ILI and NDE characterization of pipeline manufacturing flaws and confirmation through full-scale testing

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PIPELINE MANUFACTURING FLAWS, such as slivers, can be difficult to accurately characterize and size through in-line inspection and in-the-ditch NDE methods. After discovery of longitudinal flaws of varying depths and lengths in a natural gas pipeline, full-scale burst tests and metallography were conducted to confirm the size and morphology of the features. Metallography indicated that the flaws present were consistent with original manufacturing mill slivers. The metallography also confirmed that the flaws showed no evidence of in-service growth. While flaw depths varied, the remaining wall thickness of the pipe accounting for the depth of the sliver was within API 5L minimum tolerances. Flaw depths measured via metallography were compared to those reported by the original in-line inspection vendor (ILI), phased array ultrasonic testing (PAUT), and Applus RTD's IWEX system. Flaw depth measurements varied between methods but were consistently greater than those determined through metallography. Slivers are typically very shallow flaws; consequently, they can be difficult to accurately size with typical NDT methods such as PAUT. Sizing the flaws in these samples was further complicated by the presence of inclusions and laminations typical of vintage pipeline steels. In this respect, the IWEX system had an inherent advantage in that it allowed the user to visualize the flaw through the pipe wall. In this case, the flaw orientation was shown turning parallel to the pipe's outer surface in the IWEX scans. Research indicated that manufacturing flaws such as slivers represent a minimal integrity concern in pipelines unless they grow during fatigue cycling which is unusual. This assertion was confirmed through full scale cyclic and burst tests of the flaws.

STRESS ENGINEERING Services, Inc. (SES) was provided with four pipe samples containing axial flaws found during a recent in-line inspection (ILI). The subject pipeline has a nominal 30 inch diameter with a 0.312 inch wall thickness, and was constructed in 1974 from API 5L Grade X65 Kaiser DSAW pipe material.

Background information indicated this pipeline underwent two field hydrostatic tests, one following original construction and one following conversion from liquid to gas service. Both hydrostatic tests exceeded 1,232 psi. The pipeline was coated with an AGF-7 (Asphalt-Glass-Felt) coating and may have experienced extra protection with cathodic protection.

Flaws of varying depths and lengths were originally identified during an ILI run using a Multi-Channel Caliper (MCC) and an Ultrasonic Crack Detection with wall thickness measurement combo tool (UT Combo). The samples were removed from the line based on calculations performed using the Log-Secant method which showed the burst pressure to be less than the MAOP. Furthermore, the ILI indications were called out as notch-like flaws. It was determined that the flaws affected the entire pipe joint after Phased Array Ultrasonic Testing (PAUT) was performed on the identified flaws.

The ILI and PAUT results for the surface-breaking features indicated in each dig are compared in Table 1. The depth readings for Feature 8981 and 8982 from Sample 2 correlate reasonably well between the ILI and PAUT data. The remaining features were reported as significantly deeper by PAUT as compared to ILI. Four total pipe lengths with axial flaws were cut out and sent to SES for analysis, identified as Samples 1 through 4.

Sample	Feature ID	ILI		PAUT	
		Inch	**% WT[1]**	**Inch**	**% WT[1]**
1	2648	0.079	25	0.119	38
2	8981	0.039	12.5	0.020	6.4
	8982	0.039	12.5	0.024	8
3	8988	0.079	25	0.131	42
4	9678	0.079	25	0.120	38.5
	9679	0.039	12.5	0.140	45
	9680	0.039	12.5	0.125	40
	9681	0.079	25	0.170	54.5
	9682	0.039	12.5	0.087	29

Table 1: Feature depth by ILI and PAUT.
[1] *Percent wall thickness calculated based on nominal wall thickness of 0.312 inch.*

The goal of this study was to analyze the features present in the four samples provided and determine whether they represent an integrity threat to the pipeline under current operating conditions and under what conditions they may become a future threat to the integrity of the pipeline. Additionally, a comparison between various NDE methodologies was discussed.

Visual examination

All four samples were visually examined upon arrival. External surface breaking flaws were visually identified, such as the one shown in Figure 1 from Sample 4. A combination of external surface breaking, internal surface breaking, and mid-wall flaws was identified by the PAUT vendor and confirmed visually according to the markings present on the pipes. All of the external surface breaking flaws were visually similar to the one shown in Figure 1. SES visually examined these flaws; some were noted to be intermittently external surface breaking down the length of the pipe.

Nondestructive examination methods

Selected areas along the pipe samples were examined via magnetic particle inspection (MPI). Additional examination was performed by circumferentially grinding across the feature to determine whether the flaws were consistent with a crack or a rolled-in surface flaw. If the flaw is consistent with a rolled-in surface flaw, the tip of the MPI indication will travel circumferentially as the grind is deepened. If the flaw is consistent with a crack or notch-like defect extending into the pipe perpendicular to the outside surface, the tip of the MPI indication will remain at the same circumferential orientation.

An example of this inspection on Feature 8988 from Sample 3 is shown in Figure 2 and Figure 3. Figure 2 shows the MPI indication after light buffing with a wire wheel to remove flash rust. Figure 3 shows the MPI indication after lightly touching the grinder perpendicular to the flaw. As described above, this feature was found to be consistent with a rolled-in surface flaw because the tip of the MPI indication traveled circumferentially around the pipe. The total grind depth was rather shallow at less than 10% of the wall thickness. This grinding indicated that the maximum flaw depth in the area inspected was also shallow.

Table 2 summarizes the NDE methods performed on various features across all four samples. The NDE methods performed includes ILI, PAUT, Applus RTD Inverse Wave Field Extrapolation (IWEX) system, and circumferential grind. IWEX is an ultrasonic technique that produces an image of the inspected volume, rather than a plot of the collected signals. These results were then compared to metallography. Finally, two of the samples were subjected to full-scale burst tests.

