Welding on Pipe with Laminations

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Abstract

Operators with existing pipelines with laminations may have the desire to perform welding to install fittings or other appurtenances. This paper presents the results of an evaluation of the potential threat of lamellar tearing under in-service fillet welds. The research included modeling to determine the minimum recommended distance for welding at or near laminations, and a full-scale hydrostatic pressure-hold test on laminated pipe with welded fittings to demonstrate if the presence of laminations would interfere with the welds.

Four different scenarios were investigated: (1) fitting welded over laminated area, (2) portion of weld bead place on top of a localized lamination, (3) weld bead some distance from localized lamination, and (4) fitting welded on non-laminated area of pipe with laminations elsewhere. The developed approach was a unique and innovative way to evaluate welding on pipe with laminations.

Introduction

A pipeline operator was interested in installing thread-o-ring (TOR) fittings on an existing segment constructed of 1990 vintage 36-inch diameter 0.585 inch wall thickness (WT) API 5L X60 line pipe. The steel was known to have mid-wall laminations from its manufacturing process.

In prior work [1], finite element analysis (FEA) was used to conduct a Level 3 fitness-for-service assessment per API 579-1 [2] to determine the susceptibility to lamellar tearing associated with the installation of welded fittings on a pipeline with known areas of laminations. That project provided recommendations for location selection, deposition of the fillet welds during the fitting installation, and final inspection. From the FEA results, it was determined that the most severe lamellar crack would be close to the pipe outside diameter (OD) surface, with a moderate length of about 3-4 times the pipe wall thickness (i.e., about a 2-inch-long crack), and with the crack tip just extended outside the weld toe.

The research described here provides an evaluation of the potential threat of lamellar tearing of laminations located at or near in-service fillet-welds, based on full-scale hydrostatic pressure hold testing of a pipe containing mid-wall laminations and welded fittings. This project physically demonstrated that the developed procedures and assumptions in the FEA modeling are applicable to (1) ensure the mechanical integrity of the fitting welds and (2) avoid growth in size or decohesion of the laminations at the welded fittings due to applied internal pressure in the pipe.

Objective

The objective of the work was to validate the assumptions underlying the FEA model and the procedures to install welded fittings on the pipe with laminations by physically demonstrating the pressure-hold performance at 1.5X the maximum operating pressure.

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Scope of Work

A 15-feet long sample from the pipe segment with mid-wall laminations was provided for this research. The sample was removed from an area where it operated at a maximum operating pressure (MOP) of 960 psig, which is equivalent to 49.2% of the specified minimum yield strength (SMYS).

The scope of work consisted of (1) inspecting the pipe for laminations, (2) welding on fittings and inspection of welds, (3) hydrostatic pressure hold testing, (4) post-test reinspection, and (5) material characterization. The approach for each of these activities is described in more detail below.

Approach

Inspecting Pipe for Laminations

The pipe sample was visually inspected for markings and photographed. Automated ultrasonic testing (AUT) was performed from the pipe inside diameter (ID) surface using a robotic setup to document the axial and circumferential locations of laminations and the lamination locations within the pipe wall thickness. Based on the AUT results, four areas of interest were selected for further testing. The external coating was removed from those areas using hand tools and organic solvents. The cleaned areas were then inspected using a straight-beam ultrasonic testing (UT) technique to confirm the locations and sizes (length, width, % wall thickness from the OD) of any laminations.

Welding Fittings on Pipe and Inspection of Welds

TOR fittings of 2-inch nominal size and Class 600 were used. A standard welding procedure specification (WPS) for base metal – pipe/fittings was provided by the pipeline operator. The WPS was applicable for pipe and fittings with a SMYS of less than 65,000 psi, which includes API 5L Grade X60. The WPS covered all diameters of pipe, and wall thickness of less than or equal to one inch. A drawing of the specified joint detail is shown in Figure 1.

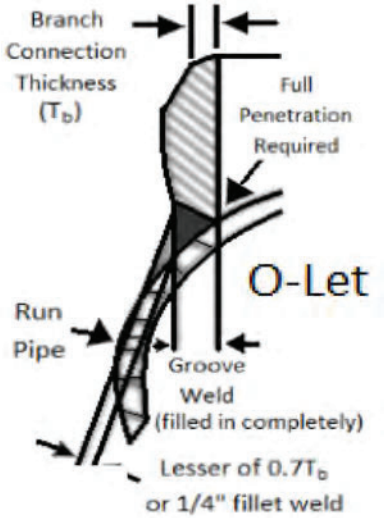

Figure 1. Joint detail for welding an O-Let per welding procedure specification.

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To simulate field conditions, fittings of the same type were ordered and welded to the pipe using the same WPS. The following joint specifications were selected:

- Joint Configuration: Branch
- Joint Design: Fillet weld
- Bevel: Single, manufactured (O-let)
- Root opening 1/16-inch and Root face 1/16-inch
- No pre-heat and no post-heat treatment
- Procedure: Submerged Metal Arc Weld (SMAW), Manual
- Filler Material: AWS A5.1, Electrode E-7010-G
- Weld size: ¼-inch Fillet weld

Using the information gathered about the locations and sizes of the laminations together with the recommendations from the prior FEA modeling, four locations were selected to install welded fittings on the pipe sample. The fitting-to-laminations distances and relative locations over/near the laminations were determined such that the fitting placements were most likely to challenge the assumptions used in the FEA. The test matrix is shown in Table 1.

Table 1. Test matrix for fittings relative to lamination locations on 0.585-inch wall pipe.

Target Lamination Size	Fitting Condition	Purpose	Result from FEA analysis
Mid-wall lamination, 3-4 times wall thickness (about 2-inches long)	Fitting 1 – weld centered over lamination	Test that delamination under a fillet weld does not present an integrity threat on 0.585-inch pipe	The FEA analysis showed that delamination under a fillet weld does not present an integrity threat to the 0.585-inch pipe
Mid-wall lamination, 3-4 times wall thickness (about 2-inches long)	Fitting 2 – Weld toe just extended outside lamination	Test of closest distance of fitting with respect to lamination	The FEA analysis showed that most mid-wall laminations are permitted for 0.585-inch wall thickness pipe. The FEA analysis showed that for 0.750-inch wall thickness pipe, in some scenarios, K_s exceeds 40 ksi*in$^{0.5}$. This occurs where the crack is three times the wall thickness and the tip of the crack just extends outside the weld toe.
Mid-wall lamination, 3-4 times wall thickness (about 2-inches long)	Fitting 3 – Weld toe 1.5 inches away from lamination	Test of minimum acceptable distance of fitting with respect to lamination.	The FEA analysis showed that most mid-wall laminations are permitted for 0.585-inch wall thickness pipe. The FEA analysis showed that for 0.750-inch wall thickness pipe, the welds should be at least 1.5 inches away from the laminations when the crack length is around three times the wall thickness.
Shallow lamination, 3-4 times wall thickness (about 2-inches long)	Fitting 4 – Weld toe 8.3 inches away from lamination	Test of fitting with respect to shallow lamination.	The FEA analysis showed that for any lamination shallower than one-quarter of the pipe wall thickness measured from the OD surface, the weld should be away from such lamination by a clearance of $1.8\sqrt{Dt}$ [8.3 inches for 0.585-inch wall thickness pipe].

