NEW METHOD TO DETECT COLD FUSION JOINTS IN HIGH DENSITY POLYETHYLENE PIPE

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Abstract

This paper describes an innovative apparatus and method that uses electromagnetic energy in the microwave frequency range to volumetrically examine dielectric materials, including high density polyethylene piping fusion joints. This paper describes the theory of use and presents several HDPE inspection case studies. Specifically, this paper describes the mechanics of cold fusion joint detection and in several cases the inspection results are compared to mechanical test results that confirm the accuracy of the examination.

Introduction

The inspection method described in this paper was developed in response to a general failing of existing methods to detect common inhomogeneities in dielectric materials. Early work in this area has been previously reported [1]. Existing inspection techniques for dielectric materials include radiography and ultra-sonic methods, neither of which are ideally suited (for many reasons) for inspection of HDPE materials[2,3].

In the case of HDPE butt or thermal fusion joints, a specific type of defect known as a "cold fusion" has been the most elusive to detect. The exact definition of a cold fusion joint varies around the plastics' industry. A cold fusion joint is generally accepted as an incomplete fusion of the two pipe halves, perhaps only a molecular level, but incomplete nonetheless. A cold fusion joint typically passes initial hydrostatic testing of the piping system, but fails after some service time. The failure may be due to thermal ratcheting or some other time wise change in the piping system that is similar to a fatigue or creep failure.

Since a cold fusion joint may exist only on the level of a molecular bond, the detection by standard means has proved difficult. Unlike an inclusion or an actual "gap" between the adjoining surfaces, there may be no feature of a cold fusion that is detectable using traditional means.

For example, ultrasonic methods rely on what is called an "acoustic reflector" to reflect the sound signal and detect a problem. An acoustic reflector typically involves a drastic change in material that results in a corresponding change in the speed of sound in the material. This occurs at any location where the HDPE is in contact with air, such as at the back wall or in a back drilled hole, a common UT calibration technique.

These interfaces are easy to locate in HDPE, but a cold fusion joint typically has no such interface. They may simply be caused by differing morphologies of the same (HDPE) material. Thus, a method to reliably identify these joints is required to ensure sound fusion properties.

High Density Polyethylene Piping Fusions

High Density Polyethylene (HDPE) piping is being used in many industries, including the 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 joints commonly used in PE piping, the thermal butt fusion and the electro-fusion coupling. This paper deals solely with the thermal fusion joint, although the inspection method described herein has been shown to be quite useful in inspection of electro-fused joints as well.

The thermal butt fusion process for HDPE pipe can be summarized by three (3) operations:

1. Facing (smoothing) 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 fusion process has been previously studied and described in some detail. [4] Common defects in HDPE pipe fusions include mechanical damage, contaminants, and "cold fusion" or lack of fusion, as previously described. [2]

Since these fusions are typically accomplished in "field" or outdoors situations, there are many variables that can affect the adequacy of the joint. Some factors are external conditions, such as temperature, wind, ,and moisture (i.e. – rain), the presence of contaminants like pollen, the condition of the fusion equipment, and the rigor that the mechanics use in following the fusion procedures. All of these factors, and others can negatively impact the quality of the pipe fusion joint. It has been shown that many of these factors, either together or alone, can produce a "cold fusion".

HDPE Fusion Characteristics

In order to understand the principles of operation at work in the microwave inspection method, some discussion of the fusion process itself is necessary.

The localized heating and cooling process at a thermal fusion location is fundamentally different than the hot extrusion process that is used to manufacture the base pipe material.[4,5] It has been shown that the heating and cooling process at the fusion produces microstructure that differs from the base material.[5]

The fusion 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 HDPE material with respect to the axial fusion centerline determines the heating and cooling rates, and thus ultimately the final microstructure. It has also been suggested that the HDPE microstructure impacts the material dielectric properties, changing the dielectric constant slightly with changes in microstructure.[6,7]. This subtle material property change, it turns out, is important to the method described herein.