Sample	Feature ID	Feature Type	ILI	PAUT	IWEX	Grind	Metallography	Burst Test
1	2644	Midwall	×	✓	✓	×	✓	×
2	8978	Internal	×	✓	✓	×	✓	✓
	8981	External	✓	✓	✓	✓	×	✓
	8982	External	✓	✓	✓	✓	×	✓
3	8988	External	✓	✓	×	×	✓	×
4	9677	External	×	✓	✓	×	✓	✓

Table 2: Summary of NDE methods performed on various features.

Comparison of NDE results and metallography

The sections below compares the flaw depth determined through several types of NDE (i.e., ILI, PAUT, and IWEX) to the actual flaw depth determined through metallography. In several cases the ILI vendor did not report a flaw depth; however, this does not imply that the feature was not identified.

Sample 1

Feature 2644 was scanned in-the-ditch with PAUT and post-burst test with IWEX. A metallurgical cross-section for Feature 2644 was prepared approximately 17.2 feet from the upstream girth weld. A mid-wall inclusion was identified 0.170 inch from the outer pipe surface (Figure 4). Close-up examination revealed a line of elongated inclusions and voids. The longest void is shown in Figure 5. The indication examined does not appear to turn perpendicular to the pipe surface and does not exhibit any signs of flaw growth.

Feature 2644 was determined by metallography to be 0.170 inch from the outer pipe surface. Both PAUT and IWEX identified the flaw as 0.125 inch from the outer pipe surface. It is possible that some NDE signal was lost due to the complex cluster of elongated inclusions along the pipe's mid-wall. Visualization of the IWEX data (Figure 6) indicates that the flaw remains mid-wall and does not exhibit a surface breaking feature. Additionally, the IWEX data indicate that the tip of the flaw does not extend perpendicular to the pipe's surface. Both of these findings were confirmed through metallography (Figure 5).

Sample 2

All features in Sample 2 survived the cyclic and burst test, discussed later in this report. Feature 8978 was scanned in-the-ditch with PAUT and post-burst test with IWEX. Feature 8978 from Sample 2 was identified as an internal surface breaking indication. This feature was determined to be consistent with a scratch with a depth of 0.004 inch (1.3% of nominal wall thickness). Both PAUT and IWEX overestimated the flaw depth; however, similar to before, IWEX allows the user to visualize the flaw as shown in Figure 7.

Features 8981 and 8982 were both reported by the ILI vendor. Both features were scanned in-the-ditch with PAUT, later in the lab with PAUT, IWEX, and the perpendicular circumferential grinding procedure. Figure 8 shows Features 8981 and 8982. These features were initially scanned via IWEX. Visualization of the data (Figure 9) shows a horseshoe-type shape running along the length of the pipe. The top image shows the received data during the scan and the bottom image outlines the flaw with a dotted red line. IWEX determined that the flaw had a maximum depth of 0.043 inch (13.8% nominal wall thickness) at 21 feet from the upstream girth weld. The view window, enlarged in Figure 10, shows the transverse cross-section of the flaw. This image shows that the flaw is shallow, as the indication does not greatly move away from the outside surface of the pipe. Additionally, the flaw can be visualized turning circumferentially into the pipe (i.e., a sliver), rather than perpendicular to the outer surface (i.e., a crack). A sliver is defined by API 5T1 (2010) as "an extremely thin elongated piece of metal that has been rolled into the surface of the parent metal to which it is attached usually by only one end." Also, it appears that the tip of the flaw does not extend perpendicular to the outer surface, indicating that there is no flaw growth. It should also be pointed out that ILI data identified a similar horseshoe type flaw (shown in Figure 11); however, it was reported as a notch-like feature.

The PAUT vendor subsequently rescanned Feature 8982 at 1 foot intervals along the length of the sample. Similar results were reported when compared to original in-the-ditch PAUT results. During the rescan, the PAUT vendor noted that it is difficult to accurately size surface related flaws with PAUT. The NDE operator must interpret these signals, which may be difficult to accurately analyze due to the shallow nature of these flaws. In this situation, final results are highly dependent on the NDE operator, and may vary between NDE operators.

Lastly, a select flaw present from Sample 2 (Feature ID 8981 and 8982) was characterized using the circumferential grinding procedure described above. Photographs of the inspection and the results are presented in the metallography section above. Flaw depth after grinding was measured every 1 foot starting 19 feet from the upstream girth weld. The grind depth was measured after the flaw was no longer visible via MPI (Table 3). The flaw depth varied along the length of the feature, with a maximum depth of 0.0215 inch (7% of nominal wall thickness). Photographs summarizing this inspection on the bottom portion of the flaw (Feature ID 8982) located 19 feet from the upstream girth weld are shown in Figure 12.

Distance (ft)	Feature ID	Grind Depth	
		Inch	% WT[1]
19	8981	0.0012	0.4
19	8982	0.0025	0.8
20		0.0215	7
21		0.010	0.3
22		0.00115	0.4
23		0.0011	0.4

Table 3: Grind depth to remove flaws from Sample 2.

[1] *Percent wall thickness calculated based on nominal wall thickness of 0.312 inch.*

Table 4 compares all the NDE results collected on Features 8981 and 8982. The inspection by grinding results are accurate assuming the depths where measured once the flaw tip disappeared during the grinding process. The first PAUT scan correlates best with the grinding measurements. IWEX provides the user with the ability to visualize the flaw along a cross-section of the pipe. Although the feature was overestimated, IWEX could be used determine that the flaw was consistent with a sliver-type flaw.

The most significant indication determined through the grinding procedure was at 20 feet from the upstream girth weld. This flaw corresponds to 7% of the nominal wall thickness. This flaw depth is within API 5L wall thickness tolerances for both API 5LX 1973 and API 5L 2013, which are -8% and -10%, respectively.

