A Validation Study of Computed Tomography Inspection Technology Using Full-scale Test Articles with Crack-like Features

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ABSTRACT

The aging pipeline infrastructure in the United States has created the need for advanced engineering assessment methods. A critical part of this process involves the use of inspection technologies, primarily in-line inspection (ILI) and in-the-ditch technologies. To validate ILI technologies, it is essential to have advanced Non-destructive Examination (NDE) inspection technologies to verify ILI measurement accuracy. Current NDE methods are available for inspecting deformations and corrosion; however, inspection of cracks and seam anomalies remains a significant challenge. Computed Tomography (CT) is an advanced inspection technology that delivers greater accuracy than conventional NDE inspection techniques for these challenging features.

This paper presents details on a study designed to validate the CT technology by evaluating the growth of various crack-like features subjected to cyclic pressure. Simulated crack-like features were generated using electronic discharge machining (EDM) to form notches in pipe materials. The simulated defects formed cracks after a certain number of pressure cycles were applied, leading eventually cause pipe sample failures. After a designated number of pressure cycles were applied, cracks were inspected using the CT technology and compared to results based on measurements from actual sectioned features.

The elements of this program will contribute significantly to advancing inspection capabilities for the pipeline industry. The results of this study provide a basis for establishing industry calibration and reference standards against which ILI technologies can be evaluated. A critical limitation in the pipeline industry is the absence of reference standards based on real-world samples and the necessity to destructively test samples used in technology evaluations. The successful implementation of CT addresses current inspection limitations and is poised to make significant advances in validating ILI measurements.

INTRODUCTION

The use of Computed Tomography (CT) can be used for the inspection of crack-like features in high pressure transmission pipelines to provide higher resolution data than conventional NDE technologies. One challenge associated with the inspection of crack-like features is their geometry, including their relative sharpness and narrow profile. These characteristics make it difficult to detect and size using conventional non-destructive examination tools. Computed tomography has the potential to measure these small crack-like features. ADV was contracted by Inspection Associates, Inc. to generate a variety of crack-like features in full-scale pipe samples using EDM-starter notches. The test program was designed to permit Inspection Associates to analyze the crack geometries using their in the ditch CT tool, and then compare the inspection results to a micrographic analysis of each crack geometry. A photograph of Inspection Associates' CT tool is provided in Figure 1.

Three (3) 12.75-inch x 0.375-inch, Grade X42 pipe samples were fabricated to include EDM notches at key locations and depths. A total of 14 EDM notches were installed in the three (3) pipe samples. The goal was to create a wide range of crack-like features that are representative of crack-like defects found in actual operating pipelines. The depth of the EDM notches ranged from 5 to 30% of the pipe's nominal wall thickness. Notches were placed in the OD pipe body, OD ERW Seam, and ID ERW longitudinal weld seam. Uniaxial strain gages were installed across each outer diameter EDM notch as a means for monitoring crack growth. To generate microcracking at the base of the EDM notches, the samples were pressured cycled until the uniaxial strain gages indicated significant change in strain range that indicated crack growth initiation. Increased strain range across the EDM notch corresponds to increasing crack depth, and thus provides a means for monitoring crack growth during pressure cycling.

Following completion of the pressure cycling phase of testing, pipe samples were provided to Inspection Associates, who scanned the crack-like features with their CT tool. ADV then sectioned the samples and viewed the features along the transverse and longitudinal profiles. The crack-like features were photographed and the feature geometries (i.e., depth and length) were measured using a stereo microscope. The measurements were provided to Inspection Associates so that they could calibrate their software. After calibration, the CT software was able to measure the geometry of the crack-like features. The average difference between the CT-measured geometries and actual values was 3.5% with a standard deviation of 5.9%; the maximum difference was measured to be 14.4%.

The sections of this paper that follow include a *Test Methods* section that provides an overview of the test samples and notch geometries used in the study. The *Presentation and Discussion of Test Results* section includes research findings, such as cycles to failure and crack depths. The *Discussion* section provides important insights on what the test results mean in terms of reproducibility of CT scans. Finally, the *Closing Comments* section provides a few concluding remarks related to findings from the overall program.

