Fatigue performance characterization of a manufacturing seam defect in high-frequency electric-resistance-welded pipe

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THE DETECTION, CHARACTERIZATION, and sizing of seam anomalies continues to be a challenge for both in-line and in-the-ditch inspection technologies. This paper presents a testing program developed to evaluate the fatigue performance on a planar manufacturing defect removed from service in high frequency electric resistance welded (HF ERW) pipe. This defect was identified in the field by in-line inspection (ILI) and confirmed in the lab by phased array UT. In addition to the manufacturing flaw, several artificial flaws were sized and placed in the seam weld to evaluate the fatigue performance of the HF ERW seams. Fatigue was simulated in all flaws through a pressure cycle and surge test program based on the pipeline operational characteristics. At the conclusion of testing, a metallurgical evaluation analyzed the defect fatigue performance, and was compared to the original ILI and phased-array UT data. The metallurgical evaluation also characterized the fatigue growth and provided comparisons to analytical crack growth estimates. This work provides insight into the fatigue performance of early vintage HF ERW seams and comparisons between ILI and NDE sizing methods.

Introduction and background

Integrity management programs that are responsible for electric resistance welded (ERW) pipe rely on proper detection, characterization, and sizing of manufacturing seam defects. This continues to be a challenge for in-line and in the ditch inspection technologies which inherently have their own uncertainties. This uncertainty can be reduced through full-scale testing and metallurgical examination of anomalies removed from service. The information gained from testing, along with subsequent ILI inspections, can be used as a means for ensuring the integrity of seam defects. The following paper provides insight into the fatigue performance of an early vintage high frequency (HF) ERW seam through a test program designed to evaluate the behavior of planar manufacturing defects subjected to operational cycling. Subsequent metallurgical evaluations also provide comparisons to analytical crack growth estimates, and comparisons between ILI and NDE sizing methods.

The early vintage HF ERW pipeline at the focus of this study recently completed an in-line inspection (ILI) where the tool identified anomalies in the seam. A pipe joint with one of these anomalies was removed from service and the seam inspected with phased array UT. The remainder of the HF ERW seam was relatively clean (i.e., no other substantial flaws), so artificial defects were introduced by electrostatic discharge machining (EDM) into the center of the seams for the fatigue test program. The artificial defect depths were sized using fracture mechanics, pipe material properties, and the operational characteristics of pipeline.

The pipeline in this study is a liquid line that experiences typical cyclic pressures and has potential for occasional pressure surges. Historical pressure surges occurred in too short of a time for the monitoring equipment to capture, but were estimated to occur 1-2 times annually prior to implementation of operational changes that reduced surge potential. The pressure surges were estimated to result in pressures of 1.5 to 2 times the operational pressure. For this test program, one (1) surge was assumed to occur annually and reach a pressure equivalent to 106% SMYS in less than 10 seconds. The annual pressure surge was incorporated into three (3) different operational periods of the pipeline to create an alternating cycle/surge fatigue test program. Each operational period has a different pressure cycle spectrum representing past and future operational changes, and a total operational lifetime of 97 years.

The pressure cycle spectra for the three periods were reduced to an equivalent number of annual cycles at a pressure range from 10% to 72% of the specified minimum yield stress (SMYS) using Miner's Rule for cumulative damage. This resulted in an equivalent number of cycles for each operational period in the pipeline's 97 year expected life (past and future). The pressure cycle/surge fatigue test program proceeded with one (1) pressure surge of 106% SMYS, followed by an annual number of equivalent pressure cycles for the current operational year. This was repeated for all 97 years of operation. Through this fatigue test program, the in-service and artificial defects simulate seam defects present at the time of the pipeline construction that have experienced fatigue loadings for the expected life of the pipeline. If the defects survived the surge pressures, subsequent burst testing and metallographic examination indicated which wall thickness defects experienced growth during the test program.