Sample	Distance from U/S GW (ft)	Feature ID	Grind Depth (in)	ILI (in)	PAUT (in)	PAUT Rescan (in)	IWEX (in)
2	19	8981	0.0012 (0.4% WT)	0.079 (25% WT)	0.020 (6.4% WT)	---	0.043[1] (14.1% WT)
	18.5	8982	---	0.039 (12.5% WT)	0.016 (5.1% WT)	0.033 (10.5% WT)	
	19		0.0025 (0.8% WT)		0.015 (5% WT)	0.033 (10.5% WT)	
	20		0.0215 (7% WT)		0.018 (5.8% WT)	0.038 (12.2% WT)	
	21		0.010 (0.3% WT)		0.020 (6.4% WT)	0.044 (14.1% WT)	
	22		0.00115 (0.4% WT)		0.012 (3.8% WT)	0.044 (14.1% WT)	
	23		0.0011 (0.4% WT)		0.010 (3.2% WT)	0.033 (10.5% WT)	

Table 4: Comparison of grinding depth and NDE measurements of features 8981 and 8982.
[1] *Measured at 21 feet from upstream girth weld, shown in Figure 10.*
Percent wall thickness calculated based on nominal wall thickness of 0.312 inch.

Sample 3

Feature 8988 was reported by the ILI vendor and scanned in-the-ditch with PAUT. This feature was not scanned with IWEX. On Sample 3, the flaw depth was reported as 0.076 inch (24.4% nominal wall thickness). A metallurgical cross-section was prepared at this location and several features were identified in an unetched photomicrograph. The most severe indication was consistent with a sliver flaw created during plate manufacturing. This flaw was determined to be 0.039 inch deep (12.5% of nominal wall thickness) as measured from the outer surface (Figure 13). Ferrite banding continued parallel to the pipe surface, reaching a maximum depth of 0.046 inch (14.7% of nominal wall thickness). It can be seen that the flaw is oriented nearly parallel to the pipe surface. No flaw growth was observed in the metallurgical investigations. It is likely that both ILI and in-the-ditch inspection identified these slivers and/or elongated inclusions as a notch-like flaw or crack-like indication.

Sample 4

All features in Sample 4 survived the cyclic and burst test, discussed later in this report. Feature 9677 was scanned in-the-ditch with PAUT and post-burst test with IWEX. A metallurgical cross-section for Feature 9677 was prepared approximately 13.8 feet from the upstream girth weld, shown in Figure 14.

The indication is consistent with a sliver flaw created during plate manufacturing. This flaw was 0.005 inch (1.6% nominal wall thickness) deep as measured from the outer surface. Similar to Feature 8988, ferrite banding was identified parallel to the pipe surface. It can be seen that the flaw is mostly oriented parallel to the pipe surface. IWEX identified other features such as inclusions near the mid-wall as shown in Figure 15. Metallography identified small inclusions typical of pipeline steel. These inclusions can create difficult-to-interpret signals that can affect flaw depth sizing (Figure 14).

Summary

Metallurgical cross-sections of select flaws were prepared both before and after completion of the burst test. This data is presented in the sections above and summarized in Table 5. Three of the four flaws selected for metallography were not originally reported by the ILI vendor. However, this does not imply that the ILI vendor did not identify these features. For the most part, flaw depths determined with IWEX was more consistent with the actual results determined with metallography. The IWEX system has an inherent advantage in that it allowed the user to visualize the flaw through the pipe wall.

Sample	Feature ID	Flaw Type	Metallography Results (in)	ILI (in)	PAUT (in)	IWEX (in)
1	2644	Mid-wall	0.170[1]	Not called	0.124	0.125
2	8978	Internal	0.004 (1.3% WT)	Not called	0.041 (13% WT)	0.031 (10% WT)
3	8988	External	0.039 (12.5% WT)	0.079	0.131 (42% WT)	Not scanned
4	9677	External	0.005 (1.6% WT)	Not called	0.160 (51% WT)	0.025 (8% WT)

Table 5: Comparison of metallography results and NDE measurements.
[1] *Depth from outer surface*
Percent wall thickness calculated based on nominal wall thickness of 0.312 inch.

Full-scale testing

The pipe samples from Sample 2 and Sample 4 were prepared for pressure cycling and burst testing by installing end caps on their ends. Both samples were approximately 45 feet long and contained a short pup from the adjacent joint to reduce the additive stress contributions from the end caps. A rainflow count analysis (following ASTM E1049 (2011)) was conducted to estimate the number of fatigue cycles per year that represents typical service conditions for the pipeline. Based on the analysis, SES determined that 350 cycles between 100 and 950 psi (a range of 850 psi equates to 63% SMYS) would simulate 50 years of operation (including a factor of safety of 5).

The burst tests were performed in a shielded test pit and monitored via a pressure transducer to measure the internal pressure during testing. Each sample was cycled between 100 and 950 psi for 350 cycles. Following cycling the sample's internal pressure was gradually increased and held for 5 minutes at 978 psi (72% SMYS) and then at 1,358 psi (100% SMYS). The internal pressure was then increased until burst failure occurs.

Both samples survived the cyclic testing. Sample 2 and Sample 4 then failed during burst testing at a maximum pressure of 1,796 psi and 1,779 psi, respectively. Table 6 summarizes the burst test results. Neither sample failed at a flaw location identified by the NDE inspection, but instead failed in the adjacent pipe pups. A representative post-burst test is shown in Figure 16.

Sample	Failure Pressure (psi)	% SMYS (based on API 5L X65 Material)	% MAOP (978 psi)
2	1,796	132%	184%
4	1,779	131%	182%

Table 6: Burst test results.
Note: Pipe properties based on 2013 Edition of API 5L.

Conclusions

Based on the analyses completed the following conclusions can be drawn:

- The flaws present and examined in the samples analyzed were consistent with preexisting plate mill sliver flaws. The flaws exhibited varying depths but the majority of the measured depths were within the allowable API 5L minimum wall thickness tolerances.
- Two pipe samples subjected to pressure cycling and burst testing did not experience a reduction in burst capacity after 50 years of equivalent cycling. Both samples failed in the pipe body remote from visible and previously identified flaws.
- ILI and in-the-ditch flaw depth measurements were consistently different from those determined through metallography. NDE reflectors in the material, such as inclusions, could have created signals that were difficult to interpret. Other NDE technology, such as Applus RTD's IWEX system, could provide the opportunity to visualize the flaw morphology.
- The flaws examined by SES were not consistent with notch or crack-like features. The use of NG-18 to estimate the failure criteria would be expected to produce overly conservative results. The flaws examined are not deep enough to affect the integrity of the pipe.

