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MICROWAVE BASED NDE INSPECTION OF HDPE PIPE WELDS

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ABSTRACT
This paper describes an innovative apparatus and method that has been developed to volumetrically examine dielectric materials, including high density polyethylene piping weldments. The method employs a first of a kind apparatus that is based on the creation of an image using electromagnetic energy in the microwave frequency range.

The results of comprehensive laboratory testing and actual field inspection of HDPE thermal fusion welds using the microwave method and apparatus are presented. The specimens examined included both sound thermal welds and those that included different types of internal flaws that commonly occur in industrial application. Through this research and field application, the apparatus has been shown capable of detecting the presence of internal flaws, such as lack of fusion (i.e. - cold fusion) welds and weld inclusions. Also, thickness changes and voids in the HDPE pipe base material were detected and imaged. The results of the NDE technique are compared to mechanical pull test validation.

Finally, the scan images of the PE pipe thermal welds are compared to theoretical weld microstructure. Relationships between the HDPE weld images and the basic weld microstructure are developed.

INTRODUCTION
The method described in this paper was developed in response to a general failing of existing methods to detect common inhomogeneities in dielectric structures, including homogeneous thermoplastic components, reinforced rubber and fiber reinforced plastic (FRP) composites. Early work in this area has been previously reported [1]. Existing prior art includes radiography and ultra-sonic methods neither of which are ideally suited for inspection of these structures[2,3]. Disbonds and inter-laminar adhesion failures (delaminations) are difficult to detect using radiography, as these are essentially 2 dimensional defects which do not change bulk density to any significant degree. It has been suggested that radiography may be useful in inferring the presence of a disbond, or "cold weld".[3] Rubber and plastic materials can be highly attenuative of ultra-sonic beam energy. Also, the presence of myriad interfaces in typical fiber reinforced structures results in beam scattering and dispersion of ultra-sonic energy, making the use of conventional ultra-sonic methods problematic.

As a result, a method was sought to allow detailed, high resolution inspections of these dielectric materials which was single-sided (i.e. not pitch-catch), non-contact and fast enough to be used as a screening method for both manufacturing and field inspection environments, including HDPE thermal fusion pipe welds.

MICROWAVE METHOD, EQUIPMENT AND PROTOCOL
The novel inspection technique is based on monochromatic, phase coherent electromagnetic radiation, preferably in the 5-50 gigahertz frequency range (i.e. - microwaves). The sample to be examined is exposed to microwave radiation at discrete locations along a path whose coordinate locations are known and are returned as part of the data field, thus creating a map of the specimen. A detectable microwave signal is also returned everywhere along the path and a differing signal is generated at each interface where the dielectric constant changes (e.g. - where there are delaminations, cracks, holes, impurities, or other defects). The return signal is generated based on the angle of incidence, the differential in the dielectric constants between the materials (which is related to the index of refraction), the surface geometry, and other factors. Early testing proved that this technique can successfully detect cracks, voids, foreign material inclusions (e.g., water or oil), thickness changes, density changes, delaminations, changes in dielectric constant (which in rubber may, for example, indicate hardening), and other defects in essentially any dielectric or bulk dielectric materials. It was also found that different types of defects have distinguishable and reproducible characteristics. The testing also showed that the transducer may be moved relative to the specimen at any desired speed and the scanning speed need not be uniform.

The equipment consists of a probe, approximately 2 inches in diameter and 10 inches long, that contains the microwave generator, a position (x, y, or x, radial) monitoring device, an analog/digital signal converter, and a computer that collects and displays the data. All of the equipment is portable and the probe can be mounted on multiple types of scanning platforms. The probe is moved in a continuous fashion along the surface of the sample, either in contact or near the surface. No couplant is required. The return signal is voltage from the probe and position along the specimen. A map is generated from these signals that can be manipulated and displayed.

