Innovative Application Of Microwave Non Destructive Examination Of Composites

Microwave NDE Techniques to Stacked Defects in Laminate Structures

Abstract

Composite materials are increasingly being incorporated into aerospace, automotive and other high end applications. The structures of these new materials are often complex, involving multi-layer laminates over honeycomb and other 3-dimensional structures. The geometrical complexity of these structures, coupled with the embedded fibers and fabrics make non-destructive examination (NDE) very challenging.

Conventional NDE techniques have found limited application, but many of these new structures have been considered essentially uninspectable. The ability to look deep into a structure, beneath the outer laminate to find defects is highly desirable. The ability to detect and size "stacked" defects, where a second delamination or similar defect lies beneath a first has been difficult to achieve.

This paper will examine an emerging technology whereby microwave interferometry is used to image just such deep and stacked defects in modern composite structures. Specific examples will be given showing microwave inspection images of multi-layer laminate covered honeycomb structures, as well as other geometrically challenging specimens. A comparison will be made of the inspection results obtained using the new technology and an existing NDE method on the same calibration standard.

Additionally, several very complex samples will be inspected and the results presented. One sample consists of an aluminium honeycomb structure which is sandwiched between and cemented to multi-layer carbon fiber laminate on both sides. In the presented scan, intentional thickness changes of the carbon composite laminate are detected from the opposite side of the sample.

The other sample is an oxide-oxide ceramic matrix composite (CMC) honeycomb structure with oxide-oxide CMC laminate on both sides. In the presented scan, damage to the laminate is detected and characterized from the opposite side.

In each of these cases, there are extensive air gaps and substantial distances through the thickness of the honeycomb which render more conventional NDT techniques ineffective.

Background

High-performance technical composites are widely used in many modern manufactured products. Composites which include ceramic bodies embedded in complex laminate structures are utilized in body armor, aircraft armor and ground vehicle armor. 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. The physical interaction of ceramic armor with a projectile results in damage on sufficiently energetic impact.

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. A ceramic insert becomes uninspectable by conventional means when the laminate used to contain it becomes damaged and or de-laminated from the insert. Microwave NDT can be used to inspect the embedded ceramic in the presence of substantial damage to the outer laminate covering.

A means to detect damage from non-projectile impact, handling and manufacturing defects is needed to determine the integrity of the ceramic armor. Degraded functionality of ceramic armor through non-ballistic impact greatly increases risk. In order to have a timely and efficient condition assessment, it is desirable to monitor the ceramic armor in-situ, with minimal access cost and without having to remove encapsulating materials. This would best be performed with access from one surface only, and without removal of appliqué panels. It would be desirable to have real time determination of service readiness by means of immediate nondestructive imaging and go/no-go condition assessment criteria. It is desirable to detect surface and internal cracks in the ceramic tiles, and disbonds between the encapsulation material or interlayer and/or backing material. The system and technique for performing in-situ NDE/health monitoring of ceramic armor should be designed for deployment at the depot/motor pool level, requiring low cost, easy to use technology.

The objective of this activity was to demonstrate the feasibility of the application of a patented microwave scanning device as a portable NDE methodology to perform monitoring of the health of ceramic armor from non-ballistic impacts. The scanning process is referred to here as **Evisive Scan™**. This method has been used successfully in preliminary studies on many different types of dielectric materials. It has been shown to be highly effective for quick, accurate detection of discontinuities in monolithic ceramics including samples of ceramic armor panels. The Evisive Scan image has been demonstrated to be useful in comparing test samples to a standard and in comparing images of a part before and following service induced degradation.

This method has been demonstrated on armor panels provided by the US Military and processed with the support of numerous independent third parties. The Evisive Scan method permits real time evaluation by inspection from one surface only, using non-contact inspection through complex laminate encapsulating materials.

The Evisive Scan Methodology

The Evisive Scan method uses a microwave transmitter to bathe the subject part in microwave energy, and uses multiple receivers to detect the integrated emitter and reflected signals as shown in Figure 1. The method and equipment is covered by U.S. and international patents. It utilizes microwaves as an interrogating beam to penetrate a dielectric material. The microwaves are reflected at areas of changing dielectric constant. This reflection and the interrogating beam combine to form an interference pattern. The microwave signal is measured by the receiver as voltage differences at locations over the surface of the material. The voltage pattern is displayed as an Evisive Scan image and indicates the presence of a potential defect, internal structure of interest, or change in material dielectric properties.

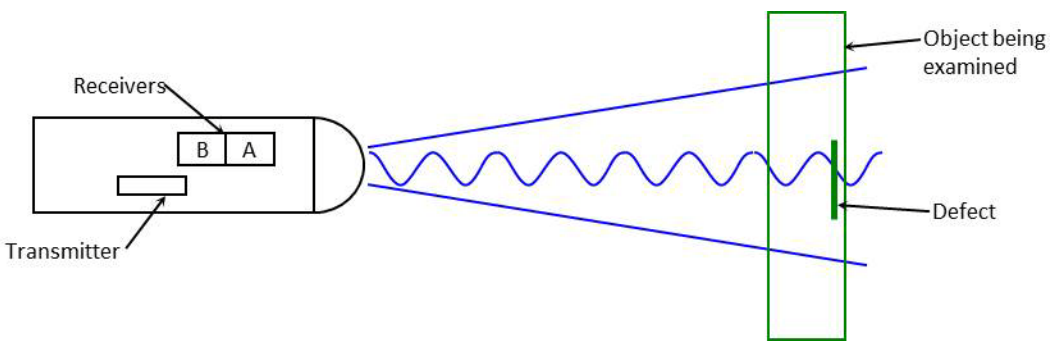

Figure 1: Microwave Scanning

Figure 2 Illustrates the combined signal which produces an interference pattern from a reflector at a The received microwave signal yields a point cloud which uniquely characterizes the volume of the inerrogated material. The difference between the emitter signal and reflection is a standing wave pattern in which the Z distance to a reflection within a wave length defines phase relationship of the reflected signal to the emitted signal and the amplitude of the difference signal. The difference is a variable DC voltage. This DC signal creates the image value for a given point over the part surface. This point cloud is the Evisive Scan data and yields the images directly. The

Evisive Scan images presented here are generated directly from data files of the scan voltage.