Annex A

Figures

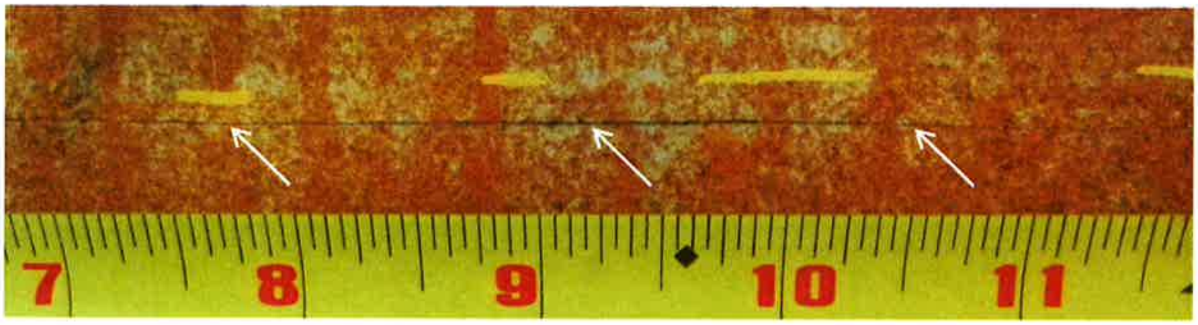

Figure 1: Photograph of flaw from Sample 4. Numbered scale divisions are inches.

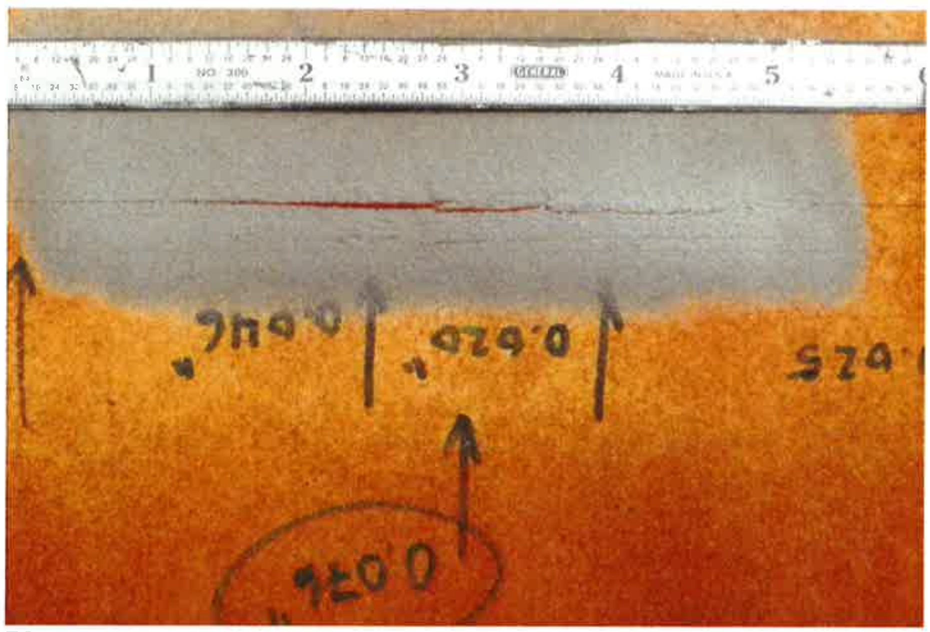

Figure 2: Photograph of Feature 8988 from Sample 3 showing MPI indication. Numbered scale divisions are inches.

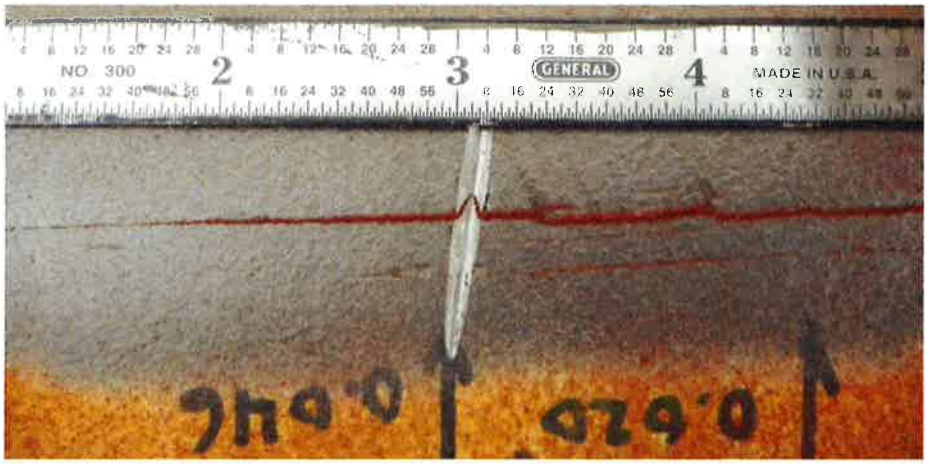

Figure 3: Photograph of Feature 8988 from Sample 3 showing MPI indication after second grinding pass. Numbered scale divisions are inches.