Microwave Inspection Method

The inspection technique is based on bathing the sample to be inspected in monochromatic, phase coherent electromagnetic radiation, preferably in the 5-50 gigahertz frequency range (i.e. - microwaves). The microwave radiation behaves, in a fashion, similarly to how light behaves at boundaries of materials of varying refractive index. At these interfaces the light energy is either reflected, refracted, or transmitted based on the relative indexes of refraction and the angle of incidence. This is also similar to sound traveling in a medium, only the sound reacts to changes in acoustic impedance (i.e. – speed of sound). In a similar fashion, microwave energy is also reflected, refracted and/or transmitted at each interface of differing dielectric constant. We will call these interfaces “edges”. These edges can be contained in the material itself, or simply be an external interface with the environment.

At these edges, a detectable microwave signal is reflected back to the transceiver. This microwave signal will have some phasic relationship with the outgoing microwave signal. These signals are combined at the receiver (microwave detector) location. The combination of incoming and outgoing microwave signal will result in a signal based voltage generated at the detector location. In a specific material, this voltage has characteristic values depending on the sort of edge detected.

The voltage that is generated is based on several variables including, 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 others. 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.

Therefore, if the heating and cooling processes associated with HDPE thermal fusion produces material microstructure differences that locally impact the dielectric constant, these changes in property may be detectable by a microwave based detection system. As previously asserted, since these types of changes may be the only changes present in a “cold fusion”, it follows that a system of this nature may be the only system capable of detecting this type of defect. It is posited then, that if the differing material properties that are created by the thermal fusion process are indeed detectable, then there should be a reproducible response from what is considered an ideal thermal fusion. If that is true, then any deviations from this “ideal” thermal fusion configuration would also be detectable.

FUSION BLOCK

In order to verify that supposition that there is a difference between the dielectric properties of the heat affected HDPE material near the fusion and the base material, and that it is detectable, a simple test was developed. It seems clear that the theory would be proven if a defect free HDPE thermal fusion could be detected and differentiated from the base material. In order to remove other possible indicators, the sample was machined flat to remove any surface irregularities that might affect the data. Eliminating any surface features (including fusion beads) eliminates the possibility of skewing the data due to geometry factors.

The block is shown in figures 1 and 2. This particular thermal fusion 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 fusion close-up, shows that the fusion line is barely visually discernable from the base material.

Figure 1. HDPE Butt Fusion Block

Figure 2. Close – up of HDPE Block Fusion Zone

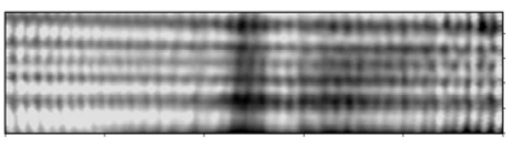

Figure 3. Microwave Inspection of HDPE Fusion Block

As can be seen in figure 3, the zone of fused material is clearly visible as the dark band in the middle of the image. This result was previously reported [11] and supports the conclusion of others [5,6] that the HDPE fusion heat affected zone has a different microstructure than the base material, and that this different microstructure changes the material dielectric properties. Since the fusion structure can be imaged by the microwave technique, it follows that subtle changes in the structure from a sound fully bonded fusion to a “cold fusion” may also be detected and imaged.

Current State of Microwave Inspection, a Case Study

Microwave inspection of HDPE thermal butt fusions has gained increased recognition as a reliable and simple way to inspect HDPE thermal fusions. There have been several recent inspections and on-going research, which are worthy of further discussion.

A specific case study involved inspection of multiple fusions in a coal slurry pipeline. The pipeline inspection was deemed necessary as a result of a recent failure of a butt fusion.

In order to perform an adequate inspection, acceptance criteria were developed for HDPE thermal butt fusions. The acceptance standards are based on inspection of many hundreds of acceptable and flawed specimens. In some cases, the specimens were mechanically tested to verify their mechanical properties.

The acceptance criteria is illustrated in figure 4.