HIGH DENSITY POLYETHYLENE PIPING WELDS

High Density Polyethylene (HDPE) piping is used extensively in the petro-chemical and utility industries for various services, including harsh environment service. Its use is becoming more prevalent in other industries, including commercial nuclear power, due to its low cost versus steel piping, durability, damage tolerance, its ability to withstand corrosive environments, and its relative ease of construction.[4] There are two types of weldments commonly used in PE piping, the thermal fusion butt weld and the electro-fusion coupling weld. This paper deals with the most common, the thermal fusion weld.

The thermal butt fusion of two ends of HDPE are performed by 3 operations:

1. Facing the two piping ends
2. Heating both ends simultaneously using a hot plate
3. Joining the two pipe ends under pressure (following removal of the hot plate)

The welding process has been previously studied and described in some detail. [4] One of the outstanding issues with the use of HDPE in ASME applications is the current inability to easily examine the weldments. Standard methods, such as radiography and ultrasonics, have proven to not be capable of reliably detecting flaws in the weldments, [2-4] although some reports of successes with TOFD methods have been made.

Common defects in HDPE pipe welds include mechanical damage, contaminants, and “cold weld” or lack of fusion. [2] By far, the most difficult to detect is the “cold weld” defect. This is because the defect may not result in any actual gap or separation in the weld zone. Unfortunately, the “cold weld” is also the largest threat to pipeline integrity, since its failure is typically brittle in nature.

HDPE WELD CHARACTERISTICS

The localized heating and cooling process at a thermal weld location is different than the base material.[4,5] It has been shown that the heating and cooling process at the weld produces microstructure that differs from the base material.[5] The weld microstructure was broken into 5 distinct structures, namely:

1. Skin Remnant
2. Spherulitic, slightly elongated
3. Columnar
4. Boundary nucleation
5. Spherulitic

The location of the material with respect to the weld centerline determines the heating and cooling rates, and thus ultimately the microstructure. It has also been suggested that HDPE microstructure may impact the material dielectric properties, changing the dielectric slightly with changes in microstructure.[6,7]. Therefore, if the heating and cooling processes associated with HDPE thermal fusion welding produces material microstructure differences that locally impact the dielectric constant, these changes would be detectable via the microwave method. It also follows that if these differing material properties are indeed detectable, then deviations from the ideal weld configuration would also be detectable.

WELD BLOCK

In order to further understand the microwave technique and its ability to fully interrogate the HDPE weld, a method was needed to determine if the heat affected HDPE material near the weld indeed had properties that allowed the technique to distinguish it from the base material. The most effective way to accomplish this was to scan a defect free HDPE thermal fusion weld that had been machined flat on each surface. This would eliminate any surface features (including weld beads) that might skew the data due to geometry factors. Such a block was fabricated by Acuren and delivered for scanning. The block is shown in figures 1 and 2.

The weld was cut out from a thick section of HDPE pipe and shaped into a 3.5” by 4” block. The sides were machined smooth so there are no surface features and no inner or outer beads. Figure 2, the weld close-up, shows that the weld line is barely discernable from the base material.

The Evisive microwave scanning technique was used to scan all 4 sides of the block. The scan results appear in figures 3 through 6. Because the scan method is an interference method, special techniques were required to scan the block in order to reduce the magnitude of the interference pattern from the sides and ends of the block. The HDPE is an especially good transmitter of energy in the microwave frequency, so even using special scan techniques, all reflections from the edges of the block appear in the scan, although their amplitude is sufficiently diminished to determine details of the weld itself. These patterns would not appear in an actual pipe weld.

As can be seen in figures 3 through 6, the weld material is clearly visible in the middle of the scan. Also, the scans taken on opposite sides of the HDPE block indicate that the weld profile is the same on the opposing sides, but different on the adjacent side. It is expected that the weld heat affected zone profile would be different on the pipe ID and OD (where the weld beads were located) than on a section through the axial portion of the weld. The difference in profile is likely due to the different cooling rates at the two sections, since the cooling rate in the radial direction differs than the axial cooling rate due to the different boundary conditions and the material properties are directly affected by the rate of cooling.