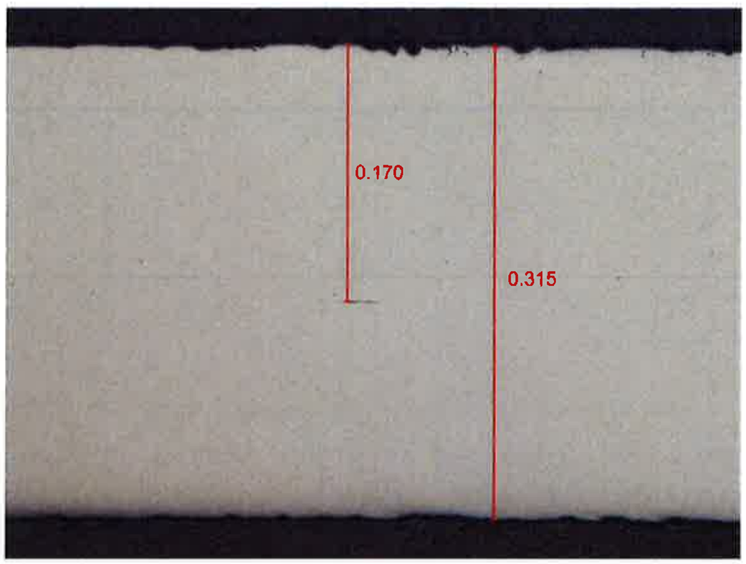

Figure 4: Photomicrograph of flaw from Sample 1 (Feature 2644) identified as a mid-wall inclusion. Unetched; original magnification is 10x.

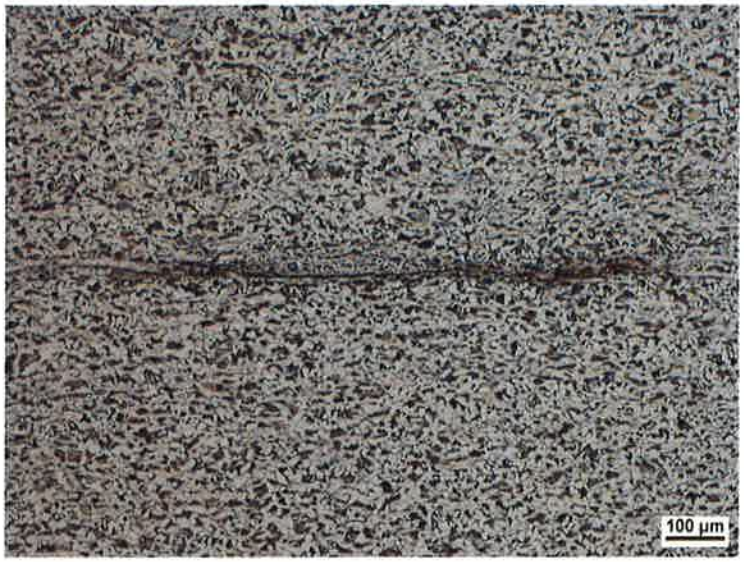

Figure 5: Photomicrograph of flaw from Sample 1 (Feature 2644). Etchant is 2% Nital; original magnification is 100x.

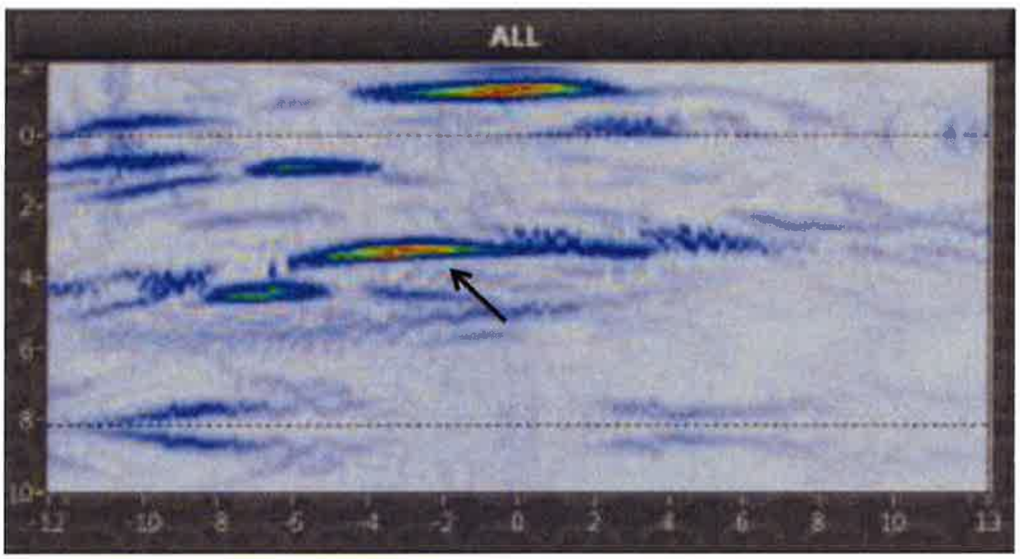

Figure 6: IWEX visualization of Feature 2644 from Sample 1 located 17.22 feet from upstream girth weld.

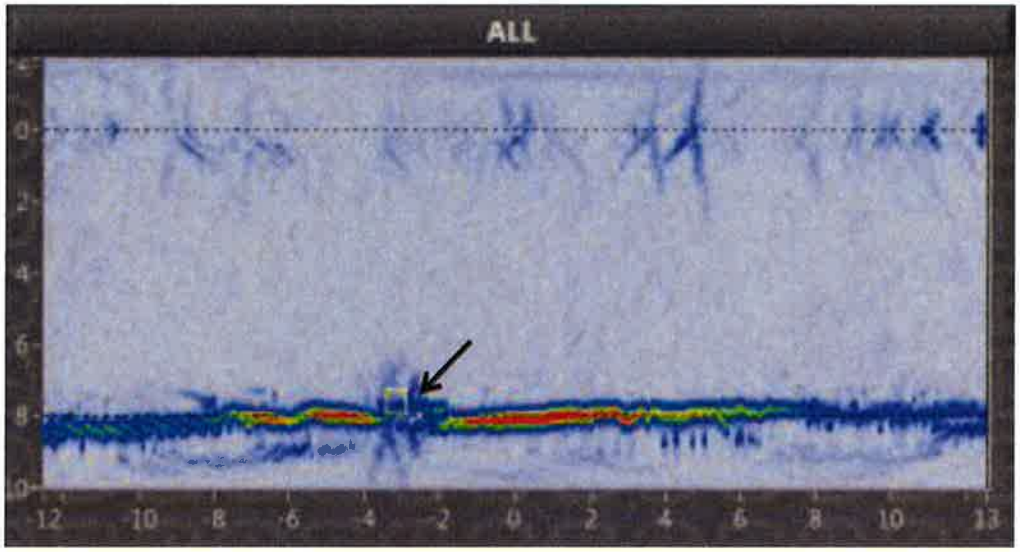

Figure 7: IWEX visualization of Feature 8978 from Sample 2. Flaw indicated by arrow.