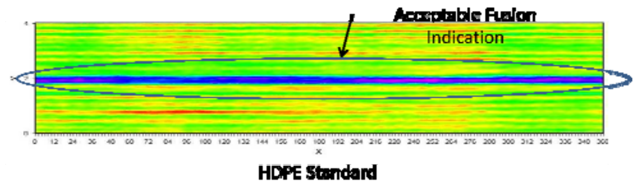

Figure 4 – HDPE Acceptance Standard

Figure 4 illustrates an example of a known good fusion. In this image, the X axis is the pipe diameter and the Y axis is a length of pipe that contains the fused zone. The fused zone is located at the center of the image (Y=2) from X=0 to X=360 degrees. The colors are false color representations of the voltage scale. The recorded voltage, as you may recall from previous discussions, is the result of the presence of materials of differing dielectric constants that pass under the transceiver.

An acceptable fusion has, therefore, been shown to be one where the difference between the fused zone and the base material results in a very clear unbroken change in voltage form the base material. This is very clear in the image shown in Figure 4.

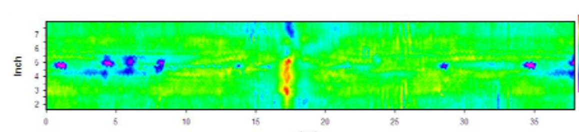

Figure 5 – Field Inspected Joint 1

Figure 5 shows the inspection image of a field joint. The inspected piping was of the following specification:

- 10” IPS
- Driscoplex PE 3408
- DR 7.3

This is one of approximately 40 joints that were inspected in 3-1/2 days by a single crew with 1 microwave scanner. This particular joint was deemed to be of very poor quality.

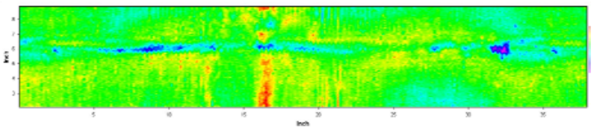

Figure 6 – Field Inspected Joint 2

Similarly, a second poor quality joint, as seen in the field inspection image in Figure 6, was selected. These were determined by the inspection to be the two worst quality joints. These joints were cut into sections and the fusion zones were mechanically tensile tested in accordance with Appendix B of WIS 4-32-08. The results of the tensile testing are shown in figures 7 and 8.

Figure 7 – Tensile Test Result Joint 1 Sections

Figure 8 – Tensile Test Result Joint 2 Sections

Figures 7 and 8 show that both joints failed had brittle fracture results for the tensile test, and thus failed the test. In fact a close-up of a Joint 1 section, shown in Figure 9, shows a very smooth brittle fracture site with no trace of ductility. These joints clearly fall into the "failed" category, as described by the WIS criteria, and could easily have failed in service.

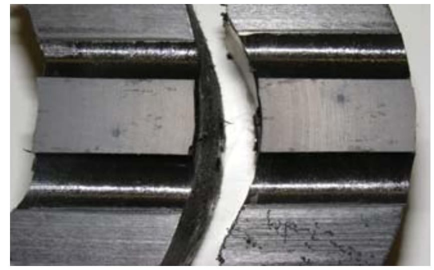

Figure 9 – Tensile Test Result Joint 2 Close-up

Conclusions

It was posed that the thermal fusion zone of an HDPE butt fusion could result in changed dielectric properties that would make the heat affected zone detectable by means of a microwave inspection method. It was further proposed that if this was the case, then subtle changes to the heat affected zone, such as are present in "cold fused" joints, would also be detectable by the same inspection method.

Based on the results presented herein, it has been demonstrated that a microwave inspection of HDPE thermal butt fusions can indeed differentiate the heat affected zone from the base material in the presence of a butt fusion joint. It has also been shown to that the same microwave inspection method can detect flaws in the fusion based solely on changes in the molecular structure of the material due to changes in the dielectric constant of the heated material.

The inspection method is therefore capable of detecting "cold" fusions in the absence of other defect indicators, such as gaps or included material, that are required by other methods. The ability of the method to be used to detect poor quality joints in field situations has been demonstrated by validation with mechanical testing.

It should be noted that this inspection method has found similar applications in HDPE electro-fusion couplings as well as several types of glass reinforced plastic (GRP or fiberglass) piping and fittings. These applications have also been implemented in field service and validated by mechanical testing, thus proving the versatility of the method.

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