AN AUTOMATED SYSTEM FOR MAPPING AUTOHESION AND OTHER JOINING RELATED DEFECTS IN POLYETHYLENE HEAT-FUSED PIPE JOINTS

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INTRODUCTION AND BACKGROUND

The development of an automated system for ultrasonic mapping of autohesion and other joining related defects in heat-fused polyethylene gas distribution pipe joints is discussed. Leading into the system description a brief summary of how polyethylene is joined and the types of defects that can occur is presented. Elastic wave interactions with polyethylene and autohesion defects are outlined to define the flaw detectability problem, particularly, as it relates to the requirements for development of an automated system.

Polyethylene pipe is joined by a heat fusion process in which bonding results from an autohesion mechanism. Two pipe sections to be joined are rigidly clamped in a joining device and a chamfering tool machines the pipe ends so that the surfaces are parallel. The parallel ends of each pipe section are pressed against a heating plate to melt the surfaces, the heating plate is removed, and the fused surfaces are then pressed together. As the pipe surfaces cool a bond is formed by autohesion. The heat-fusion process is much simpler than welding processes used to join steel pipe and has been used to join several hundred thousand miles of gas distribution pipe. Although this is a simple process there are a number of joining parameters that must fall within a window of values to form a mechanically strong bond. These parameters are; (1) heating plate temperature, (2) heating time, (3) melt pressure, (4) joining pressure, (5) delay time, and (6) cooling time. A defective bond results when excursions of the joining parameters out of tolerance windows occur as well as when the surfaces are contaminated. The types of defects that result are absence of bonding, inadequate or weak bonding, voids and inclusions. For example, excessive heating can cause oxidation of the pipe surfaces leading to a weak, brittle bond and insufficient heat can result in inadequate fusion and absence of bonding between the two pipe sections. Contaminating the pipe surfaces with water can cause voids and localized absence of bond. Inclusions act as stress risers and can also result in inadequate bonding. Consequently, a nondestructive method for evaluating the structural integrity of polyethylene pipe joints is needed.

The joining process results in the formation of a bead due to expulsion of fused polyethylene when the pipe sections are pressed
together. Presently the gas utilities are using the appearance of the bead to qualitatively assess the structural integrity of the bonded interface by visually examining bead size, shape and uniformity. Although a visually unacceptable bead appearance is a consistent indicator of a defective pipe joint, it has been observed that a visually acceptable bead does not reliably assure the structural integrity of the interfacial bond. Therefore an alternative inspection method is required.

DEFINITION OF FLAW DETECTABILITY PROBLEM

Unlike voids and inclusions at a bonded polyethylene interface, the physical nature of absence of bond and weak bonding, as manifested in heat-fused gas distribution pipe, requires some elucidation to understand why these classes of defects are detectable. If absence of bond, as is often the case in bonding of other materials, is characterized by surfaces in intimate mechanical contact, then the elastic wave reflection coefficient should be approximately zero. Thus, this type of defect would not be detectable based on the interaction of an elastic wave with the unbonded interface except for possible harmonic generation mechanisms [1]. However, microscopic examinations of joint cross sections in regions of absence of bond have shown that unbonded surfaces between pipe sections separate, forming a gap as shown in Figure 1. The reflection coefficient was calculated for this gap (gap width = 1.7 µm), assuming normally incident plane compression waves and using the expression [2],

\[
R = \frac{1/4(r-(1/r))^2 \sin^2(kd)}{1+(1/4(r-(1/r))^2 \sin^2(kd))}
\]

where \( R \) is the reflection coefficient, \( r = Z_g/Z_p \), \( Z_g \) and \( Z_p \) are the acoustic impedances of the gap and polyethylene, respectively, \( k \) is the wave number for an air-filled gap, and \( d \) is the layer thickness. From Equation (1) the reflection coefficient was found to be approximately one down to a frequency of a few hundred kilohertz. Therefore the detectability of absence of bond is simply a function of the directivity of a two dimensional reflector.

The detectability of weak or inadequate bonding can be understood by comparison of the fracture surface of a weak bond with the two extreme cases of absence of bond and a well bonded interface. If a section of a pipe joint is fractured containing an unbonded region then the fracture surface in that area is featureless. In contrast if a well bonded interface is fractured then the fracture surface exhibits dense fibrillation (drawing of polyethylene filaments as the bond is ruptured). Between these extremes of unbonded and well-bonded interfaces is the case of inadequate or weak bonding, in which the fracture surface exhibits sparse fibrillation (microscopic unbonded areas interspaced between widely distributed polyethylene filaments). Thus, if the unbonded areas produce a gap similar to the more macroscopic case of absence of bond, then inadequate bonding physically manifests itself as a porous interfacial layer and is consequently detectable as a result of wave scattering from the interfacial porosity.