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The installed fittings were documented with photographs, and ultrasonic testing (UT) and magnetic particle testing (MT) were used to inspect the welds. UT was applied to inspect each of the selected locations prior to welding, and UT was repeated after welding in the areas immediately adjacent to the welded fittings, to confirm if any of the previously identified laminations had increased in size. Magnetic particle testing (MT) was applied to inspect the welds, to confirm that no surface-breaking defects were present in the as-welded condition.

Hydrostatic Pressure Hold Testing

Test Vessel Preparation

The pipe section with the welded TOR fittings was prepared for hydrostatic pressure testing by welding on end caps with in/out fittings. The closed test vessel was connected to a hydrotest system consisting of a pump and hoses, a water-volume measurement system, pressure sensor, and data acquisition.

Hydrotest Execution

A single pressure-hold test was conducted using water as the test medium. The hydrotest was conducted at a maximum pressure of 1.5 x 960 psig (MOP) = 1,440 psig (equivalent to 73.9% SMYS). During the initial pressurization, intermediate pressure-holds were applied at pressures below the target pressure to confirm there were no leaks and the system operated properly. The amount of water pumped into the pipe was recorded from the start of increasing pressure to the time the maximum pressure was reached. The hydrotest hold time was 24 hours from the moment that the desired test pressure was reached. At the end of the test, the pressure was released, and the water was drained. The test was performed indoors, and the ambient temperature was checked periodically.

Post-Test Reinspection of Welds and Size of Laminations

Following the pressure test, the fitting welds were reinspected using MT, to confirm that no surface-breaking features had formed. The size of the laminations in the pipe was reinspected using UT, to determine if any lamination growth and/or delamination had occurred.

Material Characterization

After the hydrotest was completed, a sample from the pipe base metal was removed, and specimens were prepared for mechanical testing (tensile properties and Charpy V-notch (CVN) impact properties), chemical composition testing, metallography, and micro-hardness testing. In addition to the base metal sample that was used for material characterization, cross-sections were prepared from each of the welded TORs.

Tensile Properties

Two full-wall thickness tensile base metal specimens were machined from the hoop direction of the pipe for mechanical testing. The specimens were flattened prior to testing.

Charpy V-Notch Impact Testing

Ten base metal specimens were machined from the hoop direction (transverse direction) of the pipe. CVN curves were constructed by testing the material's impact energy and shear area percentage at different test temperatures. The pipe had sufficient wall thickness to machine full-size (0.394-inch x 0.394-inch) CVN specimens.

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Chemical Composition

A sample of the pipe base metal was tested using optical emission spectroscopy (OES) to determine the chemical composition.

Metallography

Each of the tested fittings was sectioned in the circumferential direction to remove a cross-section sample. The metallographic cross-section samples were prepared by mounting in epoxy, grinding, and polishing with progressively finer grits to a 1-micron finish. The as-polished samples were viewed using an optical light microscope to reveal the locations of the laminations and any present weld defects. The samples were then etched with 5% Nital solution to reveal the microstructure of the pipe base metal with laminations, the weld fusion metal, the adjacent heat affected zones (HAZs), and the TOR base metal. The results were documented with photomicrographs.

Microhardness Testing

The metallographically prepared cross-sections were used to measure Vickers hardness (HV) on the specimens' base metal, fusion metal, and HAZ.

Results and Discussion

The pipe had a length of 187 inches (15 feet 7 inches) and was externally coated with a black mastic coating and a mesh wrap. The pipe had a double submerged arc welded (DSAW) long seam weld along the length of the pipe. No girth weld (GW) was present in this pipe sample. The pipe did not have markings indicating its origin, o’clock orientation, or flow direction, and this information was also not available. Consequently, there was no information available to match the specific pipe sample to a particular location in an in-line inspection (ILI) report, nor were any field non-destructive examination (NDE) data available.

The pipe was inspected using AUT to detect and map the locations of laminations within the pipe wall. One end of the pipe (arbitrarily designated to be upstream [U/S]), and the seam weld that ran along the entire pipe length were used as the zero-references. The AUT scan started seven inches D/S from the U/S pipe end and continued in steps to inspect the remainder of the 187 inches length of the pipe. The AUT scan was conducted in the counter-clockwise orientation, starting from the toe of the DSAW, moving upward, and continuing around the circumference. Water was used as a couplant between the AUT sensors and the pipe wall. Figure 2 shows a photograph of the AUT robot on the inside the pipe.

Data were recorded at 0.25-inch intervals along the length and circumferential directions. The inside circumference of the 36-inch OD pipe with 0.585-inch wall thickness was approximately 109.4 inches, and data were reported at 0.25-inch intervals over 110 inches (441 rows of circumferential data). Data were reported at 0.25-inch intervals over 180 inches length (721 columns of longitudinal data). The AUT inspection was performed as nine (9) separate scans, and the results were stitched into a single data file (317,961 data points). Some minor alignment (moving rows of the separate scans as needed) was done to assure that the seam weld data lined up consistently. Only mid-wall laminations were detected by AUT.

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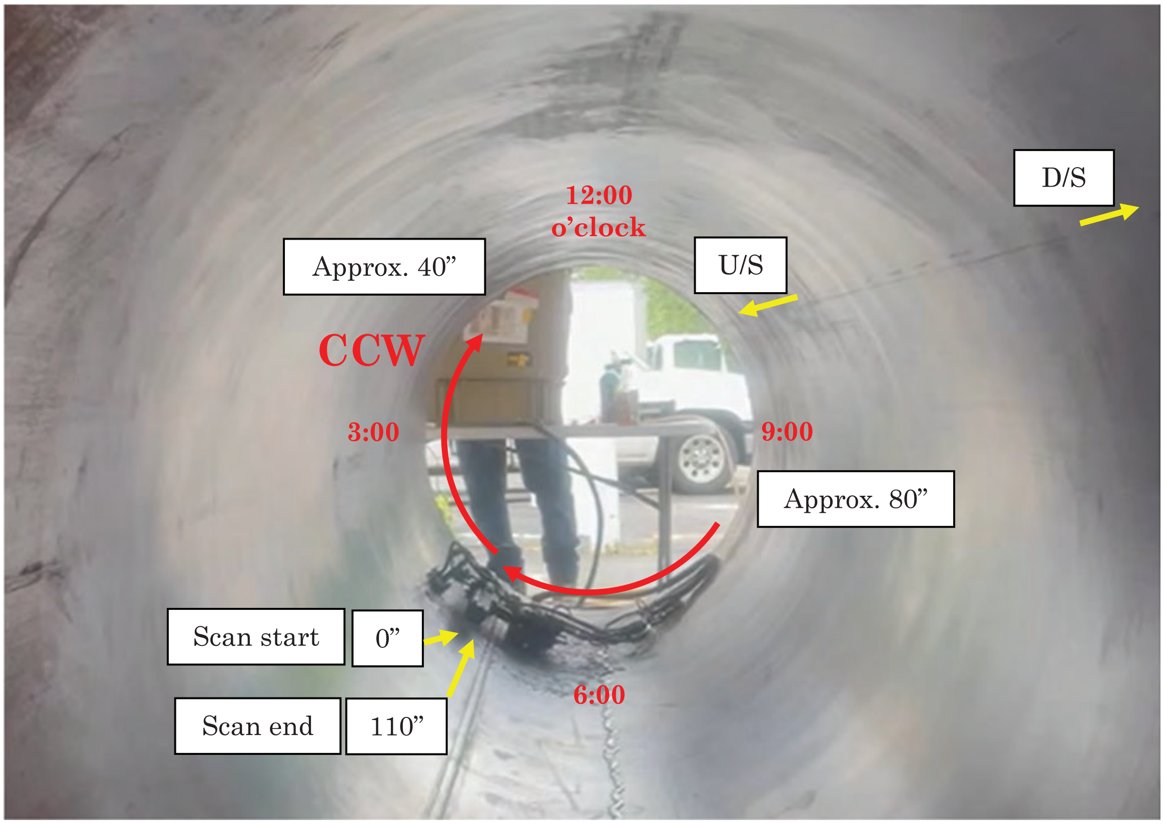