This result supports the conclusion of others [5,6] that the HDPE weld heat affected zone has a different microstructure than the base material and that this different microstructure changes the material dielectric properties. Since the weld structure can be imaged by the microwave technique, it follows that subtle changes in the structure from a sound fully bonded weld to a “cold weld” may also be detected and imaged.

COLD WELD AND OTHER RESULTS

Extensive laboratory investigation has shown that microwave inspection is capable of volumetrically inspecting the entire weld and adjoining pipe thickness. As part of the proof of principle testing for this method, many samples of welded PE piping were examined and the results documented. The samples included 2 inch through 36 inch nominal diameter piping that were scanned both in laboratory and field settings. The types of joints examined included both thermal welded and electro-fusion welded types. Only examples of thermal welded joint scans are shown in this paper since they are of primary interest. The weld samples included good welds and welds with flaws of known origin. The flaws were manufactured in the coupons and included drilled holes, inclusions of various natures, and lack of fusion.

Figure 7 is one example (of many) of a sound HDPE weld scan. In this image, the return signal voltage has been assigned a false color to make interpretation easier. Also, the outer bead has been removed to provide a smooth surface for the scan probe, as is standard for this scanning method. The weld is examined so that the axial direction is on the Y axis and the radial direction is on the X axis. The centerline of the weld is approximately at Y = 2”. The entire heat affected zone of the weld is approximately ¼ “ in width. The horizontal (parallel to the X axis) regular lines are return signals from the inner bead, which was not removed. Note that the weld appears uniform along its entire length and is little return signal (i.e. – voltage) variation.

Several other welds were inspected with differing types of flaws, mostly induced by deviating from accepted normal construction methods. These scans are shown in figures 8 through 12. The key to figures 7-12 is provided in Table 1.

Fig.	**Description**
7	Sound weld made per accepted procedure
8	10 seconds between end of heating and start of fusion
9	20 seconds between end of heating and start of fusion
10	WD-40 applied at 12 o'clock position prior to start of fusion
11	High pressure applied during fusion time
12	Threads at 2, 5, 8 & 11 o'clock position

Table 1

The scan results shown in figures 8-12 indicate that various deviations from standard accepted thermal fusion weld practice result in deviations in the heat affected zone material properties that can be detected by using microwave scanning. Even subtle changes such as a delay time between end of heating and start of fusion can be detected. This likely due to the rapid formation of a “skin” between the weld that has a different microstructure than the normal weld.[5] Also, a weld made with higher than normal fusion pressure can be detected by a change in thickness of the heat affected zone when viewed in the scan. This is simply due to most of the weld “melt” being forced from the joint, resulting in a thinner than normal bonded area.

The introduction of various inclusions or contaminants in the weld also resulted in areas where there was a lack of proper fusion, and thus, a detectable difference in the microstructure.

MECHANICAL TESTING

Limited mechanical test verification of the method results has been performed and reported by others.[2] The mechanical test results have verified the ability of the microwave scan technique to reliably detect “cold fusion” joints in HDPE pipe.

FIELD APPLICATION

In order to make to method useful, a means was required to allow piping inspection in field applications. Several manual and automated field inspection devices have been developed and successfully used in several field applications. Scan time varies from application to application. Actual field scans have realized speeds that allow up to 20 - 6 inch welds to be inspected per day.

The equipment is compact, portable, and requires minimal set-up time. The inspection technique is non-contact, requires no couplant and access to only one side of the specimen under test, and the results, as can be seen from the scans, are easily interpreted. Additionally, the images are produced from digital information that can be stored indefinitely. Once stored, the information can be retrieved and compared to information obtained from new scans to show the appearance of, or growth of, defects in the specimen.