Having defined the nature of defects to be detected it is then necessary to determine the flaw detection requirements. These requirements include consideration of wave mode, frequency, flaw and transducer directivities, and incidence angles.
Wave mode

The energy partitioning functions for a plane p-wave incident on a water-polyethylene interface were calculated and are plotted in Figure 2. Noteworthy features of the energy partitioning curves are that more energy is partitioned into the p-wave mode and the energy partitioning is less dependent on incidence angle for this bulk wave mode than the s-wave mode. From consideration of Snell's Law it is observed that only the p-wave mode can be refracted such that the wave field is directed toward the interface without reflecting from the pipe surfaces. Furthermore, attenuation versus frequency for the p-wave and s-wave modes in polyethylene [3] reveals that attenuation of the p-wave mode (3 dB/cm) is nearly an order of magnitude less than the s-wave mode attenuation (25 dB/cm). For these reasons the p-wave mode was selected for this application.

Frequency

An approach developed by Ermolov [4] to calculate the amplitude of reflected ultrasonic signals from simple target geometries was used to make an initial estimate of the optimum frequency for detecting small flaws in polyethylene. The results for a plane circular target are given in Figure 3. The expression used to calculate the signal amplitude for a circular target is

\[
\frac{V}{V_0} = K_f \frac{\lambda^2}{S} I_1 e^{-2 \alpha \tau}, \ d < 0.2 \lambda,
\]

where \(V/V_0\) is the magnitude of the flaw signal relative to the signal were the entire wave field returned to the transducer, \(K_f\) is a form factor that depends on target classification according to shape, \(\lambda\) is wavelength, \(S\) is the transducer area, \(I_1\) accounts for near- and far-field effects, \(\alpha\) is the material attenuation, and \(\tau\) is the distance between transducer and target. From Figure 3 the optimum frequency for detecting...
the small flaws is approximately 1.5 MHz. A 2.25 center frequency transmitter was eventually selected in order to obtain a sufficiently narrow temporal pulse-width without using highly damped transducers. The time domain width of the pulse was constrained by the requirement of temporal separation of an ultrasonic signal scattered from the fusion bead and a reflection from a defective bond.

Incidence Angles

An important consideration in selecting incidence angles of the elements of a transducer array is the directivity of the transmitter/
receiver and defect. Because of geometrical considerations and other operational constraints the array was designed so that the transmitter and receiver were coincident (i.e. pulse-echo operation). In Figure 4 relative defect amplitude is estimated from target directivity and transmittance of a plane p-wave at a water-polyethylene interface. The directivities of defects were approximated [5] assuming a rectangular shaped flaw, reradiating incident plane waves, similar to a source with a linear double taper displacement distribution, into an omnidirectional point receiver. The linear dimension of the flaws in the radial direction of the pipe are given in the figure and the width of the flaws in the circumferential direction was taken to be 2 mm. As expected the signal amplitude for very small defects is small but independent of incidence angle. As the defect size increases the dependence of the signal amplitude on incidence angle increases, and for large flaws, the signal amplitude becomes a complex function of incidence angle. If line DT is the detectability threshold, then for certain incidence angles large critical defects would not be detectable even though smaller defects are detected. Thus, in applications such as this, where the ultrasonic wave field is obliquely incident on a planar defect, it is necessary to employ multiple incidence angles to assure the detectability of large flaws.

**Temperature Effects**

Also important in the development of an automated system for field inspection applications is the effect of environmental factors, specifically temperature in this application, on the propagation of the ultrasonic wave field in the material. The p-wave velocities in polyethylene pipe materials were measured as a function of temperature using the pulse-superposition method. A linear regression of the data gives a velocity temperature coefficient of -6 (M/S)/C. Although this velocity change has only a small effect on the time domain aspects of flaw detection (e.g., time delay of flaw signals) it has a very significant effect on flaw detectability because of changes in refracted angle. The calculated and experimentally observed effects of temperature are an increase in refracted angle and a decrease in the directivity of the transmitted wave field as the temperature decreases. An experimental investigation of these effects on flaw detectability consisted of fabricating a joint containing embedded, 0.08 mm diameter, flat bottom
holes oriented perpendicular to the bond interface and distributed around the pipe circumference in 1-mm incremental depths from the outer surface to the inner surface. A thermocouple was embedded in the pipe and the pipe cooled to less than -5 C. Data was acquired at incremental changes in temperature from 20 C to -5 C for three array elements oriented to give nominal incidence angles of 34 degrees, 38 degrees, and 40 degrees. It was observed [6] that there is a temperature range over which each array element can operate satisfactorily; the smaller the incidence angle the greater that temperature range. Specifically, the 40 degree array element orientation performed satisfactorily from 25 C to 12 C, the 38 degree orientation from 25 C to 2 C, and the 34 degree orientation from 25 C to less than -5 C. These results illustrate the need to have array elements at various orientations and to activate the appropriate array elements for particular temperature ranges.

DESCRIPTION OF SYSTEM

The salient design and operational features of the automated ultrasonic system are presented here beginning with a summary of the system requirements. The flaw detection requirements, as determined from the analysis and experiments to define the detection problem, are a multi-oriented, multi-element transducer array and a means for selecting the appropriate array element orientations for particular temperature ranges. The operational requirements are automated acquisition and interpretation of defect data, accommodation of 2-inch through 4-inch pipe diameters and the range of polyethylene molecular weights associated with gas distribution piping materials, and field portability.