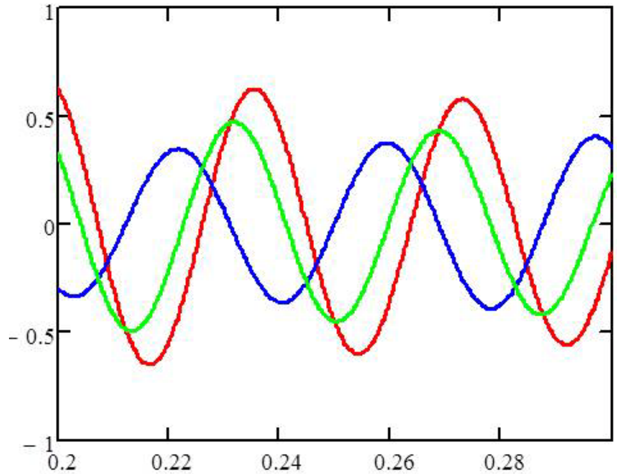

Figure 2: Interference Pattern DC

Equipment Configuration

The **Evisive Scan TM** equipment is shown in Figure 3. The equipment consists of a microwave probe, processing instrumentation, an interface computer and display, and a probe positioning or tracking mechanism (not shown). Operating, interface and display software resides on the interface and display computer.

Figure 3: Evisive Scan Equipment

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.

The examination data is collected in a single scan of 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 is available in near real time, and as illustrated in the following images, the microwave scan data presentation is intuitively interpretable.

The Tracking System used for field applications with manual probe manipulation is shown in Figure 4, where it is set up in the laboratory for scanning a piece of FRP pipe elbow. The position tracking system uses an OptiTrack IR camera to follow the probe position. Position data is fully integrated with Evisive Scan TM control and data presentation software. Some data was collected with a stationary x-y plotter table in the laboratory.

Figure 4: Position Tracking System

Flaw Detection

In the specimens evaluated to date, flaw detection has been determined by correlation of microwave scan data with visually observed defects in the scanned part, known morphology of artificially created defects and with nondestructive test data from alternative methods. X-ray images were made of artificially cracked sample panels by an independent third party and made available for this report. Until the advent of the method currently under discussion, digital radiography had been employed as the reference method for these inspections. When using an X-ray method, whether digital or the more traditional methods which utilize a radioactive source, the armor panels must be removed from the vehicle to permit inspection.

Alternative ultrasonic nondestructive testing methods are ineffective in the presence of separation or disbonding of encapsulation from the inspected part surface. Alternative radiographic nondestructive testing methods are limited by requiring access to both sides of the specimen (as discussed above), by face contact (two dimensional flaw morphology) in flaws and by flaw orientation relative to part surface plane. Alternative thermographic inspection methods are limited by encapsulation materials and face contact (two dimensional flaw morphology) in flaws.

The Evisive Scan technology has been successfully applied to ceramic armor panels provided by the US Government.

The following figures include images of sample panels provided by the US Government. The material was supported here by a ¼ inch steel plate to simulate the situation in which it is installed on a vehicle made of steel. Access was accommodated only from one surface. The specimen was examined at Evisive before and after a selected tile was cracked by an independent third party.

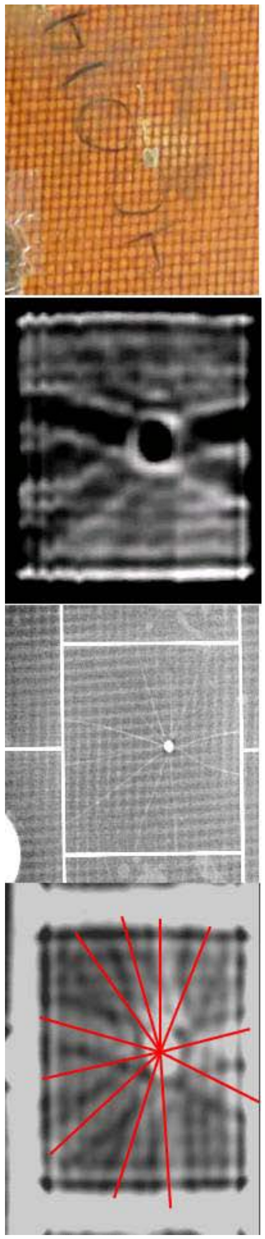

Figure 5: Cracked Tile 1

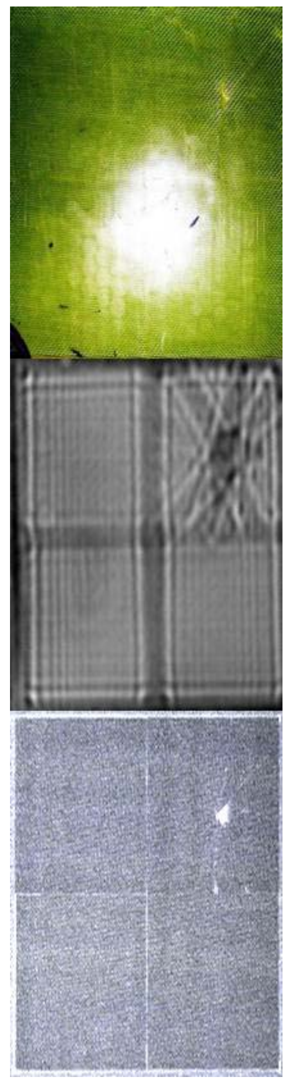

Figure 6: Cracked Tile 2

Cracked Tile Images

The images in Figure 5 clearly show the crack pattern and the reduced ceramic section in the non-projectile cracked tile. From the top: a photo image of the surface of the composite encapsulation from which the Evisive Scan examination was made, the Evisive Scan images of the cracked tile, an x-ray of the tile and an operator interpretation of the Evisive Scan image, illustrating the identified cracks.

The cracks show as pairs of lines characteristic of the reflection interference pattern from the well-defined discontinuity. Precise measurements can be made from the image in real time by the operator. The measurements and parameters of features analyzed by the operator are saved with the **Evisive Scan** TM data file. This image compares precisely with the x-ray image of the cracked tile. The x-ray image was created by examining the part with through transmission, an x-ray source requiring access to both surfaces of the panel. The artifically added red lines in the bottom figure indicate the operator interpretation of crack locations in the **Evisive Scan** TM image. The lines were added to show the orientation and placement of cracks identified in the Evisive Scan image and are clearly coincident with the defects detected in the x-ray image of the panel. Actual interpretation of the **Evisive Scan** TM is documented in the image data file and is explicit for each artifact analyzed by the operator. The cracks are clearly visible by the paired interference pattern reflection of the permeability change at the crack surface. The rectilinear pattern in the Evisive Scan image is the reflected edge of the tile. The x-ray is shown in “negative” format. The cracks appear a thin white lines.