CONCLUSION

This paper presents a theoretical rationale for the basis of successful microwave inspection of HDPE thermal fusion welds. The theoretical results are correlated to the results of a scan of an intact weld that has been machined to remove any surface features. The results indicate that the heat affected zone of an HDPE thermal fusion weld has different properties from the base material that allow the heat affected zone material to be differentiated from the base HDPE material, when bathed in a beam of monochromatic, phase coherent electromagnetic radiation, in the 5 to 50 GHz range. This allows an image of the weld to be created and characteristics of a good weld standardized and distinguished from a poor quality weld.

Several examples of scans of poor quality welds are provided as examples of how they differ from good welds. Note that the scan results shown in this paper represent only a small fraction of the total body of work performed to develop and perfect the technique. Mechanical testing of weld specimens have been conducted by others that verify the ability of the microwave inspection system to reliably identify poor quality welds, including welds that have a lack of proper fusion, commonly known as “cold welds”.

ACKNOWLEDGMENTS

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FIGURES

Figure 1
HDPE Weld Block

Figure 2
Close-up of HDPE Weld Block Showing Weld Location

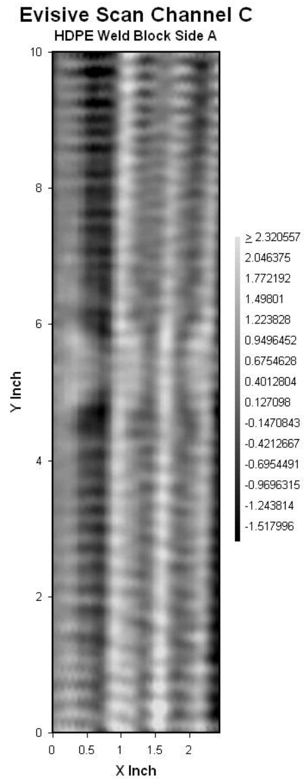

Figure 3
Scan of Side A

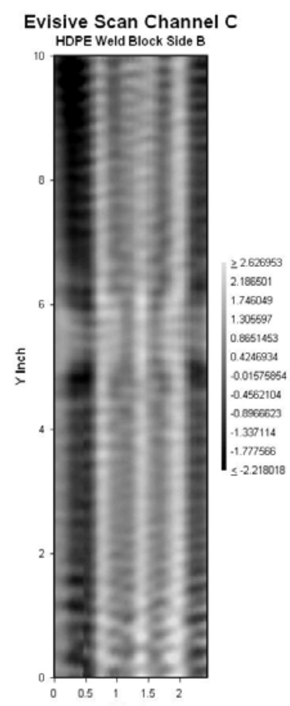

Figure 4
Scan of B (Opposite of Side A)

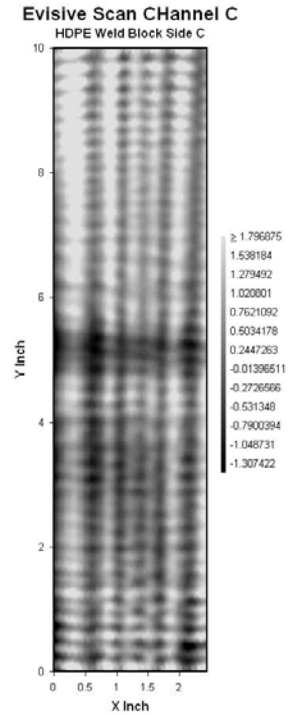

Figure 5
Scan of Side C

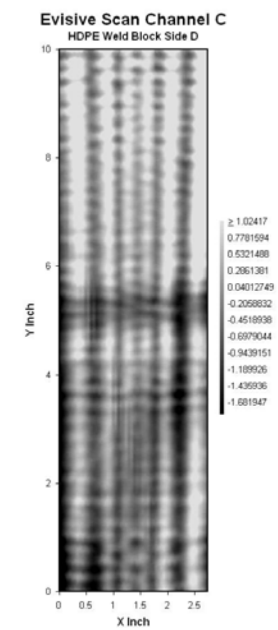

Figure 6
Scan of Side D (Opposite of C)