Mechanical Accommodation of Range of Pipes Sizes

The scanning mechanism consists of a motor driven track assembly, transducer carriage, and integral transducer array and coupling fluid reservoir. Its attachment to a section of pipe is shown in Figure 5. The track assembly is adapted to different pipe sizes by attaching inserts to the inside of the track. The track assembly assures the proper positioning of the transducer array elements with respect to the bond interface. The track is positioned on the pipe using a positioning tool consisting of a cross hair in a spacer bar that is aligned with the part line in the bead. The bead part line defines the location of the bond interface. The track is set against the end of the spacer bar to properly locate the track. To further adapt the system to different pipe sizes a transducer array and coupling fluid reservoir assembly were designed for each pipe size. The array assembly appropriate for the pipe diameter to be inspected is attached to the transducer carriage assembly.

Figure 5. Attachment of scanning mechanism to pipe.
**Temperature Compensation**

Temperature compensation is accomplished by measuring p-wave velocity with an array element oriented perpendicular to the pipe surface. Depending on the wave speed the appropriate array elements are selected by the microprocessor.

**Automation of System Operation**

To automate the inspection system the data acquisition and instrumentation operating parameters are microprocessor controlled. A block diagram of the major system components is given in Figure 6. The operation of the device is menu driven. The microprocessor selects the array elements, driven by a multi-channel pulser, based on the pipe size and material menu selections entered by the operator. For each array element the microprocessor sets the amplifier gain, gate delay and width depending on pipe temperature determined from a velocity measurement. The menu is displayed on a liquid crystal display housed in a hand-held control panel containing software defined function switches. The current function of each switch is displayed directly above its position on the control panel. Menu options are selected by moving a cursor to the desired entry which is then displayed in reverse video. Upon completion of the inspection, the circumferential location of the detected flaws are displayed for each array element along with the accept or reject decision as shown in Figure 7. The decision criteria for accepting or rejecting pipe joints is as follows. If $S_U$ (the summation of signal amplitude above threshold $T$ around the pipe circumference) is less than $D_U$, and $S_L$ (the summation of signal amplitude below threshold $T$ around the pipe circumference) is less than $D_L$, then the pipe is accepted. Otherwise the pipe is rejected. $D_U$ and $D_L$ are 3X3 matrices whose elements have values determined by pipe size, pipe material, and transducer array element. Because of design objectives requiring minimization of the cost of a commercialized device, a peak detector was used to facilitate an inexpensive and, consequently, slow analog-to-digital converter to input the data to the microprocessor. The evaluation criteria was developed to accommodate this hardware constraint and therefore lacks the quantitative aspects that could otherwise have been implemented. However, this simple criteria enables the device to discriminately accept a small isolated flaw while rejecting a large population of spatially distributed, small flaws.

![Block Diagram of Basic System Elements](image-url)
Field System Prototype

The inspection system is shown in Figure 8. A manufacturing prototype is currently under development by T. D. Williamson, Inc. (TDW) in Tulsa, Oklahoma. T. D. Williamson has designed the instrumentation, motor drive, electronics, and control panel to fit inside a housing on the track assembly that is approximately the size of the motor housing (A) shown in Figure 8. Also, in the manufacturing prototype the pressurized coupling fluid tank (B) has been replaced with a recirculating pump and much smaller tank to further enhance the portability of the device.

RESULTS OF SYSTEM LABORATORY EVALUATION

The system is designed so that reflections from the bead are excluded from the evaluation. Thus a good joint should exhibit a horizontal trace with an amplitude near zero and $S_H$ and $S_L$ should be near zero or small. In Figure 9(a) is the array response for a sample containing a distribution of artificial targets, Figure 9(b), described,

Figure 8. Prototype of an automated ultrasonic inspection system for defect mapping in polyethylene gas distribution pipe.
previously in the discussion of temperature effects. The design of the array consists of individual element orientations that optimize sensitivity to small flaws in an outer, center, and inner region of the bond interface while also covering overlapping regions to assure multiple angles of incidence, thereby, increasing the detectability of large flaws. The ultrasonic test results for pipes containing regions of absence of bond and weak bonding were verified by removing 0.5-inch wide samples from the pipe joint as illustrated in Figure 10 and fractured using a modified Izod impact test also shown in Figure 10. The impact test samples were soaked in liquid nitrogen to reduce the load necessary to fail the samples and to minimize the distortion of the fracture surface when failure occurred. The sensitivity of the device was adequate to detect flaws that were sufficiently small to have no measurable effect on the impact strength of the tested samples. The system detected flaws as small as 10 μm wide regions of absence of bond. Detailed results of the system performance have been reported in [6].

CONCLUDING SUMMARY

An automated ultrasonic system capable of mapping autohesion and other joining related defects in heat-fused polyethylene gas distribution pipe was developed. The device is presently being commercialized by T. D. Williamson, Incorporated, Tulsa, Oklahoma, with production of the device expected to begin October 1987.
REFERENCES


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