This experiment demonstrates that the **Evisive Scan** TM technique can detect non-ballistic cracking of the vehicle armor tiles, with access from one side of the armor panel, and that the scan image is substantially consistent with x-ray imaging of the part using transmission through the part (access from both sides).

The images in Figure 6 present a similar experiment conducted with a ceramic armor panel of different construction. The surface of the overwrap, seen in the upper image, is marked by the impact blow in the upper right quadrant. The pattern of fracture lines and the irregular penetration of the tile are clearly visible in the Evisive Scan image (middle). The image is consistent with the x-ray image made of the same part (bottom) using access from both surfaces. The x-ray image is presented in “negative” format.

The tile in the upper right position was cracked using a non-projectile impact blow. The prominent vertical and horizontal pattern in the Evisive Scan image in the Evisive Scan image is the interference pattern image of the rectilinear edges of the tiles. The lower left tile in Figure 6 also exhibits a voltage difference (gray scale difference) suggesting a feature in the encapsulating material, such as an absence of material, inclusion of foreign material or a disbond. Such features are explored in the next section.

The varying density pattern of the tile area in the x-ray image is the sum of the weave patterns of the front and back encapsulation fabrics. This is also visible in the x-ray image in Figure 5. Also in that image are several areas of reduced material density (lighter irregular shapes in the tiles above and below the cracked tile). These indicate a relative absence of material in the locations.

Calibrated position measurements can be made from the microwave image, enabling analysis of observed artifacts. The Evisive Scan image was made using the scanning table, with access from one surface only. The part was backed with ¼ inch steel. Alternative positioning means such as the IR Tracking system illustrated in Figure 4 (replacing the scanning table) have been demonstrated for field use.

Disbonds and Other Features

The following figures illustrate detection and imaging of features in the ceramic composite material other than cracks in the tiles. Figure 7 is a false color presentation of Channel A data from the scan of the panel shown in Figure 5. The color spectrum associated with data voltages is shown at the right of the image.

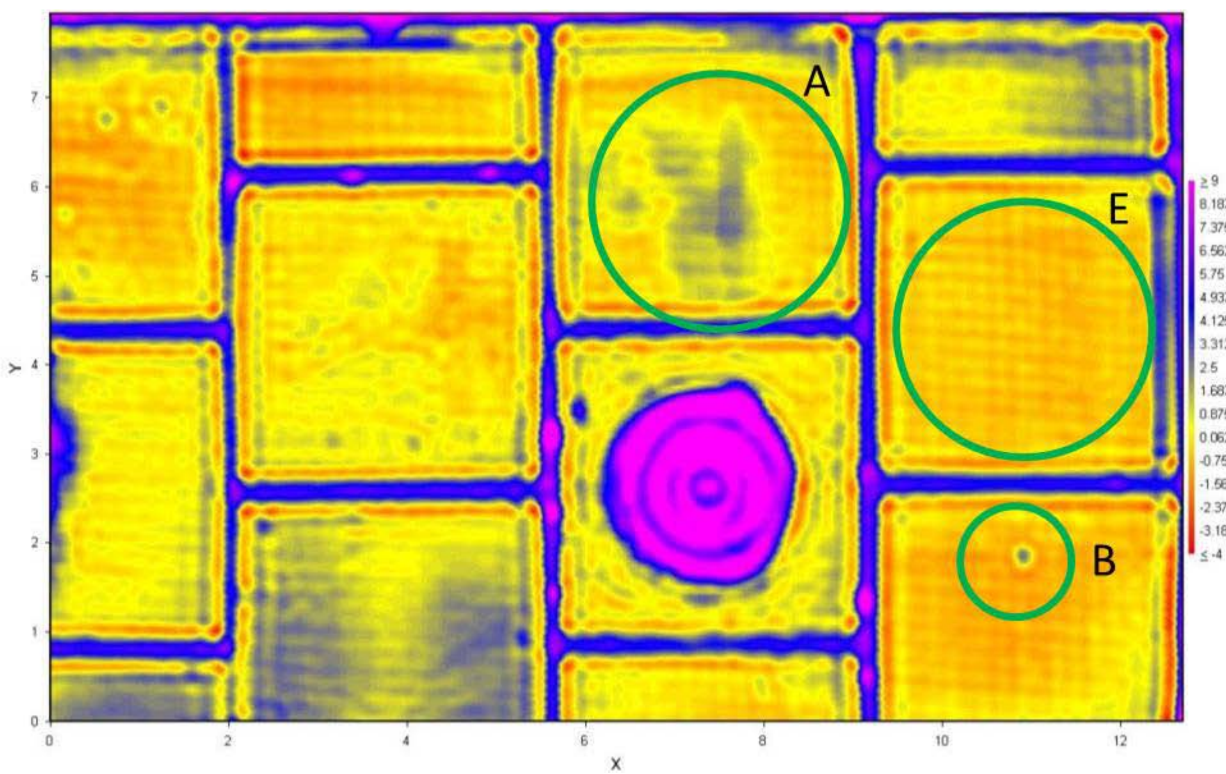

Figure 7: Specimen Panel Scan Channel A

The large round feature is a mounting hole machined through the panel. As described in Evisive Scan Methodology, and illustrated in Figure 2, this Channel A image represents the maximized phase differential at a specific depth in the material which is imaged.

Based on comparison to images of other samples, the feature identified as A is likely to be an interlayer disbond in the encapsulating material. The feature identified as B is likely to be a void in the encapsulating resin or interlayer material. The relative depth of this feature is indicated by the presence of an interference ring (the yellow ring surrounding the blue center. Similar features in the center and upper left are unlabeled.

We shall see in Figures 8, 9 and 10, that the phase differential yields significant information about the depth of features in the material, and that multiple features at different depths can be resolved (stacked features). Because the microwave signal is reflected at every change in dielectric property, laminar features without volume, such as disbonds; may be readily imaged.