TEST METHODS

The test program used three (3) 6-ft long pipe sections comprised of 12.75-inch x 0.375-inch, Grade X42 HF-ERW pipe material. A wide range of crack-like features were generated for this test program. The first sample contained six (6) pipe body defects, the second sample contained four (4) defects in the outer diameter ERW bondline, while the third contained four (4) defects on the inner diameter ERW bondline. An overview of the overall test matrix is provided below in Table 1. Samples 2 and 3 contained EDM notches in the ERW bondline. A macro-etching process was used to locates the ERW bondlines, as shown in see Figure 2.

Table 1: Test Matrix

Sample Number	EDM Notch Length	EDM Notch Location	# of notches	EDM Depths %WT
100111-OD-1	3-inch	OD base pipe	6	5-30%
100111-OD-2	3-inch	OD ERW seam	4	5-20%
100111-ID-3	3-inch	ID ERW seam	4	5-20%

EDM notches of various depths were installed in each pipe sample. Table 2 lists how the notches were labeled according to depth as a percentage of wall thickness.

Table 2: Notch depths for all samples

Notch	Depth %WT
A	5%
B	10%
C	15%
D	20%
E	25%
F	30%

After installing the notches, Inspection Associates welded end caps and ½-inch NPT bossets to the pipe sections. Next, uniaxial strain gages were installed across all outer diameter notches to monitor crack growth. A biaxial strain gage was also placed on the pipe body of each sample to serve as a generalized reference measurement. Samples were placed in an enclosed test chamber and pressure cycled from 4% to 72% SMYS (100-1,779 psig) until strain gage readings indicated that cracking had developed at the base of some EDM notches. The goal was to generate a wide range of crack-like features, and not necessarily a crack at the base of each EDM notch.

Following pressure cycling, Inspection Associates scanned the features using their CT tool. Then, the samples were sectioned and independently-examined by ADV Integrity along the longitudinal and transverse profiles. Each notch was split into four quadrants as shown in Figure 3. Quadrants III and IV were prepared as transverse metallurgical specimens and Quadrants I and II were cryogenically fractured for a longitudinal view. The transverse mounts were cold mounted in metallurgical epoxy, polished to a 0.05 μm surface, and then finished with a 2% nital etch. Both the transverse and longitudinal specimens were measured using photomicroscopy. A summary of the depth measurements from the CT scans and microscope measurements are listed in Table 3 in the Results section of this report.

PRESENTATION OF TEST RESULTS

Sample 1, which contained the deepest notch, leaked after 10,628 cycles. The remaining two samples were cycled until a leak developed in the girth weld of Sample 3 after 16,751 cycles. The goal of the pressure cycling was to produce a wide range of crack-like features to examine. Based on the strain gage readings, it was likely that Samples 2 and 3 had developed several cracks as indicated by increased strain ranges. Therefore, pressure cycling was considered complete and it was not necessary to repair the end cap to resume cycling. It was not possible to record strains on Sample 3 because the EDM notches were machined on the inner diameter of the pipe sample.

Cracks are typically visible in a transverse mounted specimen; however, in this study not all cracks were visible in the transverse mounts. In addition, the transverse views from the CT scans occasionally presented visual aberrations that made it difficult to determine the true depth of the features. An example of a transverse mount is presented to show the location of the EDM notch with respect to the ERW bondline, see Figure 4.

The longitudinal view of the broken open features proved to be the most reliable way to view the depth of any microcracking at the base of the EDM notches. In addition, the CT scans produced clearer images in this orientation with the aid of computed density to colorize the crack. Therefore, the longitudinal view was selected as the optimum orientation to compare feature depths. Figure 5 shows a side-by-side comparison of the CT scan to a photograph of the actual feature.