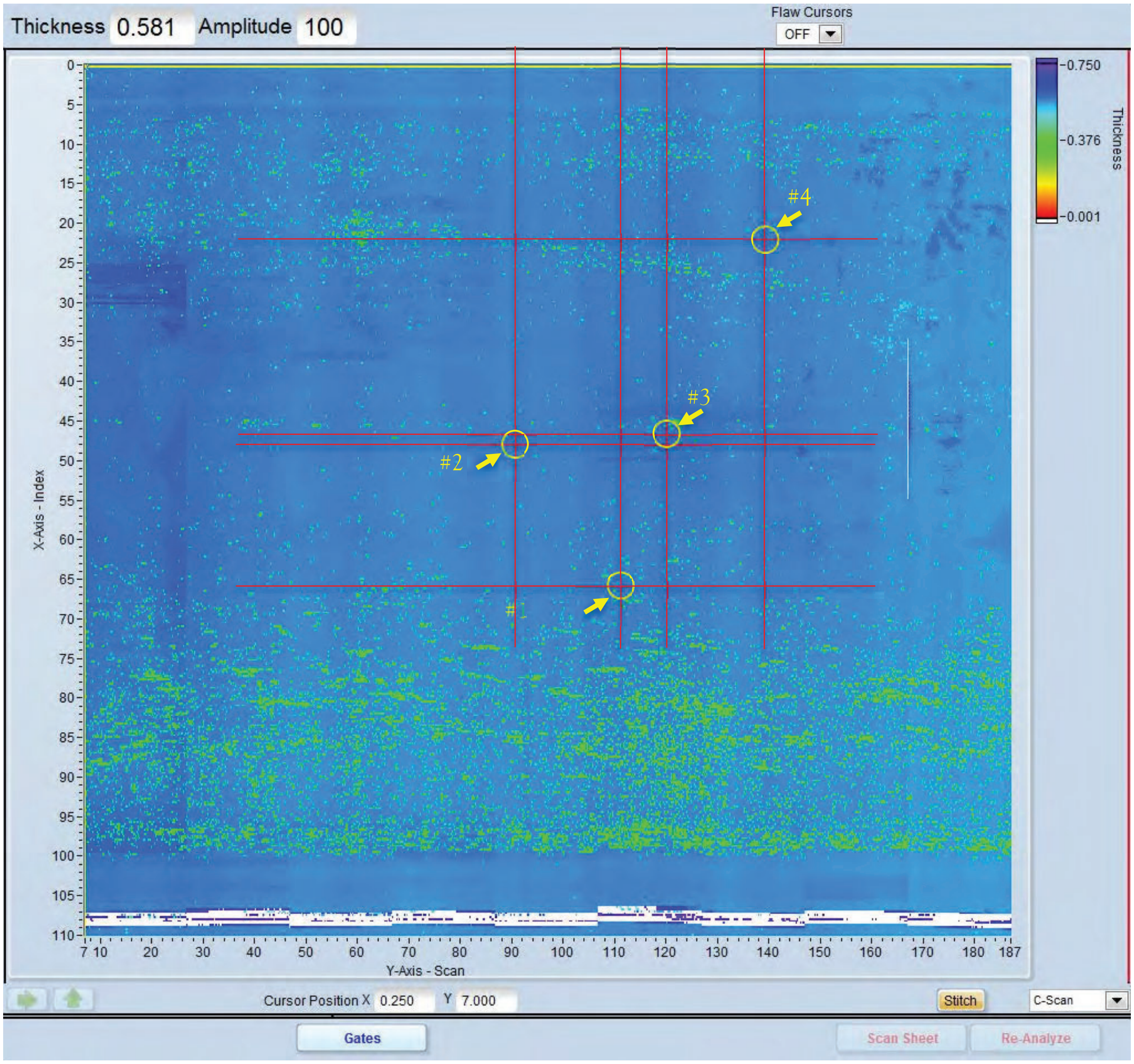
Figure 2. Automated ultrasonic testing from pipe inside diameter surface.

Approximately 1.75 inches of the circumference could not be measured because the DSAW bead was located there. Those 1.75 inches were included within a longitudinal strip of approximately 10 inches width (between 100 inches to 110 inches of the circumference), for which the tool reported no laminations at all. The AUT tool was probably not capable of detecting laminations in the areas immediately adjacent to the long-seam weld due to the weld geometry, and thus no laminations were reported there while is it very unlikely there were none. To work around this "blind spot" of the AUT equipment, these areas were avoided when selecting the locations to weld TORs.

Using the AUT data, four locations were selected to weld on fittings, as listed in Table 2. The longitudinal zero reference point was the pipe end arbitrarily designated U/S. The circumferential reference point was 1.5 inches counterclockwise (CCW) from the edge of the seam weld. The selected locations in relation to the AUT-detected laminations are shown graphically in Figure 3.

Table 2. Locations selected for welded fittings.

Fitting	Center Of Fitting O'clock	Circumferential Location (inches)	Longitudinal Location (inches)
1	10:46	98.25	115.0
2	7:55	72.25	85.75
3	7:48	71.25	129.75
4	3:55	35.75	156.75



Thickness 0.581 Amplitude 100

Flaw Cursors OFF

Cursor Position X 0.250 Y 7.000

C-Scan

Figure 3. Selected locations for welded fittings, in relation to AUT-detected laminations.

Ultrasonic Testing

The results from UT were as follows:

Location 1 (Fitting 1 – weld centered over lamination)

- Before welding: Multiple laminations were detected. The fitting position was marked such that the fillet weld would go over several of these laminations.
- After welding: Not possible to do UT scan after welding.

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Location 2 (Fitting 2 – Weld toe just extended outside lamination)

- Before welding: Distinct lamination detected. The fitting position was marked such that the edge of the fillet weld could be placed just outside this lamination.
- After welding: Not possible to do UT scan after welding.