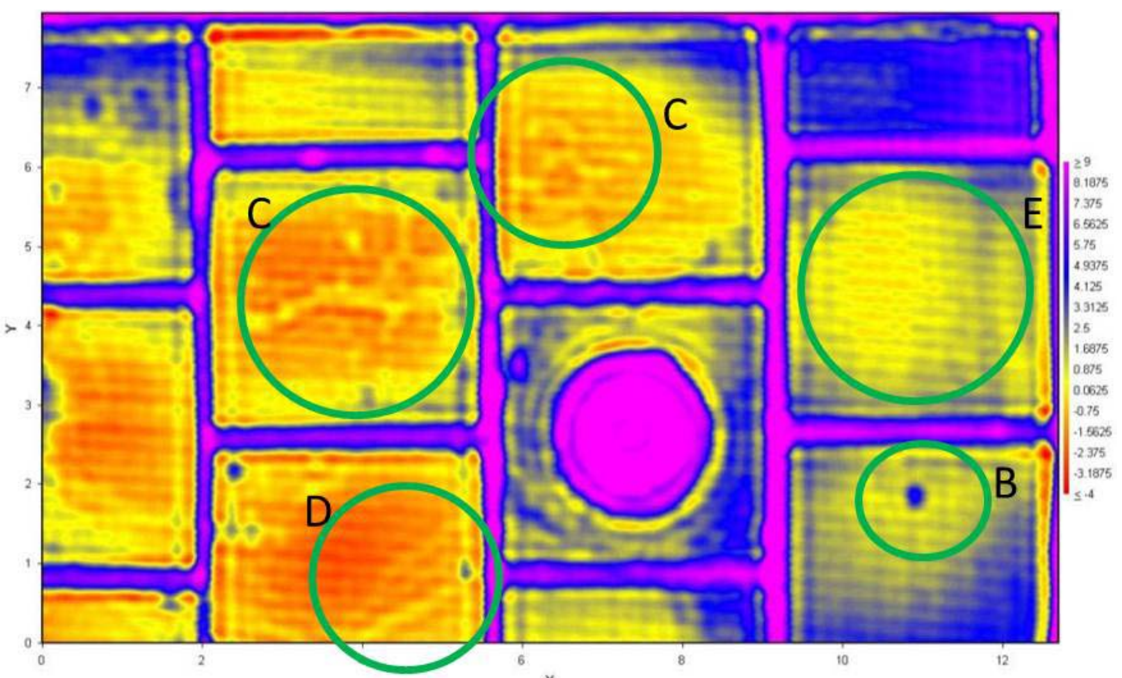

Figure 8: Specimen Panel Scan Channel B

Figure 8 is Channel B of the scan of the specimen panel. This Channel is separated in phase from Channel A (figure 7) by ¼ wavelength. Thus, features that are located at a different depth in the material are more apparent here. This is illustrated by the presence of the irregular features labeled C, which occur in the same X-Y location as the feature labeled A (in figure 7). The features are at different depths in the material, presenting themselves more vividly in the different channels. From this data it is clear that the features are in the matrix surrounding the tiles, rather than in the tile. In comparison with the x-ray image (shown in Figure 10) it is apparent that the material is of relatively uniform density in these regions. The feature labeled B is apparent in this channel as well, as are the similar features in the upper left and center regions noted in the Channel A presentation. The linear features labeled D are wrinkles in the encapsulating fabric, more apparent in the microwave image than the x-ray image because of the relatively close material densities of the fiber and resin.

Figure 9 is a Channel C scan of the specimen panel. Channel C is the sum of the information contained in Channels A and Channel B. As a result, the Channel C image contains a mix of all of the information contained in the Channels A and B scans and thus it displays information from all layers of the material under interrogation.

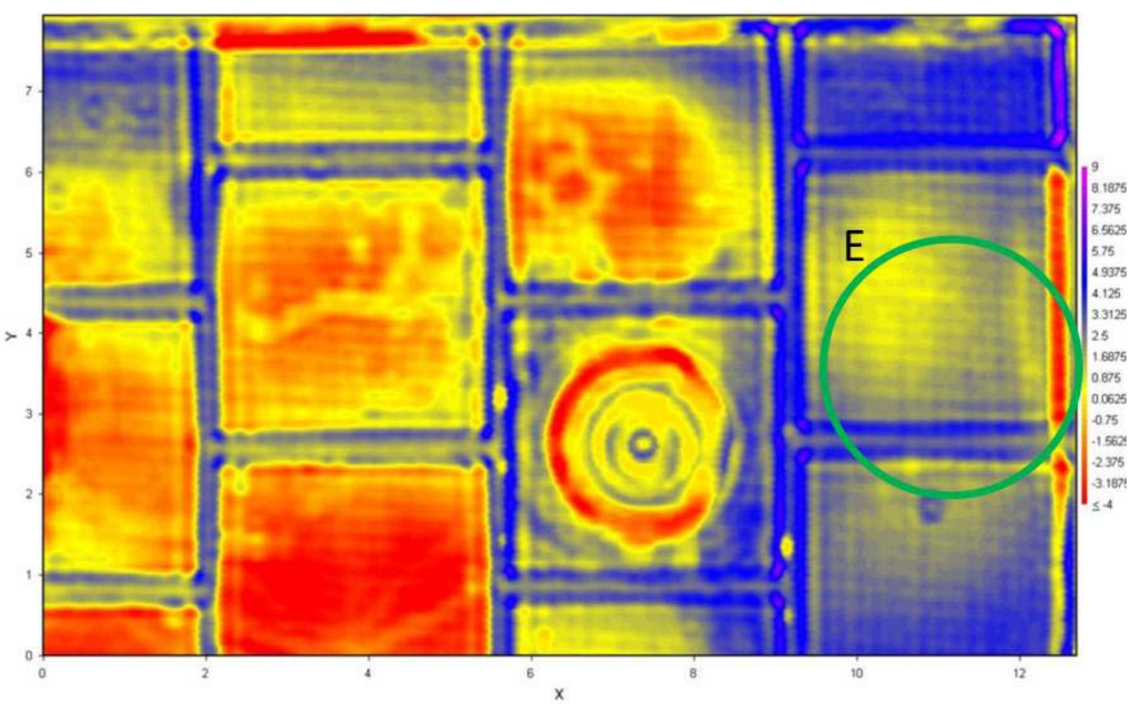

Figure 9: Specimen Panel Scan Channel C

The regular pattern labeled E in Figures 7, 8 and 9 is the lay of fiber in the encapsulating material. The near and far surface fiber matrices can be differentiated by the relative response in the separate Channels. This fiber pattern is apparent in Channel A, B and composite Channel C images. The fiber ribbons themselves are on the order of 0.125 inches wide, set at a spacing of about 0.125 inches. This illustrates the ability of the microwave interference measurement, to resolve features substantially smaller than the wavelength (here about 0.5 inches).

The x-ray image "negative" of the panel is included here for comparison as Figure 10. The x-ray image does a very good job at displaying the areas of large density difference, such as the gap between the ceramic panels, but does not show the subtle variations of construction, such as the fiber, very well. The x-ray also cannot distinguish interlayer disbond in the encapsulating material. In fact, there is no hint of the numerous inter-laminar features which are quite apparent in the Evisive Scan images.