A summary of the resulting measurements from both the micrographs and CT scan images are presented below. The Wall Thickness (WT), EDM Notch Depth, and Crack Depth were measured using a stereo microscope and their corresponding values are listed in the table below. The total depth of each feature is listed as the EDM Depth or the Crack Depth, whichever was deeper. Inspection Associates reported their values based on the total depth of the feature, as shown in the CT Depth column. Finally, the percent difference was calculated to show how CT scans may have deviated from to the measured values.

Table 3: Summary of Results

Sample	Notch	WT (in)	EDM Depth (in)	Crack Depth (in)	Total Depth (in)	CT Depth (in)	% Difference
100111-OD-1	A	0.364	0.019	0.000	0.019	0.0174	-8.4%
100111-OD-1	B	0.363	0.038	0.000	0.038	0.0380	0.0%
100111-OD-1	C	0.365	0.055	0.062	0.062	0.0709	14.4%
100111-OD-1	D	0.360	0.074	0.110	0.110	0.1107	0.6%
100111-OD-1	E	0.366	0.094	0.174	0.174	0.1775	2.0%
100111-OD-1	F	0.365	0.105	0.365	0.365	0.3745	2.6%
100111-OD-2	A	0.376	0.019	0.000	0.019	0.0210	10.5%
100111-OD-2	B	0.369	0.040	0.000	0.040	0.0410	2.5%
100111-OD-2	C	0.372	0.066	0.128	0.128	0.1304	1.9%
100111-OD-2	D	0.369	0.072	0.180	0.180	0.1798	-0.1%
100111-ID-3	A	0.382	0.020	0.000	0.020	0.0210	5.0%
100111-ID-3	B	0.378	0.039	0.000	0.039	0.0390	0.0%
100111-ID-3	C	0.380	0.056	0.000	0.056	0.0630	12.5%
100111-ID-3	D	0.382	0.075	0.083	0.083	0.0870	4.8%

DISCUSSION

The resulting crack measurements made by ADV Integrity were shared with Inspection Associates to aid their efforts in determining the best way to present the data. Initially, some of the CT scan images were producing aberrations on several of the inspected features. The results from the micrographs were used to develop a method for filtering out these aberrations. It was determined that the density of a material can be computed with the CT scan data; thus, it is possible to identify where an air gaps exists relative to where metal is present based on the observed density measurement. Using the density data, 3D models of each feature were recreated, and the resulting features are shown in red as indicated by a lower density than the surrounding metal. The density data and the x-ray images from the CT scan must be used together, alongside an experienced technician, to reproduce the results in this study.

CLOSING COMMENTS

Inspection Associates' CT technology provides an innovative and non-destructive method for examining crack-like features in pipeline materials. In this particular study a test program was conducted using three (3) 12.75-inch x 0.375-inch, Grade X42 pipe samples that included EDM notches used to generate crack-like features through the application of cyclic pressure. A total of 14 EDM notches were installed in the three (3) pipe samples. Inspection efforts included CT scans, as well as measurements generated from transverse and longitudinal views made from fracture surface by breaking open the features.

For each feature, the longitudinal profile was accurately reproduced by the CT scan; however, the transverse view did not always show the correct orientation of the crack. The depth of the feature, which is arguably the most important measurement, showed maximum error of 14.4%. As shown, many depths were identified with close to 0% error. CT scans provide an effective means for determining the total length and longitudinal profile of a feature, as well as providing an approximate depth.