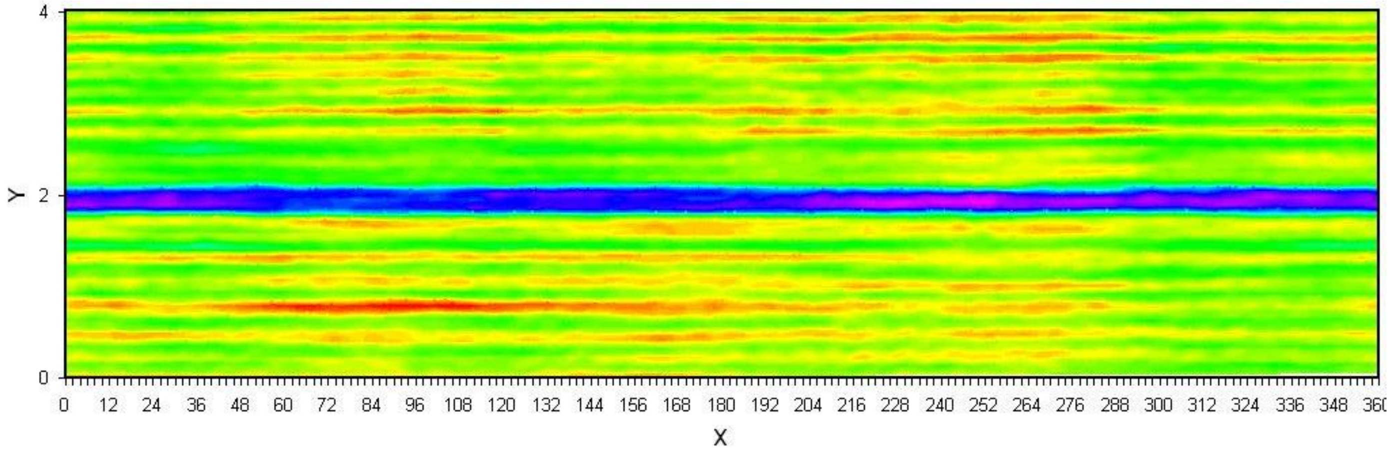

Figure 7
Microwave Scan of Sound HDPE Weld

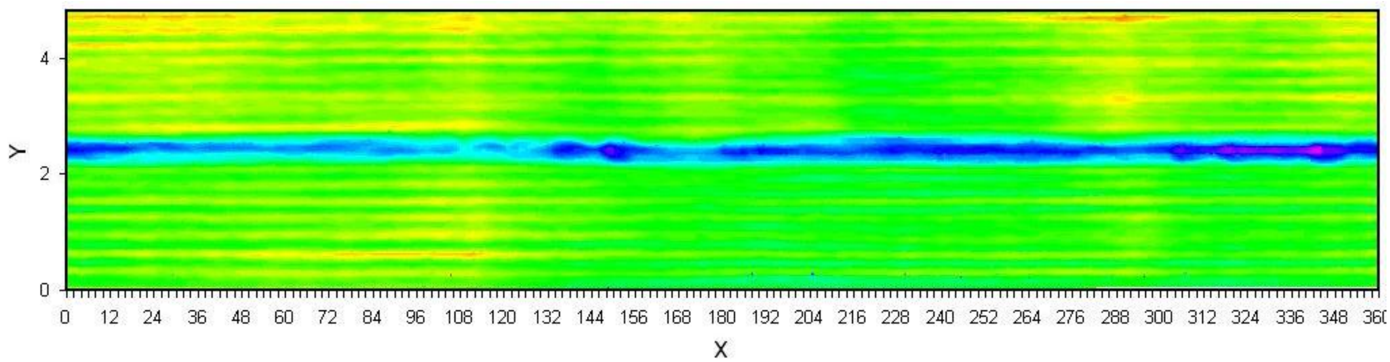

Figure 8
Microwave Scan of HDPE Weld – 10 Second Fusion Delay

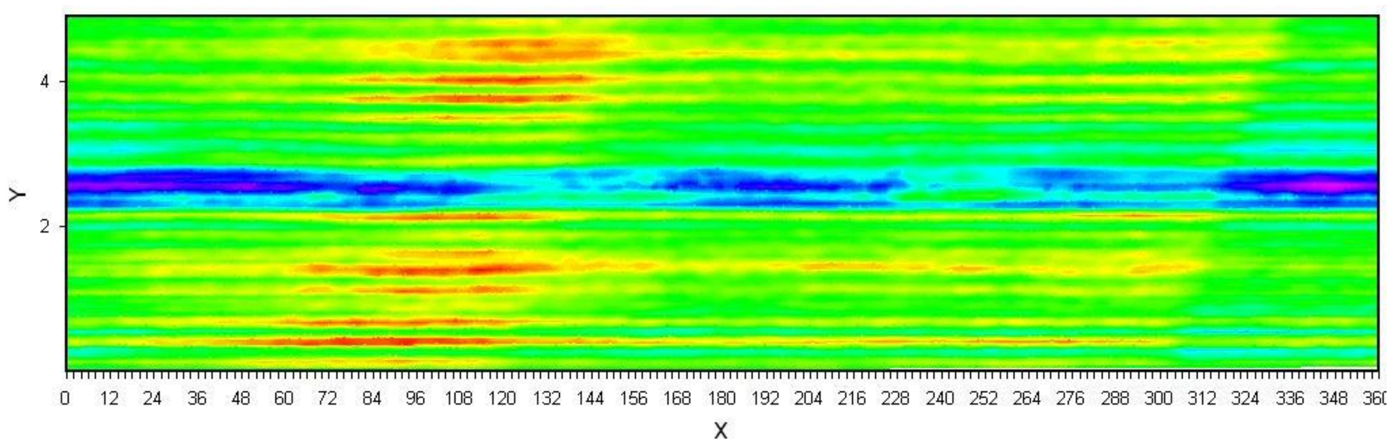