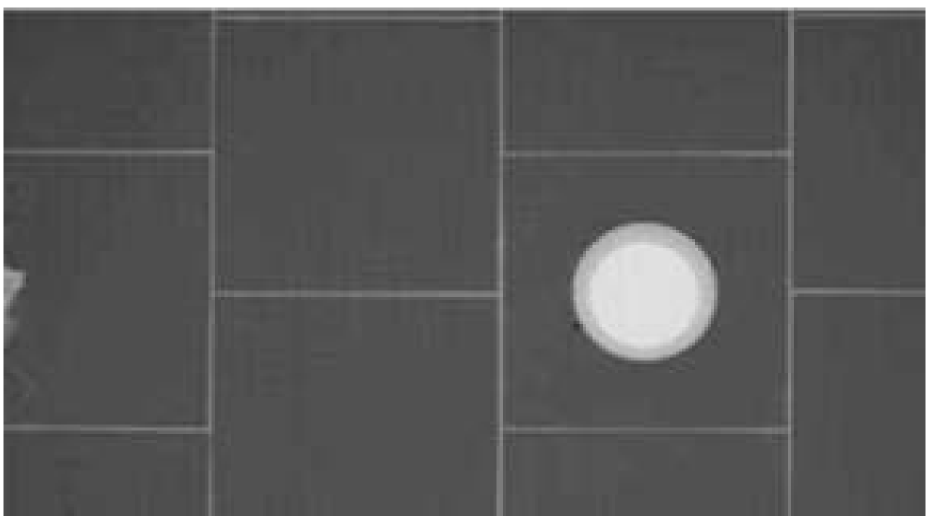

Figure 10: Specimen Panel X Ray Image

Stacked Features

In Figure 11, several features are visible at different depths in the material in same image and the different depths can be inferred from the data recorded in the in the different phases of the two hardware channels and the one artificial (software) channel from a single scan of the part.

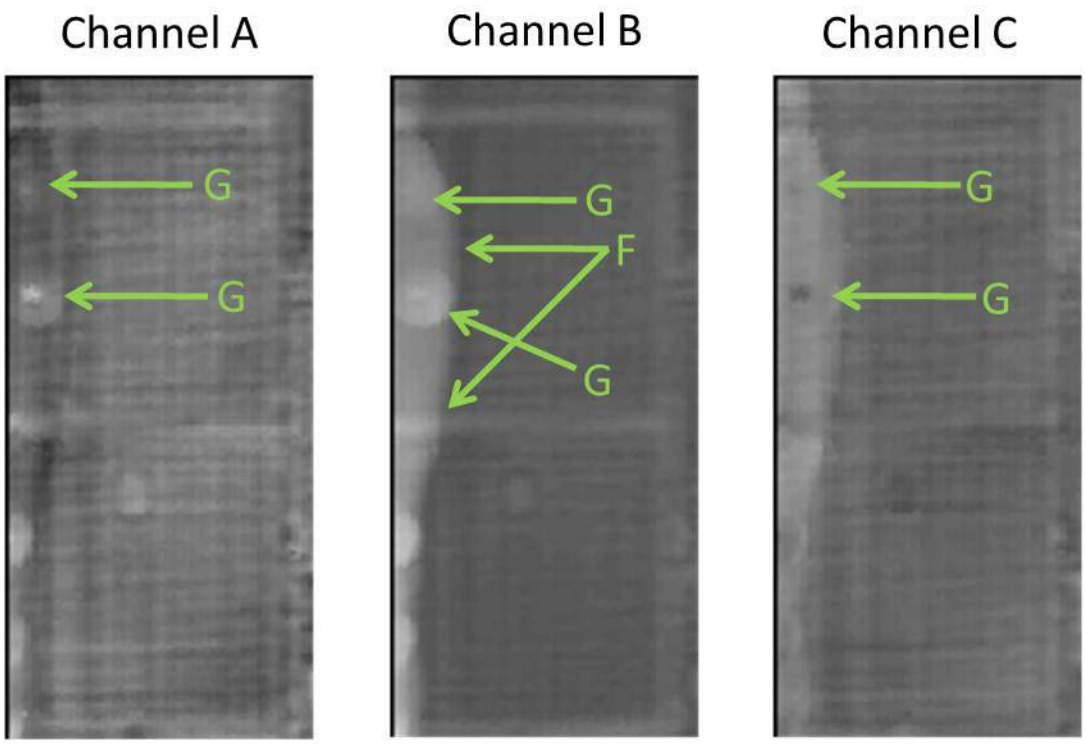

Figure 11: Stacked Features in Channels A, B, and C

The elongated feature (labeled F) on the left edge of each image is a separation of the matrix surrounding the ceramic tiles. It is most readily noted in Channel B as white (generally more positive voltage than null). The round features (labeled G) are at a different depth as indicated by the substantially voltage difference in A and B channels (in C they are dark, negative relative to null). The round features are likely to be small voids in the matrix material which have been compressed into a disbond with little or no volume.

As in the other images, the individual tiles are apparent as is the fiber cloth matrix. Other features stacked in the region of the material separation (lower left) and in the upper center of the lower tile present similarly to those discussed in the preceding figures.

Complex Honeycomb Composite Structures

Carbon fiber, aluminum honeycomb sample

The photograph in Figure 12 is of an aluminum honeycomb structure with carbon fiber laminate cemented on each side. Adhesive between composite material and honeycomb is removed between arrows, on the opposite side of the honeycomb. Composite thickness on the opposite side of the honeycomb varies as marked (in white).

Probe positions of free-hand hand scan is shown in black on scan image shown in Figure 13.