Location 3 (Fitting 3 – Weld toe 1.5 inches away from lamination)

- Before welding: Two laminations detected by UT. The fitting position was marked such that the fillet weld could be placed 1.5 inches away from the laminations.
- After welding: UT detected that two laminations remain 1.5 inches away from fillet weld toe although they appeared smaller than in the original scan.

Location 4 (Fitting 4 – Weld toe 8.3 inches away from lamination)

- Before welding: No laminations detected by UT. The fitting position was marked within an area of 20 inches x 19 inches where no laminations were detected.
- After welding: No laminations detected by UT.

Magnetic Particle Testing

MT did not identify any surface-breaking defects after fillet welding the TORs.

Welding Fittings on Pipe and Inspection of Welds

Thread-o-lets were procured in accordance with the operator's specification. A drawing of the fitting is shown in Figure 4(a). The fittings were marked as follows: SA105 36-8 X 2 3M# FS THREAD-O-LET; refer to Figure 4(b). These markings signified that the material was carbon steel per ASME SA 105 specification, that the fittings were designed for a header pipe of 8 to 36 inches diameter to connect to a branch pipe of 2-inch diameter. The fittings were Class 3M (3,000 psig pressure rating). The fittings were made from forged steel (FS) and were threaded O-shaped couplings (TOCs). In addition, there was a marking 46GGG, which was likely the Heat Identification number and SP 97, which indicated compliance with Standard Practice MSS-SP-97 [3].

The fittings were fillet welded onto the pipe OD at the predetermined locations, using the same procedure as what is used in the field. After welding the TORs onto the pipe, threaded plugs were installed in each fitting. It was found that the plugs did not thread in completely due to welding deformation of the TORs. This could probably have been prevented if the plugs had been threaded in prior to welding. For safety, it was decided to add a fillet weld to secure each TOR to its plug.

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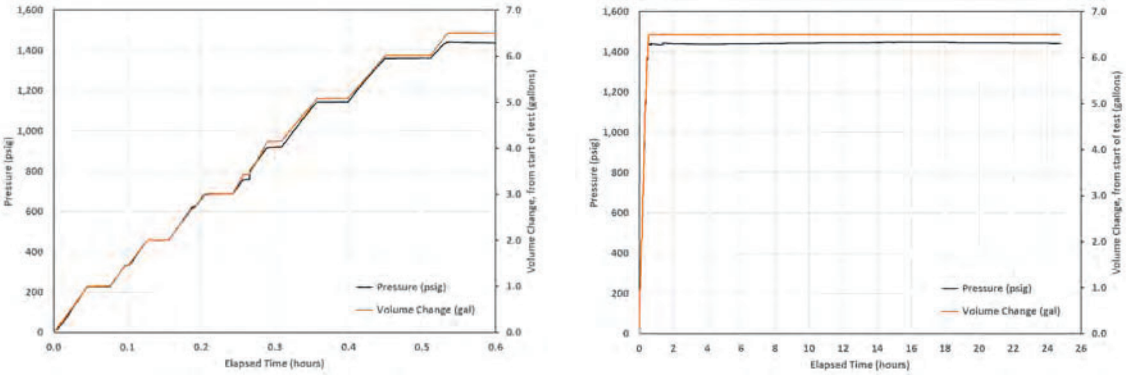
(a) (b)

Figure 4. Drawing showing (a) fitting shape, (b) photograph showing fitting markings.

Pressure Hold Testing

The hydrostatic pressure hold test with water was performed to a maximum pressure of 1,440 psig. Intermediate pressure-holds of a few minutes each were applied at pressures below the target pressure to confirm there were no leaks and the system operated properly, see Figure 5(a). The hydrotest hold time was 24 hours from the moment that the desired test pressure was reached, see Figure 5(b). The water volume pumped into the pipe increased linearly with the increasing pressure, showing that no yielding occurred, see Figure 6. This was expected, as the pipe was pressurized well below the SMYS of the material.

At the end of the test, the pressure was released, and the water was drained. The hydrotest was performed inside our laboratory, where the air temperature fluctuated between approximately 70F and 80F during the test period. The water temperature was estimated as 75F +/- 5F for the test duration.



(a) (b)

Figure 5. Pressure and water volume versus time (a) initial pressurization, and (b) entire test.

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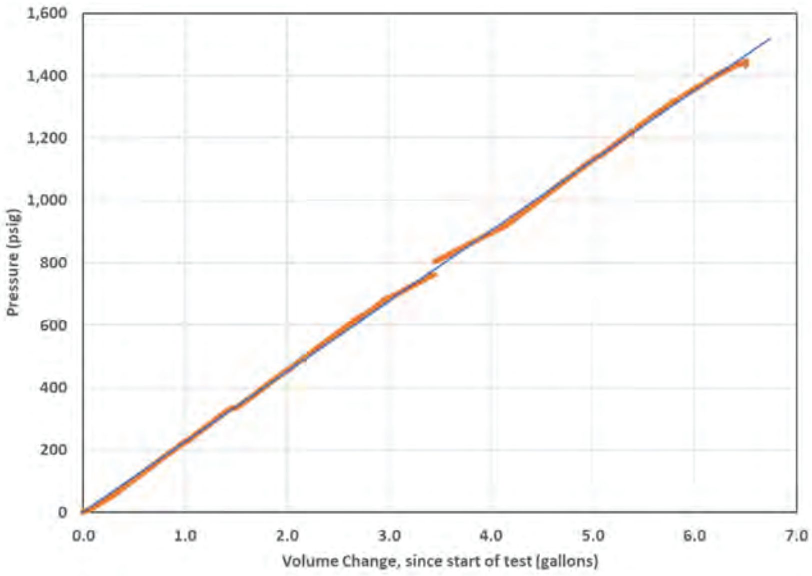

Figure 6. Water volume versus hydrostatic test pressure.

Material Characterization

Following the hydrotest, the pipe was cut to remove a sample from the pipe base metal. Specimens were prepared for mechanical testing (tensile properties and Charpy V-notch (CVN) impact strength), chemical composition testing, and metallography including micro-hardness testing. Only the base metal was characterized in this project because the TORs were all welded onto base metal areas only.

Tensile Properties

The results of the mechanical property testing are shown in Table 3, together with the applicable composition per the API 5L specification.

Table 3. Results of tensile tests performed on transverse base metal specimens from the pipe section compared with API 5L Grade X60 line pipe steel.

Parameter	Base Metal (*)	API 5L Grade X60 Specification [4] (Wt. %)
Yield Strength, ksi (0.005 EUL Method) (**)	65.0	60.0 min.
Tensile Strength, ksi	86.1	75.0 min.
Elongation, % **(2-inches gage length)**	33.8	21.8 min.
Reduction in Area, %	60.0	-

(*) Average of two specimens
(**) EUL = Extension under load

The minimum elongation in 2 inches shall be that determined by the following equation:

$$e = 625{,}000 \frac{A^{0.2}}{U^{0.9}} = 625{,}000 \frac{(0.4497)^{0.2}}{(75{,}000)^{0.9}} = 21.8 \qquad \text{Equation 1}$$

Where: A = cross-sectional area of the tensile specimen, in^2.
U = specified minimum ultimate tensile strength, psi.