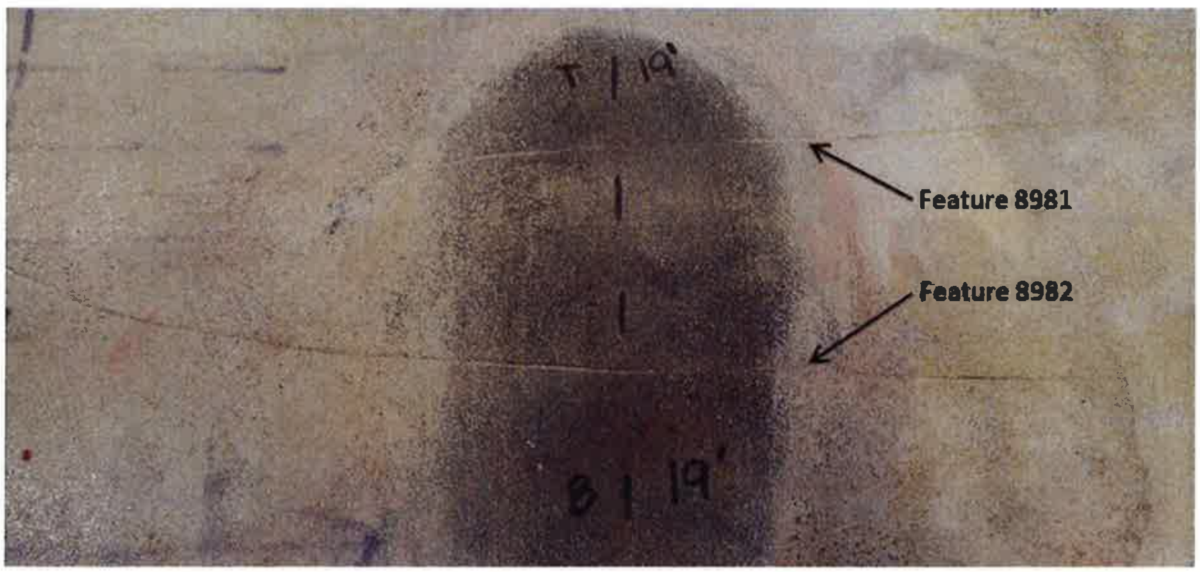

Figure 8: Photograph of Features 8981 and 8982 from Sample 2.

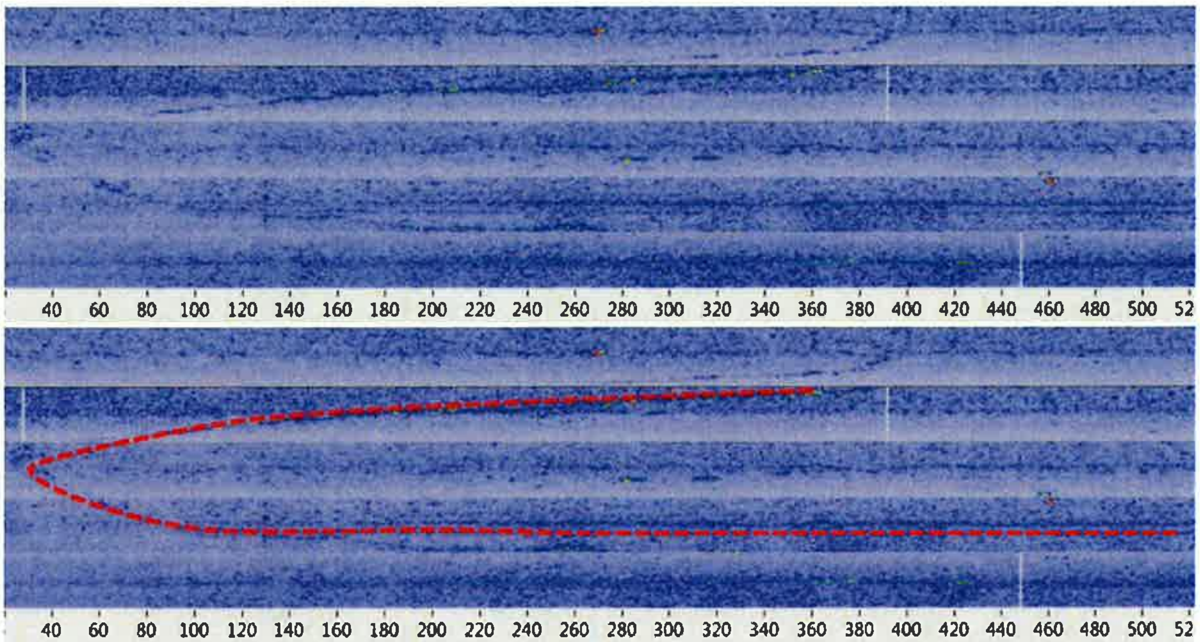

Figure 9: IWEX visualization of Features 8981 and 8982 from Sample 2.