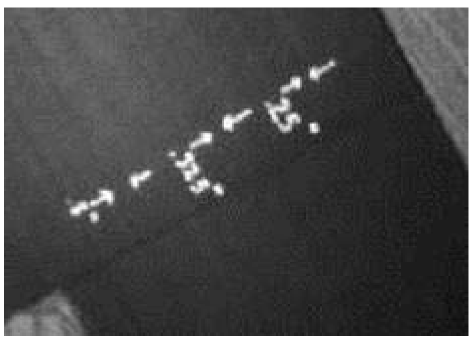

Figure 12: Aluminum Honeycomb Structure with Carbon Fiber Laminate

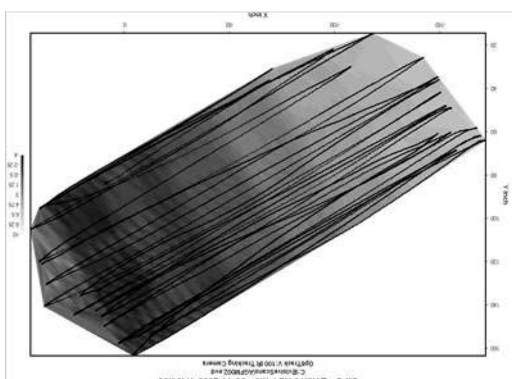

Figure 13: Evisive Hand Scan Showing Data Point Coverage

The Evisive Scan image in gray scale, shown in Figure 14, shows differences in fiber layup and regions where the adhesive between composite layer and honeycomb is absent. It should be noted that the scan image in Figure 14 was created by free-hand scanning of the part and did not require any mechanical device to determine the X-Y position of the scan transducer. In this case, the infra-red camera was used to track the hand-held probe to determine the X-Y location 100 times per second. The Evisive transducer voltages were then associated with the appropriate location and the image was created. This type of free-hand scanning is sometimes much superior to that which required a mechanical device, such as optical encoders, to establish position.

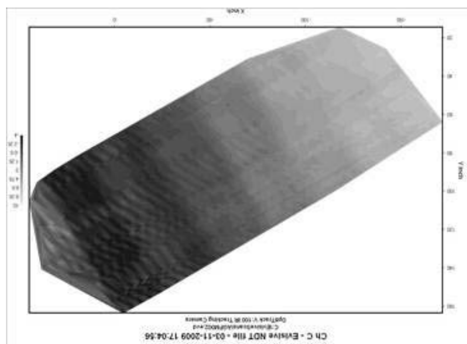

Figure 14: Evisive Scan Image Showing Carbon Fiber Laminate Thickness Changes

The Evisive Scan clearly images the changes in carbon fiber thickness across the aluminum honeycomb structure. The method works because the openings in the extruded aluminum honeycomb (which is clearly an electrical conductor) are large enough to be penetrated by the microwaves. While the carbon fibers in the laminate might, individually, be considered conductive, the bulk laminate structure is dielectric. This is because of the “pre-preg” technique of resin impregnation. The individual fibers are coated with resin and, hence, not allowed to “short circuit” once cured.

Ceramic Honeycomb Application

The technology is applicable to complex ceramic structures. The example is an all ceramic honeycomb structure called a ceramic matrix composite in which ceramic material constitutes not only the fibers, but also the matrix. In contrast, most common composites are “organic matrix composites” where organic compounds such as resins and polymers make up the matrix.

In this application study, impact defects and a protective coating are detected. Detection threshold is adequate to detect the induced defects. Access is limited to the opposite side of the part (imaging through the honeycomb). There is no contact, and no coupling medium.

Figure 15 shows a photograph of the part. Figure 16 shows the Evisive Scan of the same part.

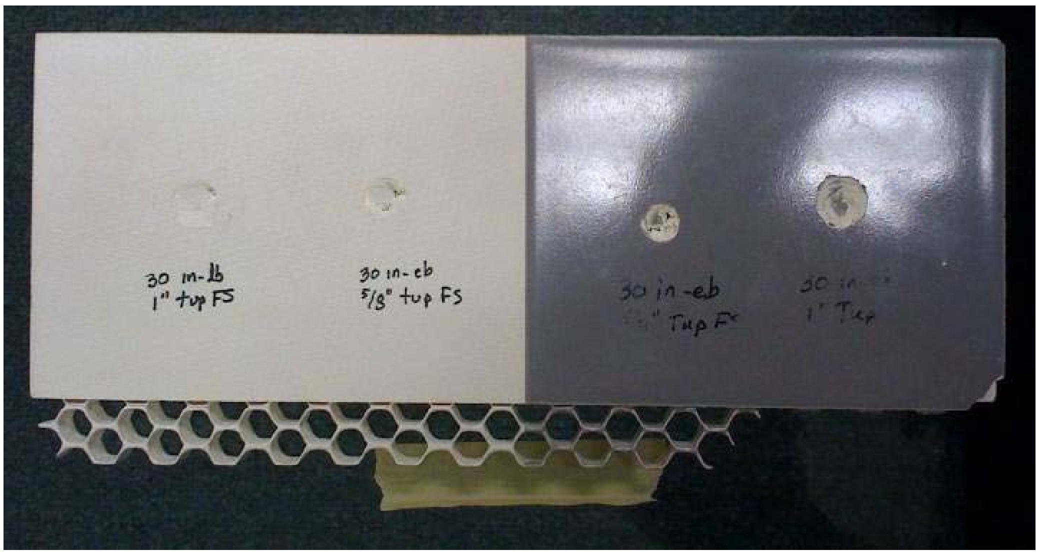

Figure 15: Honeycomb CMC Sample

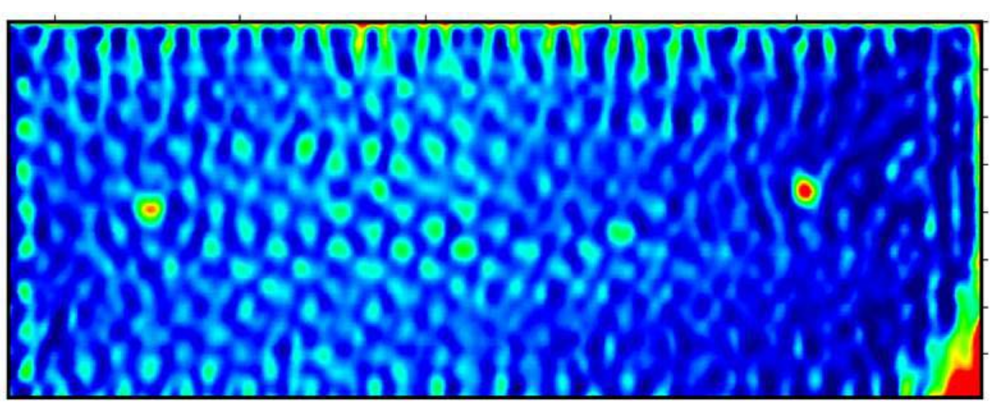

Figure 16: Evisive Scan of the Honeycomb CMC Sample

Conclusion

The Evisive Scan method utilizes microwave energy to volumetrically inspect materials which do not conduct electricity to any significant degree (dielectric materials).

Conventional NDT methods are not effective for detecting and characterizing defects which are located one beneath another (stacked defects). They are also not effective in detecting defects when a substantial air gap exists within the specimen, even if this gap is simply a consequence of the construction of the specimen.

