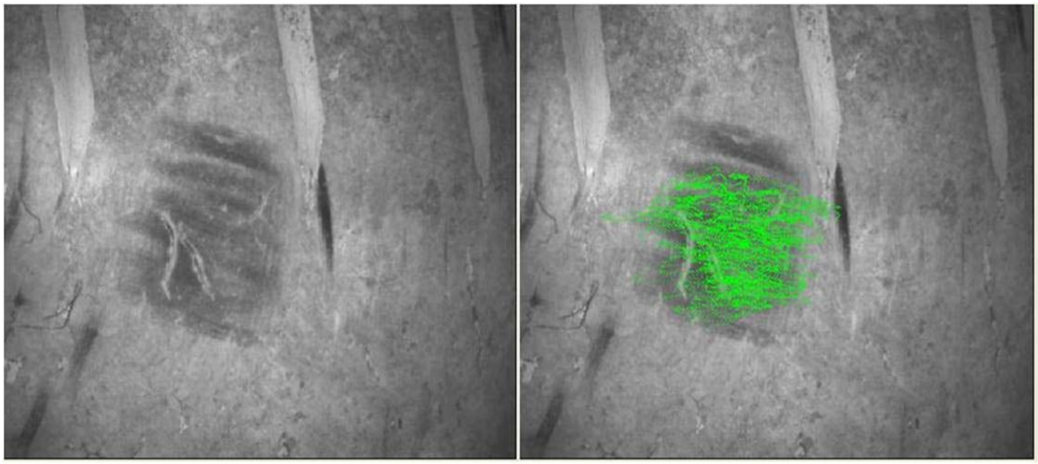


Figure 7. Scan area image and position tracking image (data points shown in green)

Figure 8. In the Wireless Handheld System, the microwave interferometry instrument electronics and controls have been incorporated into the Probe Assembly, which communicates by Bluetooth with the User Interface Computer. A miniature computer or display device functions as the operator interface.

5. IMAGES OF ARTIFICIAL LAMINAR DEFECTS

A multi-layer sample panel of ceramic composite armor was examined. The panel has multiple layers of fiber reinforced resin, ceramic tiles of two compositions, two conductive material layers and one elastomeric layer. The panel has six artificial laminar features, arranged at two depths: above and below the elastomeric layer. The scan image in Figure 9 shows that the microwave interferometry system detected all six artificial laminar features. Similar artificial features were detected below (left in the image) and above (right in the image) the elastomeric layer in the part. The difference in geometry of the left and right presentation of these features relates to contours of layers above the deeper features which are on the left in the image. The difference in depth of the features is indicated by the difference in gray scale (voltage) which relates to their relative phase positions.

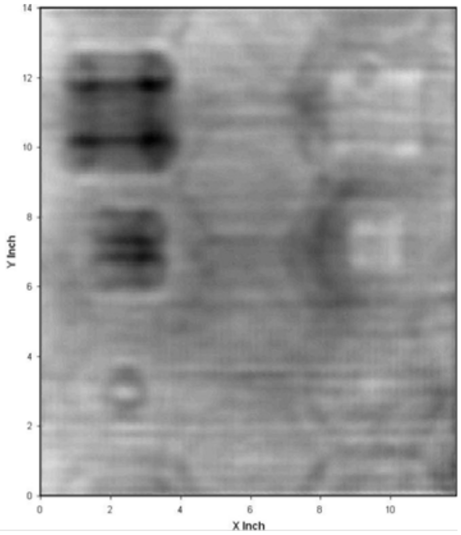


Figure 9. Scanning microwave image of a test sample with six artificial delaminations, and an unintended feature.

The phase position of laminar features can be adjusted to “focus” the acquired image data at specific depths in the material, or to minimize the effect of specific laminar features. This is particularly beneficial in optimizing the technique for detection of laminar features at a specific layer in the complex material structure.

The small circular indication at (9.5, 12.5) in the upper right is an unintended laminar feature very near the artificial feature.

The artificial feature and anomalous feature at (9.5, 12.5) were examined by through transmission x-ray and x-ray computed tomography (CT). The set up for x-ray tomography is shown in Figure 10. A welding rod was placed across a corner to create a temporary position registration. Examples of the acquired CT images are presented in Figure 11 along with the locations of the CT images relative to the microwave interferometry image data. The complex cross section structure of the specimen is clearly visible in the CT images. While the data was not available at the time of the test, it seems that the thicknesses of the very thin artificial laminar features are below the spatial resolution of the CT image. The anomalous laminar feature is also demonstrated to have a through wall dimension less than the minimum resolution of the CT image (smaller than about 0.25 mm (0.01 inches)).

These experiments demonstrate that the microwave interference scanning method is applicable to complex ceramic armor samples, and that the method seems capable of detecting very thin delaminations at various depths.

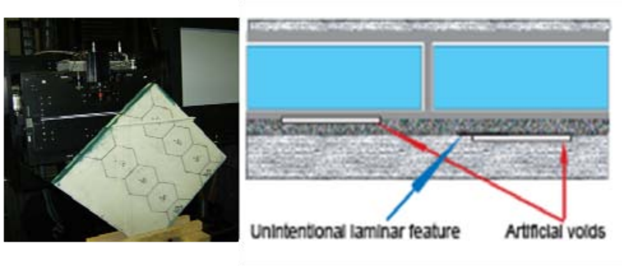


Figure 10. Photograph of the test panel in the x-ray imaging system, and cartoon of the placement of artificial voids and unintended laminar feature. The upper corner is marked off using a small diameter welding rod to validate the position.