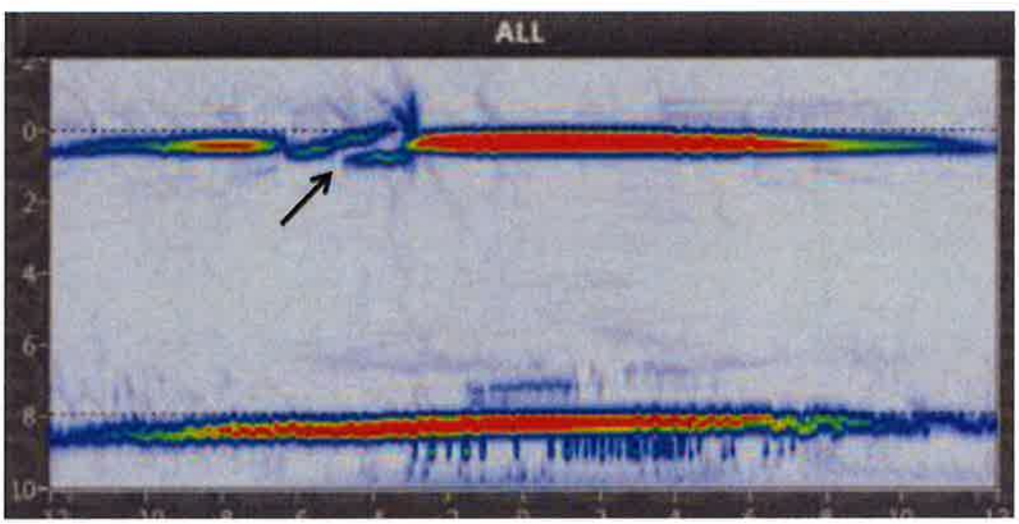

Figure 10: IWEX visualization of Feature 8982 from Sample 2 located 21 feet from upstream girth weld. Flaw indicated by arrow.

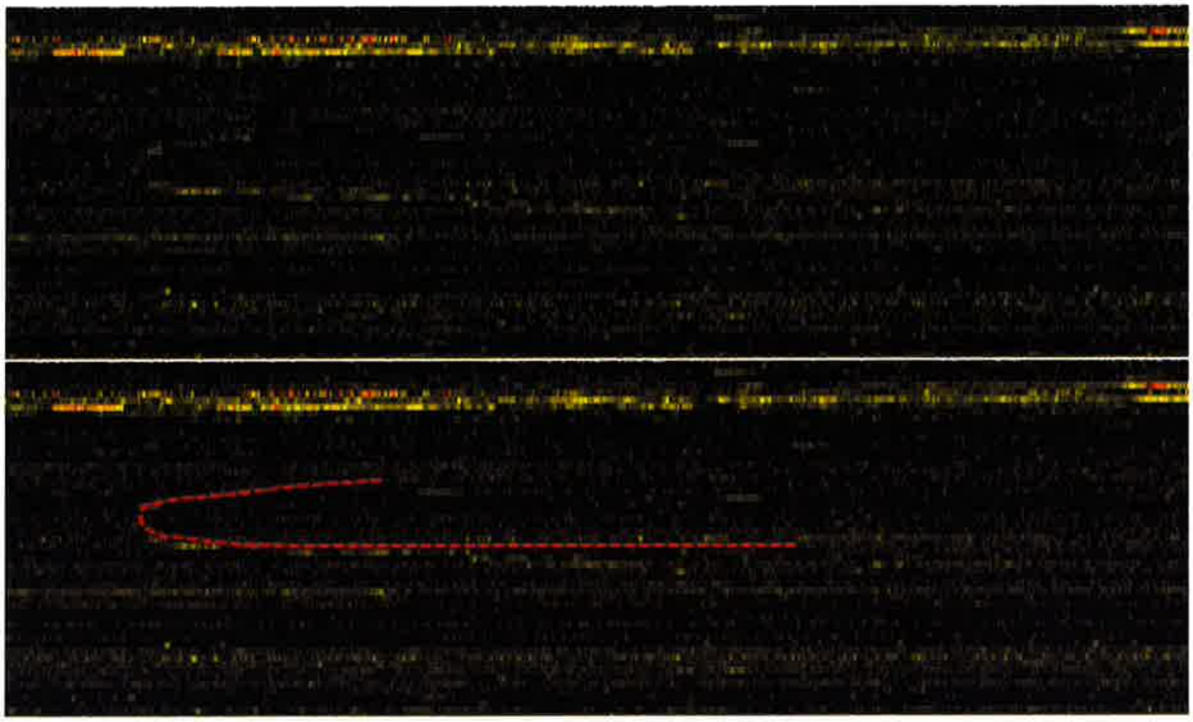

Figure 11: ILI vendor c-scan visualization of Feature 8981 and 8982 from Sample 2.

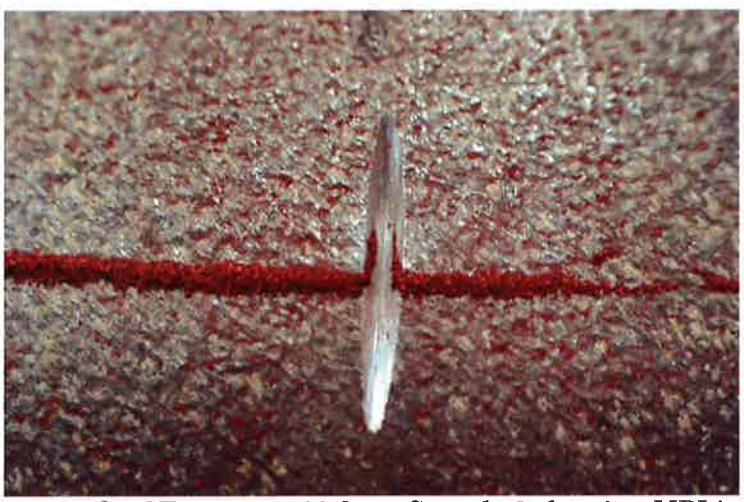

Figure 12: Photograph of Feature 8982 from Sample 2 showing MPI indication after second grinding pass. Note that the MPI indication of flaw is not seen at center of ground notch.