Figure 1: View of Inspection associates CT tool and crane truck

Figure 2: Macro-etching to locate the ERW bondline

Figure 3: Example of how notches were labeled and sectioned

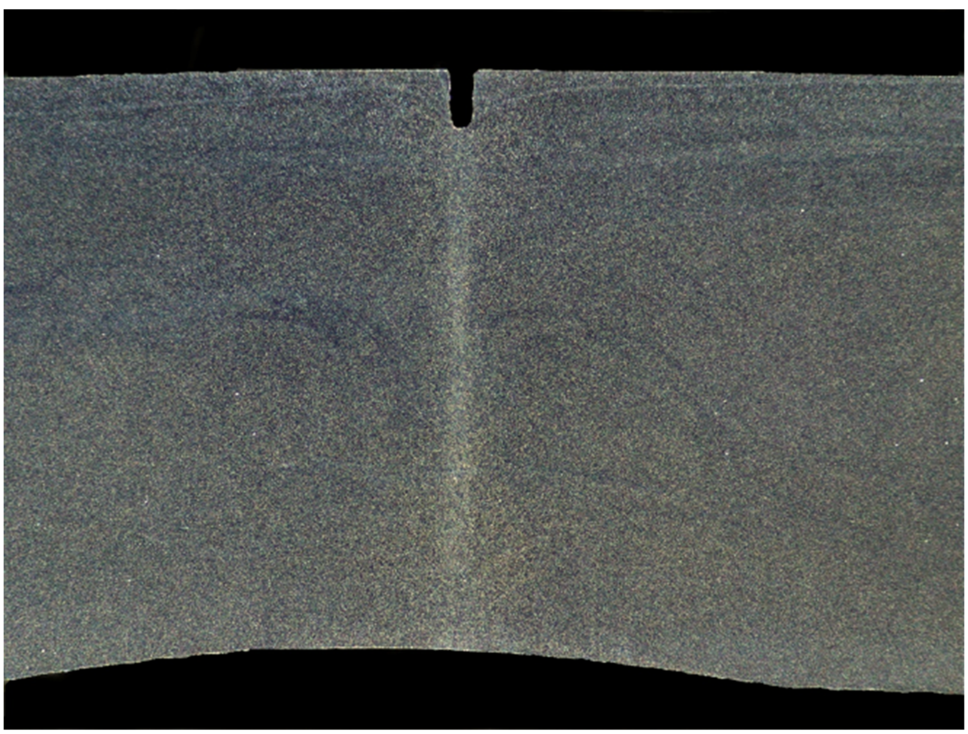

Figure 4: EDM notch in the ERW bondline, Sample 2 Notch B shown at 8X magnification

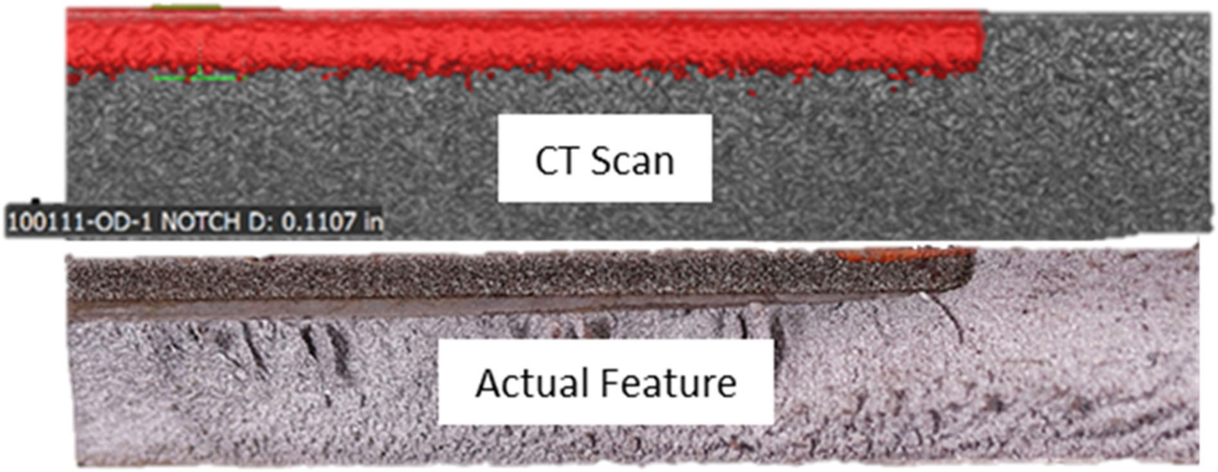

Figure 5: Comparing the longitudinal view, Sample 1 Notch D