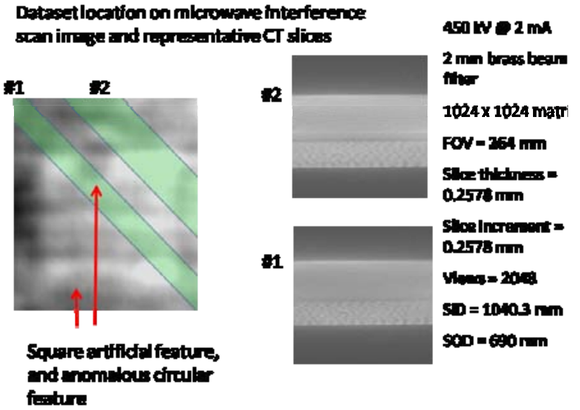


Figure 11. Correlation between high spatial resolution x-ray computed tomographic images and scanning microwave data. A)-location of x-ray Ct images, b)- x-ray CT section, c)- x-ray CT section. Scan image and CT images of artificial and anomalous features in a sample specimen.

6. DETECTION OF CRACKED ARMOR TILE

The microwave interferometry system has been demonstrated to detect cracked ceramic armor tile in a typical ceramic armor layered configuration. Figure 2 shows a photograph and the corelation between a through-transmission x-ray image and the microwave scan of the same cracked tile. The wide, light gray patterns shown in the scan follow the crack centerlines. The microwave interferometry data has sufficient dynamic range, (14 bit resoultion), to identify the centerlines and edges of features within the data position precision.

An image of the same cracked tile is presented in Figure 12 to illustrate the detailed nature of the information presented in the scan image. The scan image in Figure 12 (shown at th left) is reversed in phase from the scan image show in Figure 2. Thus, the crack features in Fiure 12 are negative (dark) values, instead of light as in Figure 2. The plot of voltage versus position for a single X value (right in Figure 12) illustrates the range of values which make up the scan image.

The data is rich with information and can easily be made convenient for interpretation.

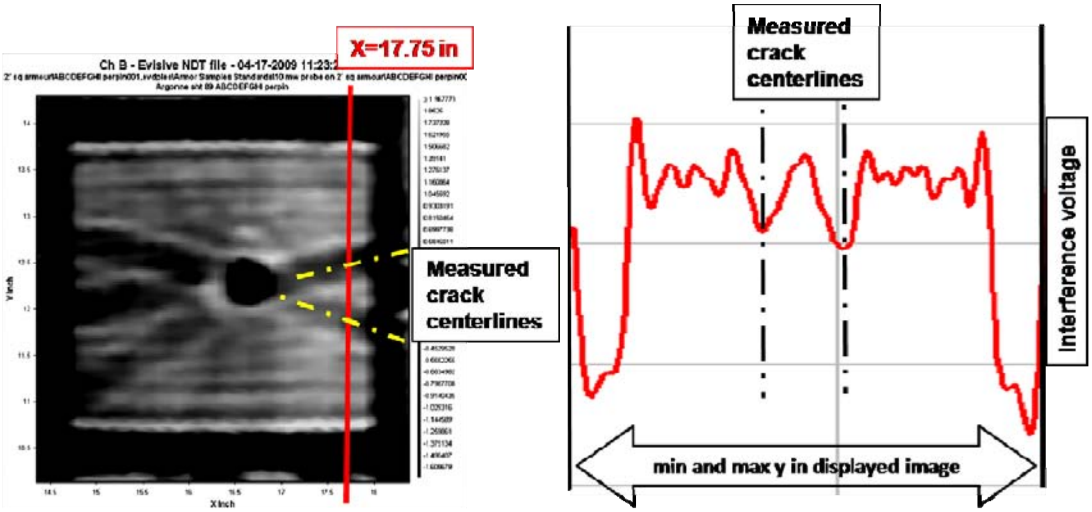


Figure 12. Scan image and cross section of voltage values associated with cracks and gaps to adjacent tiles.

CONCLUSIONS

A portable microwave-based system has been developed and demonstrated on layered ceramic armor to detect cracks and delaminations within ceramic armor systems. Examination requires access from one side only and is effective in applications with metal backing. The capability of the method allows determination of size, depth and orientation of features within the dielectric solid. The laboratory instrument has been successfully coupled to X-Y positioning systems as well as multi-axis scanning systems and free-motion position tracking systems.

The system has been miniaturized and wireless communication incorporated facilitating application in field environments.

Further laboratory testing including destructive analysis of samples will establish scan and data interpretation protocols and qualify the technique for field nondestructive testing applications. The equipment will be further optimized and hardened for field use in the Phase II SBIR project.

The system will provide means for warfighters to verifying the integrity of ceramic armor in-theater. For ceramic armored vehicles, this permits confirmation of armor integrity following non-ballistic challenges, and avoids down time for inspection of armor.

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