Figure 9
Microwave Scan of HDPE Weld – 20 Second Fusion Delay

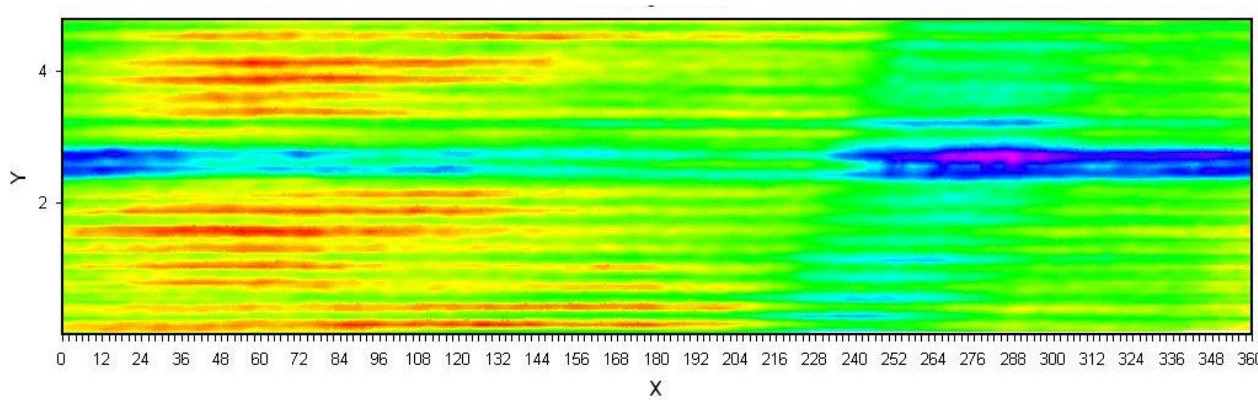

Figure 10

Microwave Scan of HDPE Weld – WD-40 Sprayed on Central Portion of Pipe before Fusion