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Thus, the material satisfied the API 5L specifications for yield strength, tensile strength, and elongation, in effect at the time of line pipe manufacturing.

Charpy V-Notch Impact Testing

The CVN impact properties are listed in Table 4 and Table 5 and shown graphically in Figure 7. These data show that the upper shelf impact energy was 72 ft-lbs and the 85% shear area fracture appearance transition temperature (FATT) was -28 °F. These values are typical for this vintage and grade of line pipe steel.

Table 4. Charpy V-notch impact tests results from full-size transverse base metal specimens.

Sample ID	Temperature °F	Impact Energy, ft-lbs	Shear, %	Lateral Expansion, mils
BA7	-100	19.0	5	20
BA4	-90	20.5	25	23
BA8	-75	45.0	30	48
BA5	-60	48.0	70	49
BA10	-45	47.0	60	52
BA6	-30	56.0	80	58
BA3	0	65.0	100	63
BA2	32	72.0	100	70
BA9	50	66.0	100	67
BA1	80	69.0	100	65

Table 5. Charpy V-notch impact test results, measured from full-size CVN specimens

Parameter	Base Metal
Upper Shelf Energy, ft-lb	72
85% Transition Temperature, ˚F	-28

(*) Based on 0.585-inch pipe wall thickness.

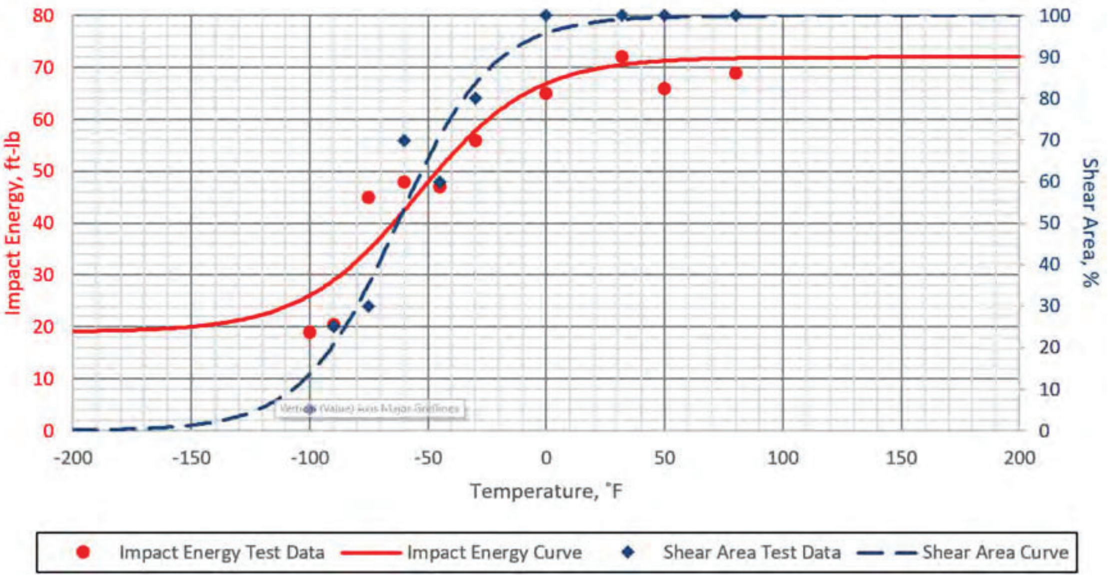

Figure 7. CVN impact energy and shear area percent for pipe base metal.

Chemical Composition

The chemical analysis results are shown in Table 6. With one exception, the results of the analysis met the composition requirements for the vintage of API 5L [4] Grade X60 non-expanded or cold expanded line pipe steel in place at the time of manufacture. The measured composition of manganese was detected at 1.551 weight %, which is somewhat larger than the maximum allowed 1.35 weight %.

Table 6. Results of chemical analysis of pipe sample compared with composition specifications for API 5L Grade X60 line pipe steel.

Element	Composition(*) (Wt.%)	API 5L Grade X60 Specification [4] (Wt. %)
C (Carbon)	0.115	0.26 (max)
Mn (Manganese)	1.551	1.35 (max)
P (Phosphorus)	0.021	0.04 (max)
S (Sulfur)	0.004	0.05 (max)
Nb (Niobium)	0.035	0.005 (min)[1]
V (Vanadium)	0.005	0.02 (min)[1]
Ti (Titanium)	0.001	0.03 (min)[1]
Si (Silicon)	0.265	-
Cu (Copper)	0.006	-
Sn (Tin)	0.001	-
Ni (Nickel)	0.013	-
Cr (Chromium)	0.022	-
Mo (Molybdenum)	0.001	-
Al (Aluminum)	0.022	-
Zr (Zirconium)	0.001	-
B (Boron)	0.0002	-
Ca (Calcium)	0.0009	-
Co (Cobalt)	0.005	-
Fe (Iron)	Balance	Balance
Carbon Equivalent, CE_{Pcm}	**0.205**	-

(*) Average of two OES measurements

For steels with carbon content less than 0.12% by weight, the critical metal parameter (Pcm) equation developed by Itto and Bessyo of the Japanese Welding Engineering Society, Equation 2 below, is recommended to calculate a Carbon Equivalent value. The risk of hydrogen cracking increases with increasing CE_{Pcm} above about 0.43%. The CE_{Pcm} of the pipe sample was determined to be 0.205%.

$$CE_{Pcm} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \qquad \text{Equation 2}$$

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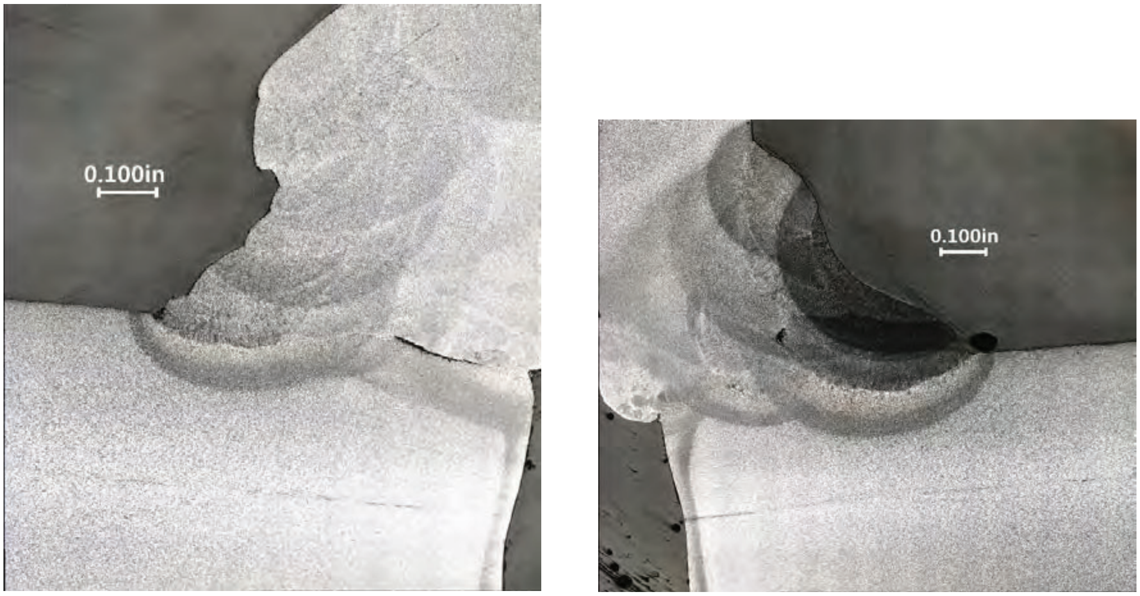
[1] Either niobium (called columbium in May 1988 edition of API Specification 5L), vanadium, titanium, or a combination thereof, shall be used at the discretion of the manufacturer.

