THE MATERIALS JOINING EXPERTS
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February 24, 2006

Mr. Warren D. Osterberg
U.S. Department of Transportation
Research and Special Programs Administration
Office of Contracts and Procurement, DMA-30
400 7th Street S.W., Rm. 7104
Washington, DC 20590

Other Transaction Agreement DTRS56-03-T-0012, "Improved Ultrasonic Inspection and Assessment Methods for Pipeline Girth Welds and Repair Welds" (EWI Project No. 46997GTH; Cost-Share Projects Numbers 47183CAP and 47416GTO)

Dear Mr. Osterberg:

Enclosed is EWI's final report for the above referenced project.

Please feel free to contact me at 614-688-5188 if you have any questions or comments regarding this project.

Sincerely,

M. G. Lozev

Mark Lozev
Chief Engineer, NDE Technology Leader

Enclosure

cc: Mr. James Merritt and Mr. Gery Bauman

REPORT

February 24, 2006
EWI Project Nos. 46997GTH, 47183CAP, and 47416GTO

Improved Ultrasonic Inspection and Assessment Methods for Pipeline Girth Welds and Repair Welds

Other Transaction Agreement No. DTRS56-03-T-0012

Final Project Report

July 2003 through December 2005

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Submitted to:

U.S. Department of Transportation
Research and Special Programs Administration
Washington, DC

EWI®

MATERIALS JOINING TECHNOLOGY

Final Project Report

Project Nos. 46997GTH, 47183CAP, and 47416GTO

Other Transaction Agreement No. DTRS56-03-T-0012

on

Improved Ultrasonic Inspection and Assessment Methods for Pipeline Girth Welds and Repair Welds

to

U.S. Department of Transportation
Research and Special Programs Administration
Washington, DC

February 24, 2006

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Chapter I

Report Outline

Other Transaction Agreement DTRS56-03-T-0012, "Improved Ultrasonic Inspection and Assessment Methods for Pipeline Girth Welds and Repair Welds" (EWI Project No. 46997GTH; Cost-Share Projects Numbers 47183CAP and 47416GTO)

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Abbreviation List

ARI	Accumulation of relevant indications
AUT	Automated ultrasonic testing
CTOD	Crack-tip opening displacement
DAC	Distance amplitude curve
E-scan	Electronic scanning
ECA	Engineering critical assessment
EDM	Electro-discharged machining
FBH	Flat-bottom hole
FFP	Fitness for purpose
FFS	Fitness for service
FSH	Full-screen height
GMAW	Gas metal arc welding
HAZ	Heat-affected zone
ID	Inside diameter
IDCW	Internal diameter creeping wave
IGSCC	Intergranular stress-corrosion cracking
IPLOCA	International Pipeline and Offshore Contractors Association
IWEX	Inverse wave field extrapolation
LCP	Lack of complete penetration
LOF	Lack of fusion
NDT	Nondestructive testing
OD	Outside diameter
P/E	Pulse echo
PA	Phased array
PISC	Program for the Inspection of Steel Components
POD	Probability of detection
PRE	Primary reference level
RF	Full radio-frequency
S-scan	Sectorial scanning
S/N	Signal-to-noise ratio
SAFT	Synthetic aperture focusing technique
SAW	Shielded arc welding
SDH	Side-drilled holes
SNCF	Strain concentration factors
TCG	Time-corrected gain
TOF	Time of flight
TOFD	Time-of-flight diffraction
VC	Volumetric cluster
VI	Volumetric individual
VR	Volumetric root

Executive Summary

This report presents results from a project jointly supported by U.S. DOT/PRCI/EWI and that extends previous EWI work to include an evaluation of the emerging phased-array (PA) automated ultrasonic testing (AUT) method and further assess the performance of AUT and PA AUT techniques to detect and size flaws in the current pipelines with a relatively wide range of wall thickness.

Given the critical nature of pipelines and the consequences of structural failure, designers are adopting reliability and fitness-for-purpose (FFP) design methods to ensure that structural integrity can be guaranteed throughout the entire design life. The use of reliability and FFP-based design methods requires the use of improved assessment and inspection techniques that can reliably detect and size fabrication flaws produced during construction and repair. Over the last five years, AUT has been used increasingly in cross-country and offshore pipeline construction to improve defect detection and sizing reliability. AUT inspection offers many advantages over conventional manual UT including:

- Improved reliability and performance (defect detection and sizing)
- Ability to obtain an electronic copy of inspection results
- Increased speed.

However, even with advanced AUT methods, there are still uncertainties in defect detection using the current zonal discrimination techniques applying multi-probe or linear PA search units with focused, fixed angle beam, and an amplitude-based approach for defect sizing.