It can be concluded from the described work that the Evisive Scan method can be used successfully to inspect monolithic dielectric materials which have been encapsulated using complex laminate structures. This inspection can be used to detect, characterize and size defects in the underlying monolithic material, even in the presence of de-laminations and disbonds in the overlying laminate. It can also be used to detect, characterize and size inter-laminar defects in both the encapsulating laminate itself and the interface between the monolith and laminate.

Additionally, the method can be used to detect, characterize and size what are referred to as "stacked defects", where one inter-laminar defect exists partially or completely beneath another defect or structure.

It is also possible to "focus" on a particular depth within a specimen such that defects at that depth are most apparent in the scan image. This ability to "tune in" to a specific depth also carries with it the converse, that is, the ability to "tune out" or ignore a particular depth. This is particularly important when the front or back surface is of no interest and it is not desirable to include surface scratches in the Evisive Scan image.

This ability to detect and characterize complex defects in complex materials, where material changes, air gaps and disbonds render more traditional NDT methods ineffective is of significant interest and will be increasingly important as composites become ever more widely used.

The ability to deliver NDT services for such inspections

Related Work

The principal investigators have been involved with the microwave scanning technology since its inception. They have been involved in developing various methodologies, tools, and fixtures for scanning many types of dielectric materials. The results of the microwave scans of polyethylene and fiberglass piping and coatings, for instance, have been well received by industry and have been commercialized in the private sector. Additional commercialization in the field of inspection of fiber reinforced rubber products is also developing rapidly, as this method permits component maintenance to be driven by component condition, not simply the time since last replacement (the difference between a “Condition Based Maintenance model” and a “Calendar Based Maintenance model”). A pair of scan images of reinforced rubber expansion joints installed in a US nuclear power plant is shown in Figure 17. The upper scan represents a component with substantial remaining life and the lower image represents a component which required periodic replacement. The method has been presented and described in various technical journals (see Inspectioneering Journal, for example) and trade organizations (EPRI, ASME, ASNT). The method has been successfully applied to Ceramic Matrix Composite (CMC) materials, resulting in Award of 11 US Small Business Innovative Research Contracts.

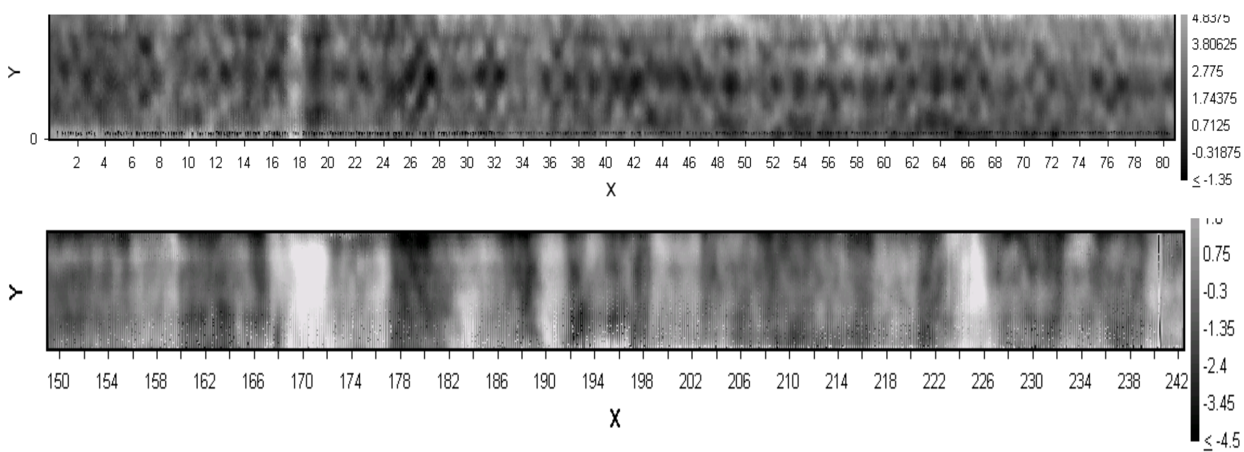

Figure 17: Evisive Scan images for Reinforced Rubber Expansion Joints

It is also noteworthy that the microwave scanning method is valid for in process manufacturing assessment of part quality. It can, therefore be used to determine in-service wear effects, as well as monitor part condition throughout the life of a part. This NDE technique is equally applicable to manufacturing in-process inspection, manufacturing quality and acceptance testing and on-going inspection throughout the useful life of an installed part. The inspection data collected by the microwave scanning method herein described is stored as digital data, making comparisons of NDE results throughout the life of a serial numbered part straightforward.

This method has also been used for in-process determination of several important bulk dielectric properties. These include density and porosity. The density applications include % maximum theoretical density in ceramics as well as resin to fiber ratio in composites.

There are also applications whereby this method is being used to determine subtle dielectric properties in homogeneous bulk dielectrics, such as thermoplastics. Several of these materials, among them, High Density Poly Ethylene (HDPE) have found wide application in pipeline construction around the world. These materials cannot be joined using solvents, and so are joined using thermal fusion butt welding techniques. These techniques are subject to poor fusion for a host of reasons and an NDT technique which can detect this lack of fusion was needed. The Evisive Scan method can detect the subtle difference between a properly fused joint and one in which the individual parts are in contact, and yet not fully fused. These “cold fusion joints” are problematic for the more traditional NDT techniques. Figure 18 shows an Evisive Scan image for an HDPE thermal butt fusion weld which was found to be acceptable. Figures 19 and 20 both show scan images of welds which were found to be unacceptable. Both the acceptability of the pipe weld in Figure 18 and the unacceptability of the welds in figures 19 and 20 were confirmed using destructive analysis by an independent third party.