Metallography

Figure 8 shows composite photomicrographs of the etched metallographic cross-sections of the welds of the four fittings. The weld fusion metal, HAZs, fitting base metal, pipe base metal, and pipe mid-wall laminations are all visible. No macroscopic cracks were found in any of the fillet welds or in the base metal.

Fitting 1 Fitting 2



Fitting 3 Fitting 4

Figure 8. Photomicrographs showing position of welds in relation to pipe mid-wall laminations.

Using optical light microscopy, the weld HAZs did not appear to visually overlap with the mid-wall laminations. The welds to fittings 2 and 4 had minor (< 0.005-inch diameter) porosity in the center of the fusion metal. The weld to fitting 2 had an approximately 0.030 inches long linear lack-of-fusion (LOF) defect, and the weld to fitting 3 had an approximately 0.120 inches long LOF defect. In both

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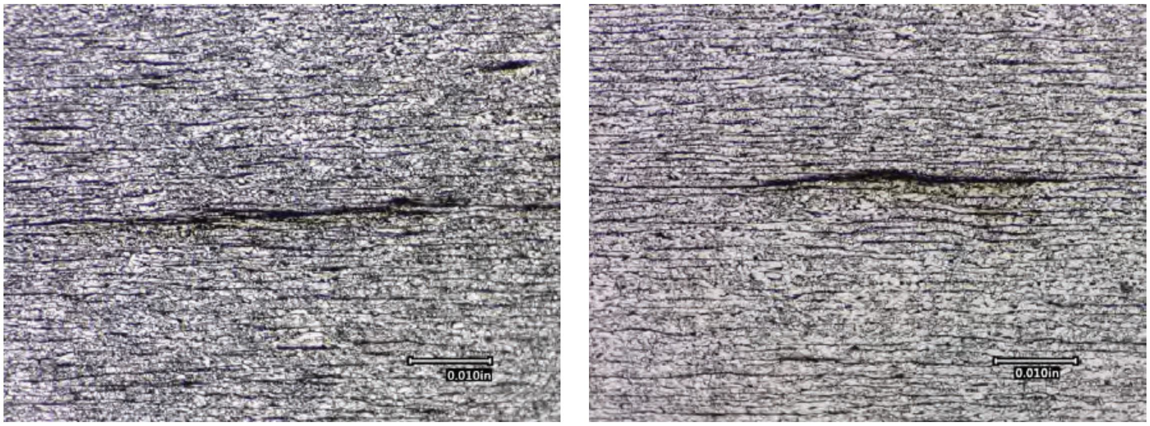
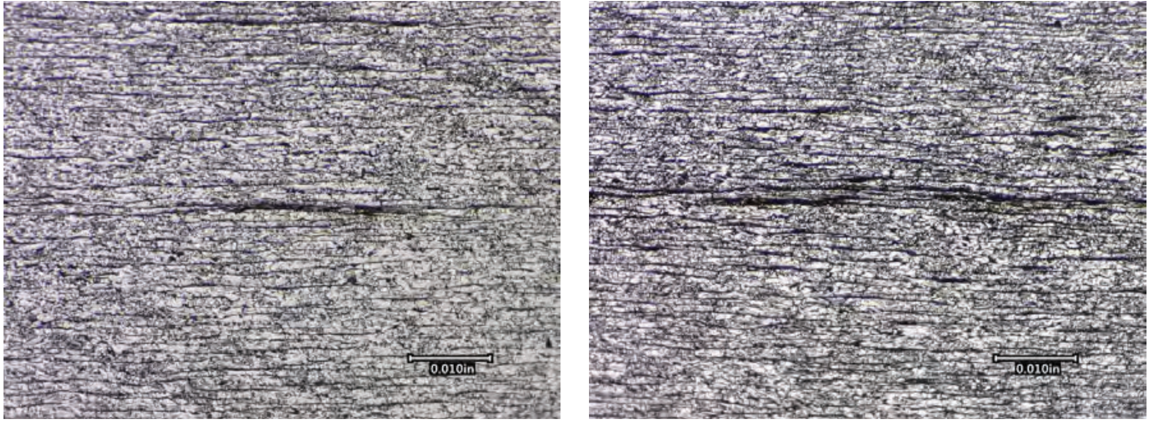
welds, the LOF was located on the pipe-side of the weld between the fusion metal and the carrier pipe. Also at both welds, the carrier pipe had visible HAZs immediately adjacent to these LOF locations. The weld to Fitting 1 had no notable porosity and no LOF. No macroscopic cracks were found emanating from any of these defects.

Figure 9 shows high-magnification photomicrographs of mid-wall laminations on the four metallographic cross-sections in the as-polished, and as-etched conditions, respectively. No microscopic cracks were found at any of the mid-wall laminations, nor were there cracks associated with any of the fillet welds or elsewhere in the base metals. In the as-polished condition, the laminations appeared as a non-continuous line of inclusions. In the etched condition, the flattened ferrite and pearlite grains throughout the microstructure were visible.

- The laminations appeared as narrow dark lines, indicating that both sides of the laminations were still close to each other, and laminations had not widened. Thus, there was no decohesion along the laminations, as would have been possible with a crack-like feature of which the flanks would have separated, and the crack would have opened.
- At both ends of each of the visible the laminations, the narrow line shape did not deviate from the mid-wall center-line, indicating that there was no crack growth in another direction.
- From the sharp shape of the individual laminations, and the overall appearance of an undeformed lamellar base metal grain structure, there was no evidence of lamination growth in the mid-wall direction, and no evidence of coalescing laminations.



Fitting 1 Fitting 2



Fitting 3 Fitting 4

Figure 9. Photomicrographs showing pipe mid-wall laminations (Nital Etch).

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Using an optical light microscope even at a moderate magnification (20X), mid-wall laminations were seen in all four cross-sections. In contrast, AUT and manual UT found few or no laminations in the same areas. It is possible that the short length of the individual laminations plays a role in this. For the current research, it was not a problem that laminations were present in areas where AUT and manual UT identified none, especially because no cracks were found originating from any of the laminations.