The capabilities and limitations of the current AUT techniques that are based on combinations of amplitude-based pulse-echo (P/E) method or pitch-catch mode using single-element multi-probes (focused or non-focused) or PA transducers with beam-fixed angles and the time-based time-of-flight diffraction (TOFD) method are reviewed in the report. Examples of advanced detection and sizing techniques such as PA electronic (E-) and sectorial (S-) scanning using multiple angles for better detection, advanced imaging, and time-based diffraction techniques for sizing are included in the review. Limited probability of detection (POD) and accuracy of sizing data are shown also. The most extensively used standards for AUT system requirements, AUT procedure development, AUT system qualification and acceptance criteria are reviewed in a separate chapter. AUT practices and experience are discussed also.

During the course of this study, various imaging and data fusion (data-combining) techniques were evaluated to determine their effectiveness for improving flaw detection and sizing. The popular imaging techniques, as well as recent advancements that can be beneficial for girth weld inspection are explained in the report. The effort on the development of improved AUT imaging program is described. A methodology in representing PA UT inspection data in 3D has been investigated, and some promising results were found. Additionally, some of the filtering techniques that proved to be useful in real-work applications are also demonstrated.

It was found that the use of data merging or data fusion techniques greatly enhanced the ability to determine the location and size of flaws. For example, the use of a polar view and fused D-scan helped to visualize the circumferential locations of flaws and the through-wall extent. It was also found that by merging data from the different beam angles collected, it was possible to get a composite view of the weld.

One other important aspect of this study was the use of ultrasonic modeling and simulations to evaluate the benefits and limitations of each AUT technique. Models of ultrasonic beams for each UT technique were produced in order to determine the relative intensity of the sound energy along the path of beam propagation. In addition, the models allowed the beam spot size to be determined at selected locations perpendicular to the direction of propagation. These beam models were helpful when comparing differences in experimental scan results from one technique to another on scans of the same flaw. The modeling and simulation was performed in two steps. The first step was to model the beam profiles for each geometry in order to determine the beam dimensions at different focal depths. The second step was to interact the beams with simulated flaws to study the response from different flaw scenarios. UT modeling and simulation results revealed that uncertainties using amplitude-based techniques are larger for flaws with unknown orientation. It was predicted that is not possible to size accurately girth weld flaws with vertical height less than 1 mm (0.04 in.) using amplitude-based techniques and also the current advanced time-based sizing techniques. The predictions were validated experimentally.

UT modeling, simulation, and modal analysis on two hot tap geometries revealed that the tilting of hydrogen-induced cracking was a major factor in the signal amplitude response. Since crack tilt is somewhat unpredictable, the use of multiple angles should be considered for improving detection of cracks at the weld toe and root.

The results of several trails using different PA techniques applied on girth weld samples in a lab environment are presented in a separate chapter. AUT of girth welds in small and large-diameter pipes with a relatively thin and tick walls were evaluated during this project. The flaws in the samples were implanted or fabricated by varying the welding parameters during the welding process. Very good results were achieved using non-zonal PA approach implementing focusing, steering, and electronic capabilities of PA techniques.

Detection and sizing of service-induced fatigue cracks is often challenging because of the narrow crack-tip opening and the smooth face of the fracture surface. P/E and tandem pitch-catch non-zonal PA techniques were used for detecting and sizing of fatigue cracks. The best detection of the crack face on through-wall cracks was achieved using tandem pitch-catch and dual-PA pitch-catch techniques with shear wave beam angles in the range of 45 to 50 degrees and a probe frequency in the range of 4 to 10 MHz. These techniques provided the best detection with the lowest noise level. Good through-wall sizing was obtained using shear wave beam angles in the range of 50 to 70 degrees and a probe frequency in the range of 4 to 10 MHz. Fatigue cracks less than 1.5 mm (0.06 in.) in height were difficult to size because the relatively weak crack tip signal was usually not fully resolved from the strong corner trap signal and root geometry echoes. PA P/E techniques worked well for crack sizing when using the sector scan technique to electronically steer the sound beam through a range of angles. Even when a tip signal could not be detected, the sector scan display gave a good estimate of the through-wall extension of the cracks. The use of data merging techniques proved very useful for visualizing the through-wall extent of cracks, as well as the crack length.

With the cooperation of Trans Canada PipeLines Ltd. and two AUT companies, a field trial was conducted in January 2004 in Alberta, Canada, with an average temperature of approximately -20°C or -4°F. The purpose of the field trial was to compare inspection results between PA UT and multi-probe UT on the same welds under realistic conditions on 250 girth welds on pipe having 61-cm (24-in.) diameter with a 7.8-mm (0.31-in.) wall thickness. Both AUT inspections used the zonal approach described in ASTM E1961 and were very similar regarding calibration procedures and beam angles used for each zone. The test frequencies were slightly different, but all were in the range of 4.0 to 7.5 MHz. The only major differences were that one inspection used linear PA probes which allowed focusing in the active plane, and the other inspection used round unfocussed probes. Acceptance criteria for these welds were based solely on flaw length. The multi-probe inspection identified one weld, as rejectable due to a crack indication. The PA inspection identified eight welds as being rejectable, including the weld rejected by multi-probe inspection. The multi-probe data was later analyzed by a third party to look at the welds that contained rejectable indications found during the PA inspection. The data revealed that flaw lengths measured during the PA inspection were generally longer than those measured during the multi-probe inspection. This caused some flaws to fall into the rejectable category based on measurements greater than 12 mm (0.5 in.) for surface flaws.