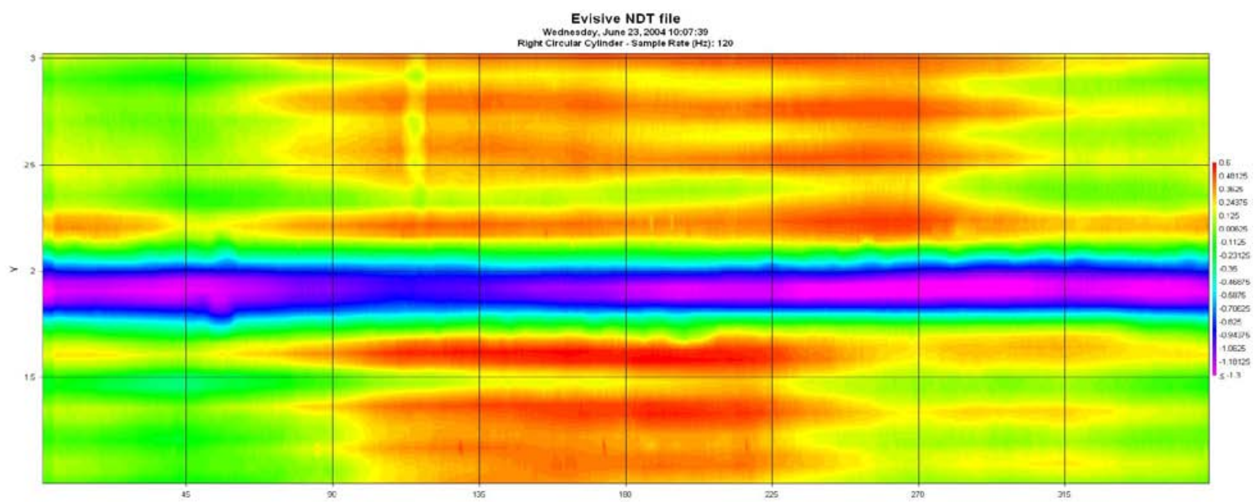

Figure 18: Evisive Scan image of an acceptable HDPE Thermal Butt Fusion Weld

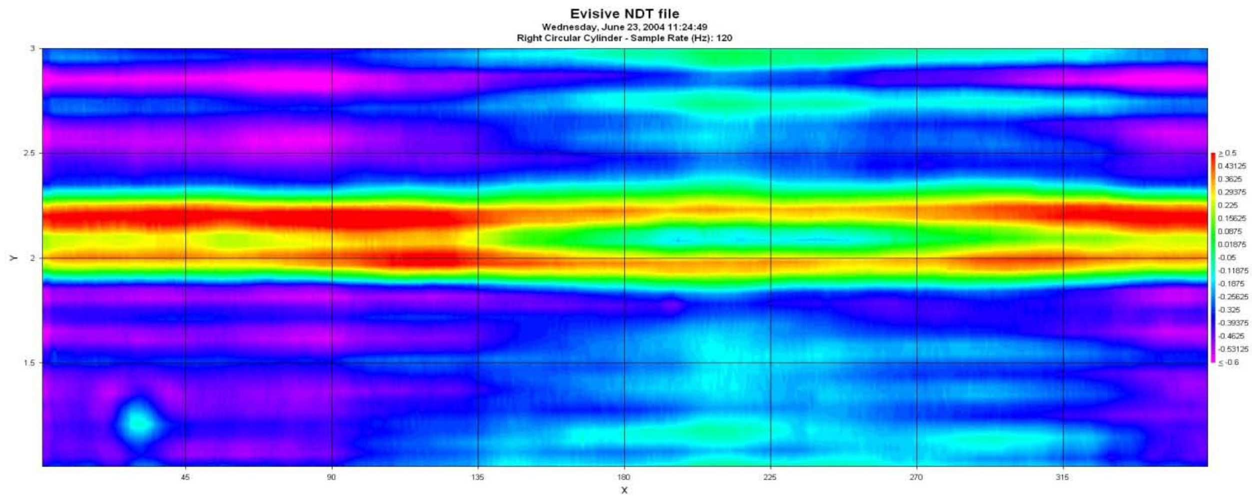

Figure 19: Evisive Scan image of an unacceptable HDPE Thermal Butt Fusion Weld (flaw is lack of fusion from 150 to 200 °)

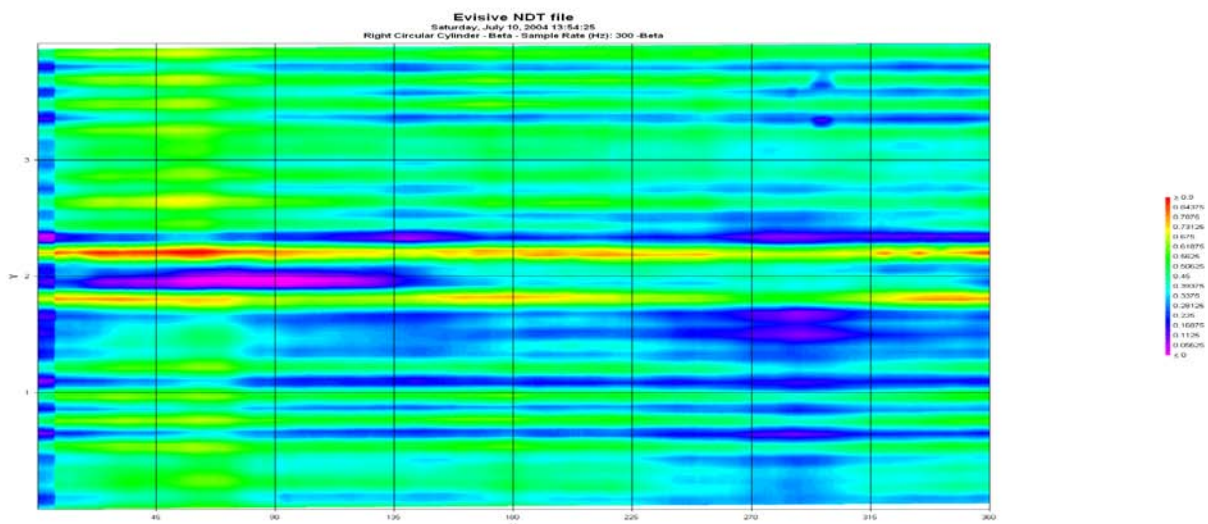

Figure 20: Evisive Scan image of an unacceptable HDPE Thermal Butt Fusion Weld (flaw is lack of fusion due to uneven assembly pressure)

United States and International Patents:

1. "APPARATUS AND METHOD FOR NONDESTRUCTIVE TESTING OF DIELECTRIC MATERIALS", U.S. Patent 6,359,446, MAR. 19.2002
2. "INTERFEROMETRIC LOCALIZATION OF IRREGULARITIES U.S. Patent 6,653,847, Nov. 25, 2003
3. "HIGH-RESOLUTION, NONDESTRUCTIVE IMAGING OF DIELECTRIC MATERIALS", PCT/US2005/026974, International Filing Date 1 August, 2005
4. "NONDESTRUCTIVE TESTING OF DIELECTRIC MATERIALS", Canadian Patent 2,304,782, Mar. 27, 2007
5. "NONDESTRUCTIVE TESTING OF DIELECTRIC MATERIALS", Australian Patent 746997, New Zealand Patent 503733
6. European Patent issued
7. PCT/US2005/026974, International Filing Date 1 August, 2005