To quantify the amount of laminations in the material at the different locations, the lengths of individual laminations and the linear spacings between them were measured in each of the four prepared metallographic cross-sections. As an example, Figure 10 shows a photomicrograph of the Fitting 1 section in the as-polished conditions with the measurements shown. The results are presented graphically in Figure 11. The edge of the fitting hole was used as the zero-distance reference. The location of the fitting OD and the approximate average location of the fillet weld toe on the pipe side are indicated in the figure.

As expected (and planned), the area under the fillet welds to Fitting 1 and Fitting 2 revealed most laminations. The area under the fillet weld to Fitting 3 also had laminations, but fewer were located underneath the weld than outside the welded area. Fitting 4 had laminations, but those were the fewest of the four locations.

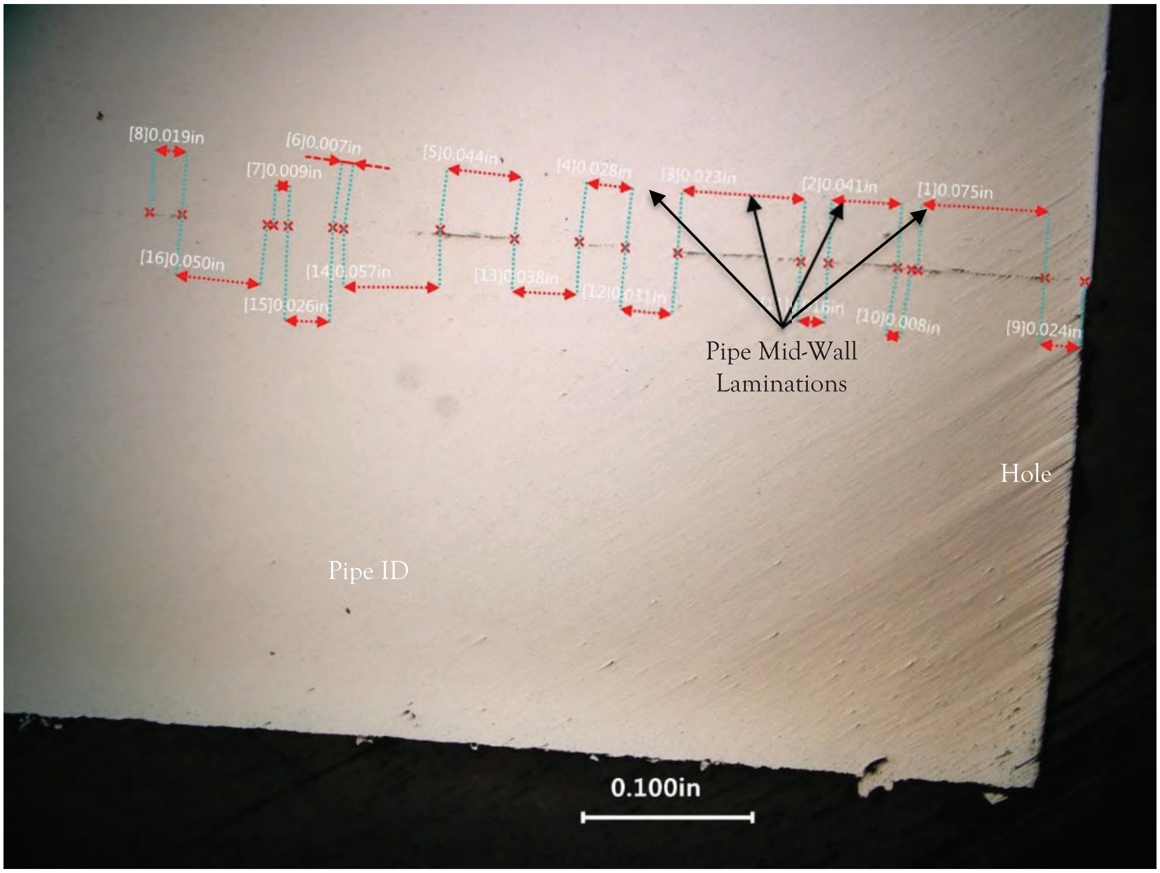

Figure 10. Example (Fitting 1, as-polished) of measured lamination lengths.

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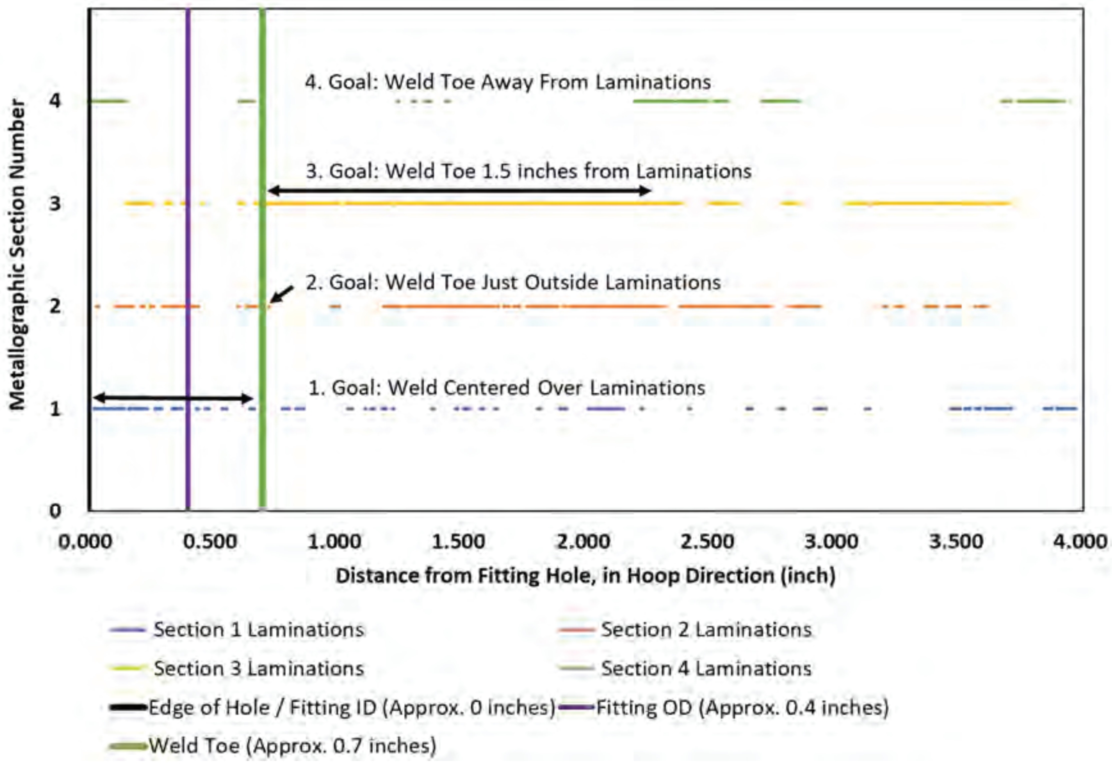

Figure 11. Distance of laminations from fitting ID, fitting OD, and fillet weld toe.

Microhardness Testing

Using the four metallographically prepared cross-sections, Vickers hardness measurements were taken along a trace from the carrier pipe ID to the weld fusion metal. Figure 12 shows the hardness data graphically and Table 7 summarizes the average hardness values for the different materials along the trace.