An AUT round robin was conducted at the McDermott facility in Batam, Indonesia, to evaluate multi- and PA probe techniques for inspection of pipe girth welds under actual tropical field conditions August 2004. In addition, to the electrical noise tests, the welds were also scanned before and after heating to determine the effects of temperature on the test results. Overall, no adverse effects were noted from the noise level tests or the elevated temperature tests.

During these trials, the welds were scanned using two separate PA inspection systems and three multi-probe systems. The pipe was 601-mm (24-in.) diameter with a 13.8-mm (0.54-in.) wall thickness. While both PA and multi-probe techniques were used, all inspections were performed using the zonal AUT approach similar to what is described in ASTM E1961. All AUT inspections used the same calibration reference standards for establishing test sensitivity and flaw position (distance) calibration. AUT inspectors were asked to report and size all indications using detection levels and sizing techniques that they would typically use for detecting and sizing critical flaws in girth welds. A total of four welds were inspected by the five AUT inspections while full-scale welding operations were being performed nearby. One weld was inspected in laboratory conditions applying non-zonal PA approach and implementing focusing, steering and electronic capabilities of PA techniques.

The data from UT vs. destructive comparison show that in nearly all cases flaws greater than 1 mm (0.04 in.) in height were detected; however, the UT flaw height measurements were inconsistent. Much of the inconsistency appears to be related to the actual AUT test procedure used. With the exception of one location, all the flaw heights for the lab scans were similar even when using probes having different frequencies and element sizes.

Results showed that that flaws having large through-wall heights had greater scatter in the data and were both undersized and oversized when using the zonal approach. The lab scans using electronic beam steering and raster scanning detected several flaws that were missed in the field and sized the through-wall height with less scatter. However, flaws having through-wall dimensions less than the beam spot size of approximately 2 mm (0.08 in.) tended to be oversized. It was found that the use of S-scans and data merging or data fusion techniques for non-zonal PA verification greatly enhanced the ability to detect and determine the location and size of flaws.

Two AUT procedures were developed at the end of this project and included in the report. The recommended procedures covered AUT of girth welds and repair welds inspection using and advanced non-zonal PA approach via implementation of focusing, steering, and electronic capabilities of PA techniques.

A summary of the conclusions of the project results are as follows:

- The results showed that if the zonal line scan approach with focused, fixed angle beam, and an amplitude-based sizing is used the results will be similar regardless of whether PA or multi-probe is used.

- If the electronic steering, focusing, and scanning features of PA are used an improvement in flaw detection and sizing is possible for defects with unknown orientation.

- Data fusion techniques are used to greatly aid in data interpretation.

- UT modeling and simulation tools are very beneficial in ultrasonic technique development and for technique validation purposes.

Recommendations:

- Implementing some of the recent developments in ultrasonic PA inspection technology to significantly improve AUT techniques of girth and repair welds inspection.

- Extend the current zonal approach for AUT of girth weld inspection to non-zonal PA inspection using all PA capabilities such as electronic scanning, focusing, and steering.

- Performing a global AUT qualification on typical bevels instead of project by project AUT systems qualification will significantly reduced the cost and effectiveness of the qualification process.

- Generating and publishing in the open literature statistically valid POD and accuracy of sizing data for typical materials, bevels and welding procedures is recommended.

- Organizing performance demonstration tests for AUT operators is recommended.

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1.0 Final Technical Program

1.1 Introduction

Given the critical nature of pipelines and the consequences of structural failure, designers are adopting reliability and fitness-for-purpose (FFP) design methods to ensure that structural integrity can be guaranteed throughout the entire design life. The use of reliability and FFP-based design methods requires the use of improved assessment and inspection techniques that can reliably detect and size fabrication flaws produced during construction and repair. Over the last five years, automated ultrasonic testing (AUT) has been used increasingly in cross-country and offshore pipeline construction to improve defect detection and sizing reliability. However, even with advanced AUT methods, there are still uncertainties in defect detection and sizing using the current zonal discrimination, amplitude-based approach. In order to reliably apply FFP-based design and construction methods to both current and next-generation high-strength, high-pressure, cross-country, and offshore pipelines there is a need to define the performance and limitations of current AUT methods and develop improved multi-probe AUT and phased-array (PA) AUT systems to detect, locate, and size flaws and to resolve distance between potentially interacting defects.

EWI has recently completed several independent study funded by PRCI/GTI to determine the limits of AUT for cross-country pipelines.[1.1-1 through 1.1-10] These studies included both experimental testing and computational simulation. This report presents results from a project jointly supported by U.S. DOT/PRCI/EWI and that extends EWI work to include an evaluation of the emerging PA AUT method and further assess the performance of AUT and PA AUT techniques to detect and size flaws in the current pipelines with a relatively wide range of wall thickness.

1.1.1 References

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