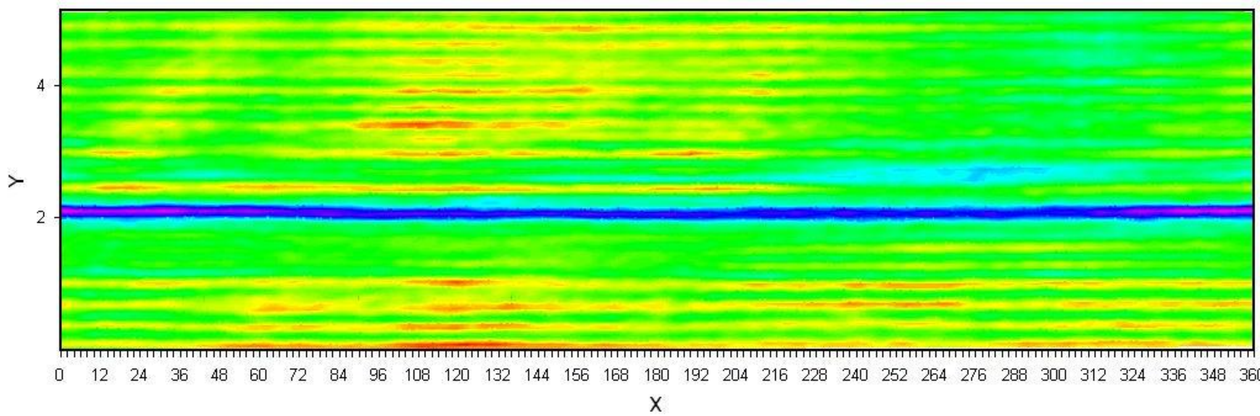

Figure 11
Microwave Scan of HDPE Weld – Assembly Pressure Higher Than Standard

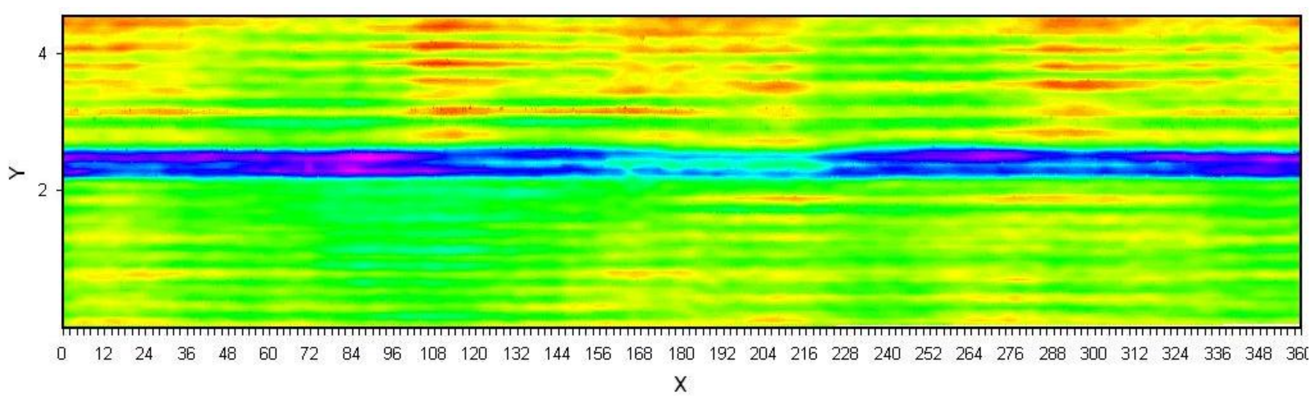

Figure 12

Microwave Scan of HDPE Weld – Cloth Threads Placed on Pipe Prior to Welding