The pipe base metal had an average hardness of 201 HV, and at the pipe mid-wall the hardness was slightly lower at 191 HV. This locally reduced hardness is most likely related to the presence of mid-wall laminations. The hardness range in the base metal hardness was larger (182 - 219 HV) than the hardness range for the mid-wall hardness (187 - 198 HV). According to Metals Handbook [5], the average hardness of 201 HV is equivalent to approximately 94 ksi ultimate tensile strength (UTS). Thus, the approximate UTS estimated from the measured hardness values of the base metal was consistent with the actual measured tensile strength of 86.1 ksi reported earlier.

The HAZ in the pipe had a hardness of 201 HV, which is the same hardness as the original base metal. The weld fusion metal had an average hardness of 191 HV.

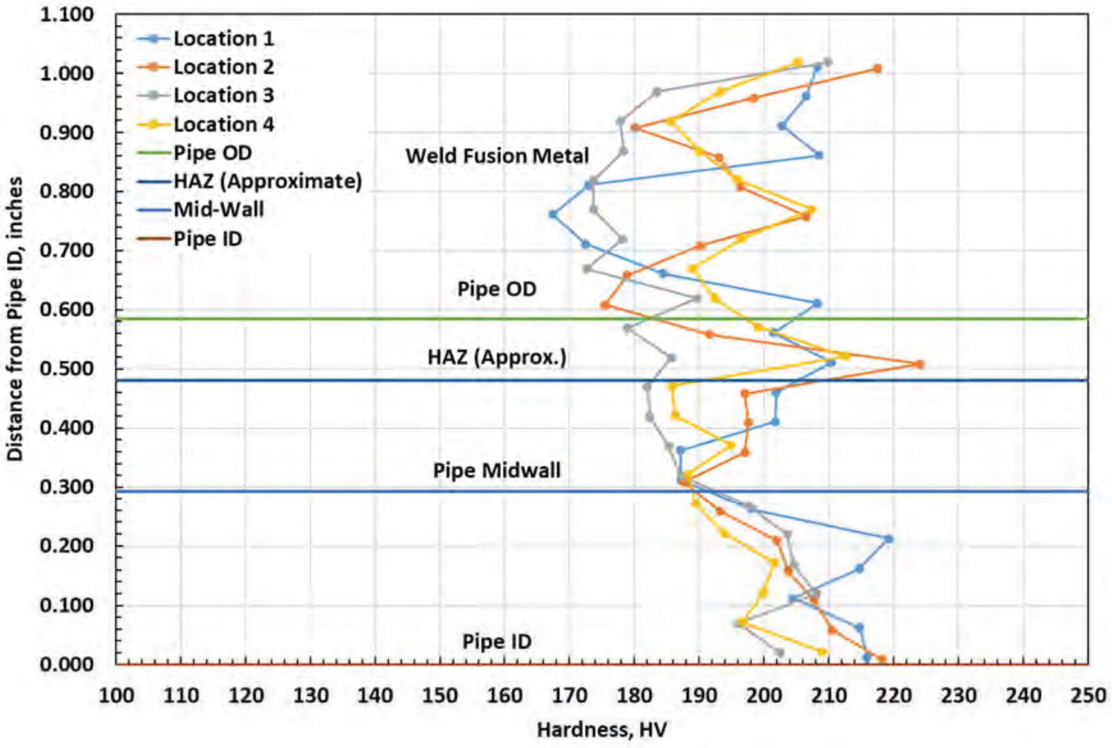

Figure 12. Vickers Hardness of Carrier Pipe, HAZ, and fillet welds to fittings, measured approximately 0.2 inches from edge of fitting hole.

Table 7. Average Vickers Hardness (HV) At and near the fillet weld for the different fitting locations.

Material	Location 1	Location 2	Location 3	Location 4	Average
Fusion Metal	192.4	192.9	182.0	195.0	**191**
HAZ	206.0	207.9	182.3	205.9	**201**
Mid-wall	192.7	190.4	192.4	188.9	**191**
Pipe Base Metal	207.5	204.2	195.6	196.0	**201**

Summary and Conclusions

The objective of this work was to validate the assumptions underlying the FEA model and the procedures to install welded fittings on the pipe with laminations by physically demonstrating the pressure-hold performance at 1.5X the maximum operating pressure.

Tests were performed on a 15-feet long 1990 vintage, API 5L Grade X60, 36-inch diameter, 0.585-inch wall thickness line pipe sample with a DSAW long-seam weld. No GW was present in this pipe sample. The pipe had known mid-wall laminations. In this project, TORs were attached to the pipe with ¼-inch fillet-welds using a manual SMAW process at different locations, representing

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different distances between laminations and the TORs. The fillet welds were made using a standard Welding Procedure Specification provided by the company.
A hydrostatic pressure hold test was performed for a 24-hour holding period at a maximum pressure of 73.9 percent of the SMYS. The absence of cracks was confirmed after the pressure test by UT, MT, and optical microscopy of metallographically prepared cross-sections.

This project physically demonstrated that the developed procedures and assumptions in the FEA model are applicable to (1) ensure the mechanical integrity of the fitting welds and (2) avoid growth in size or decohesion of the laminations at the welded fittings due to applied internal pressure in the pipe.

The following observations support these conclusions:

1) The pipe was inspected using AUT to detect and map the locations of laminations within the pipe wall. A higher density of laminations was detected in the pipe-half that contained the long-seam weld than in the pipe-half opposite the long-seam weld. Only mid-wall laminations were detected by AUT.
2) UT was performed before and after fillet-welding the TORs to confirm the distance between laminations and the fittings. UT did not detect any growth of the laminations due to welding.
3) MT was used to inspect the welds, to confirm that no surface-breaking defects were present in the as-welded condition. MT did not identify any surface-breaking defects after fillet welding the TORs.
4) Metallographic analysis by optical microscopy showed that:
    a) No macroscopic cracks were found in any of the fillet welds or in the base metal.
    b) Minor weld porosity (<0.005-inch) in the center of the fusion metal and LOF (up to 0.120 inches long) on the pipe-side of the weld between the fusion metal and the carrier pipe were found in some of the fillet welds. However, no macroscopic cracks were found emanating from any of these defects.
    c) No microscopic cracks were found at any of the mid-wall laminations, nor were there cracks associated with any of the fillet welds or elsewhere in the base metals.
    d) There was no decohesion along the laminations, no lamination growth in another direction, no lamination growth in the mid-wall direction, and no evidence of coalescing laminations.
5) The pipe material characterization identified no abnormalities:
    a) The material satisfied the API 5L specifications for yield strength, tensile strength, and elongation, in effect at the time of line pipe manufacturing.
    b) The CVN impact properties were typical for the vintage and grade of line pipe steel.
    c) The chemical composition met the requirements for the vintage of API 5L Grade X60 non-expanded or cold expanded line pipe steel in place at the time of manufacture.
    d) The approximate UTS estimated from the measured hardness values of the base metal was consistent with the actual measured tensile strength.

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