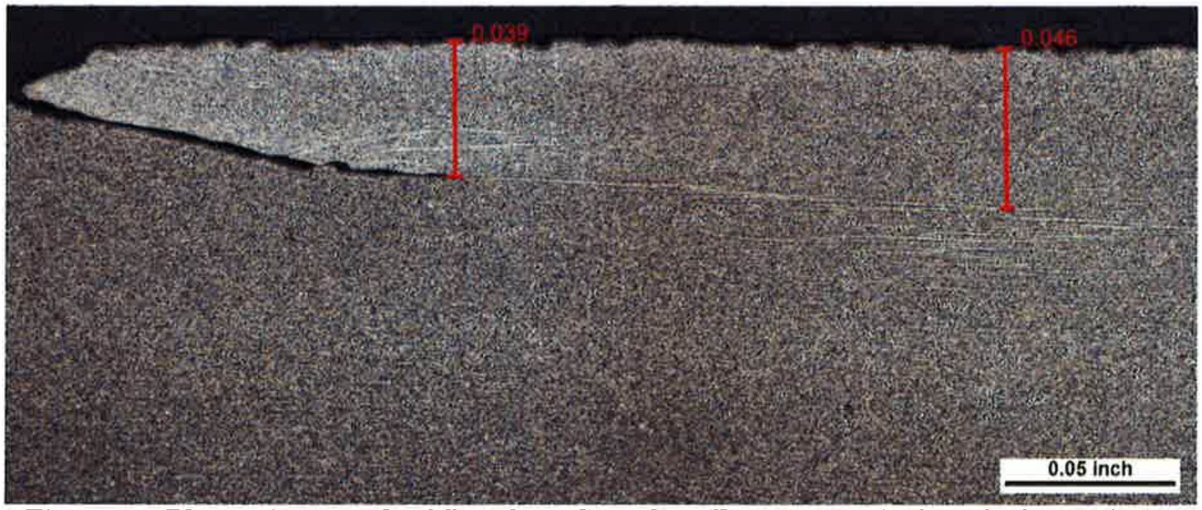

Figure 13: Photomicrograph of flaw from Sample 3 (Feature 8988) identified as a sliver. Flaw depths are reported with respect to outer pipe surface. Etchant is 2% Nital; original magnification is 25x.

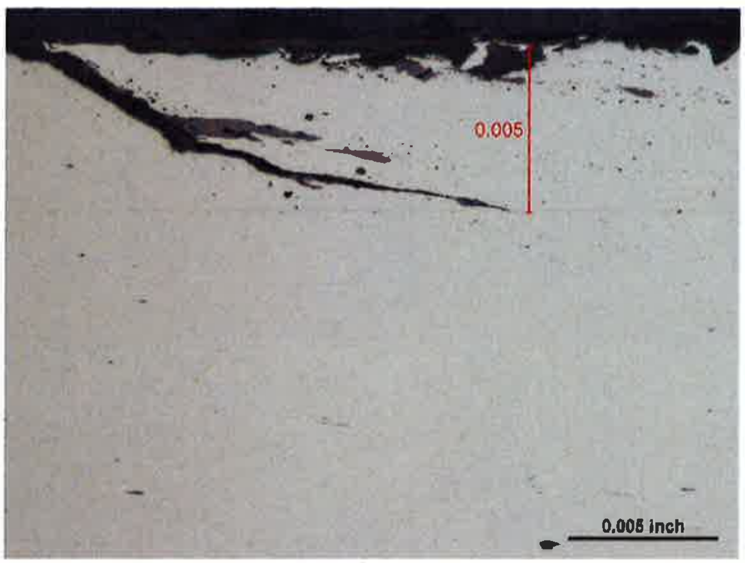

Figure 14: Photomicrograph of external surface breaking portion of the flaw from Sample 4 (Feature 9677) identified as a sliver. Unetched; original magnification is 200x.

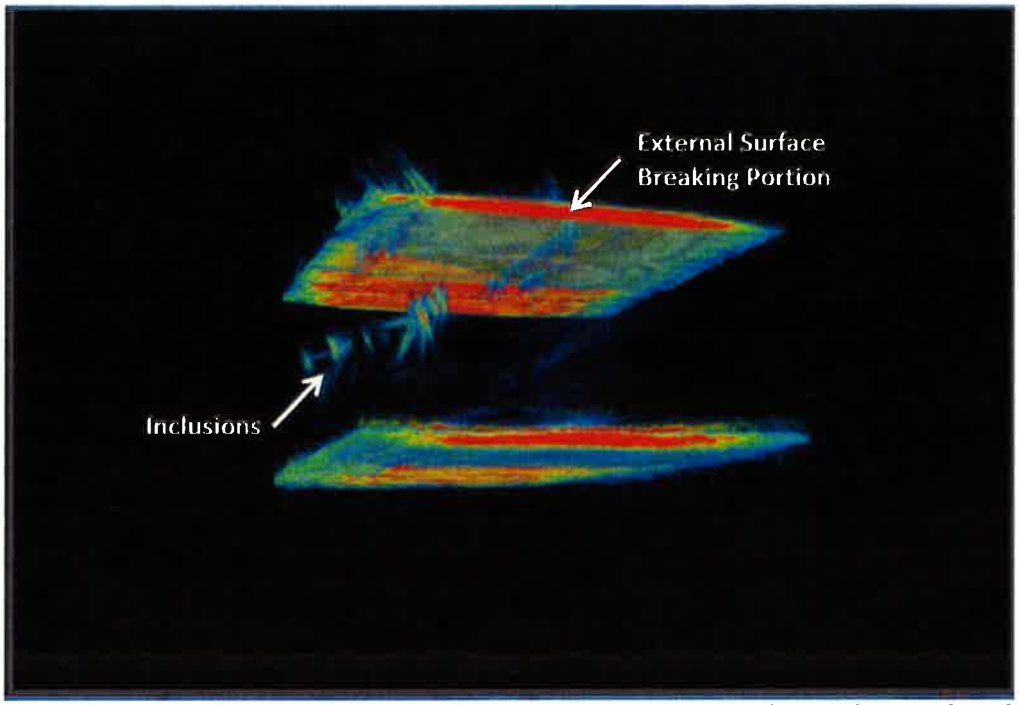

Figure 15: IWEX visualization of Feature 9677 from Sample 4 located 13.79 feet from upstream girth weld.

Figure 16: Photograph of Sample 4 after burst test sample. Failure location and several flaws identified by ILI are labeled.