Test methodology

An in-line inspection of the pipe samples provided for this test program called out a long weld anomaly, which was sized as 3.071-inch long. The long seams of the other pipe sections were inspected using magnetic particle inspection (MPI) and ultrasonic phased array to identify if other defects were present in the samples for testing. This inspection found no other substantial defects, other than the defect previously identified by the ILI tool. The ultrasonic phased array sized this anomaly as having a length of 1.5-inch and depth of 73% WT. Since there were no other defects for testing, artificial defects were introduced using electrical discharge machining (EDM). The notch sizes were based on fracture mechanics calculations and operating pressures with the following goals in mind.

- Demonstrate that defects of a certain size would fail due to a surge pressure.
- Demonstrate that surviving defects of a certain size are unlikely to grow due to operational pressures.

A test methodology was developed to meet these two goals that incorporated fracture mechanics calculations, non-destructive inspections, pressure cycle histories, full-scale testing, and metallographic examination.

Pressure cycle Historyh

Pressure cycle spectra of the pipeline in question were divided into three (3) operational periods as summarized in
Table 2-1. Each period was defined by past or expected operational changes. The pressure data used was sourced from approximately 2.5 to 3.5 years of recent pipeline service. A rainflow count was performed on the pressure cycle spectra that counted the number of pressure cycles for a given set of pressure range bins. The pressure bin data was then converted to an equivalent number of cycles at a 10% to 72% SMYS pressure range using Miner's Rule for cumulative damage and the API X' fatigue curve. This resulted in the equivalent number of cycles show in
Table 2-1 for the fatigue test program.

Table 2-1: Equivalent number of cycles at a 10% to 72% SMYS pressure range for the three operational periods.

Operational Period	Number of Years	Equivalent Cycles (10% - 72% SMYS)
1	34	44
2	13	19
3	50	37

Fracture mechanics

Two fracture mechanics calculations were performed to calculate the size of the defects for the fatigue cycle/surge test. The first calculation predicted the burst pressure using the Ln-Secant method developed by PRCI and the API 579 Level 2 failure assessment diagram (FAD). These calculations determined the smallest defect predicted to fail at a pressure of 106% SMYS. In addition, the calculations were used to calculate the size of the largest defect predicted to survive a failure pressure of 106% SMYS. The API 579 FAD calculations used low and moderate plain strain fracture toughness values for this pipe material. The second fracture mechanics calculation predicted the crack growth according to multiple crack growth models (da/dN curves). The models used the BS 7910 mean curve and the API 579 crack growth curves. These calculations determined the growth of any defects and estimated whether they would fail due to combinations of cycling and surge pressures. Mechanical testing of the pipe material provided Charpy v-notch values for the Ln-Sec calculations. The Ln-Sec calculations used the lowest measured CVN value with 100% shear. Both the API 579 FAD calculations and the Ln-Sec calculations were performed using the nominal wall thickness (NWT) and the average measured wall thickness (MWT). The results of the burst pressure calculations are shown in Figure 2-1.

For a notch length of 2-inches, the smallest defect predicted to fail at a pressure of 106% SMYS was 43% WT deep (based on nominal WT). The largest defect predicted to survive was 25.4% WT deep. The 2-inch defect length was based off the minimum length threshold for the ultra-sonic ILI tool run on this line. With this data, the notch defect for the surge pressure test was selected as 50% WT deep. This provided a sufficient margin to ensure that the defect would fail and demonstrate defects of this size will fail due to the pressure surge. Defects of 10% and 25% WT were chosen for the pressure cycle and surge test as they were unlikely to fail due to overpressure.

The crack growth estimates for the 10% and 25% defects are shown in

Table 2-2

Table 2-2. The results confirm that the 10% and 25% defects are likely to have little to no discernable growth after ≈2 years of service and little to no evidence of growth after ≈23 years of service. For the 25% WT defect, the predicted growth rates are expected to be conservative since a high pressure cycle (pressure surge) typically results in reduced crack growth for subsequent smaller cycles due to blunting of the crack tips. Therefore, these defects are expected to survive repeated cycling with intermittent surges.

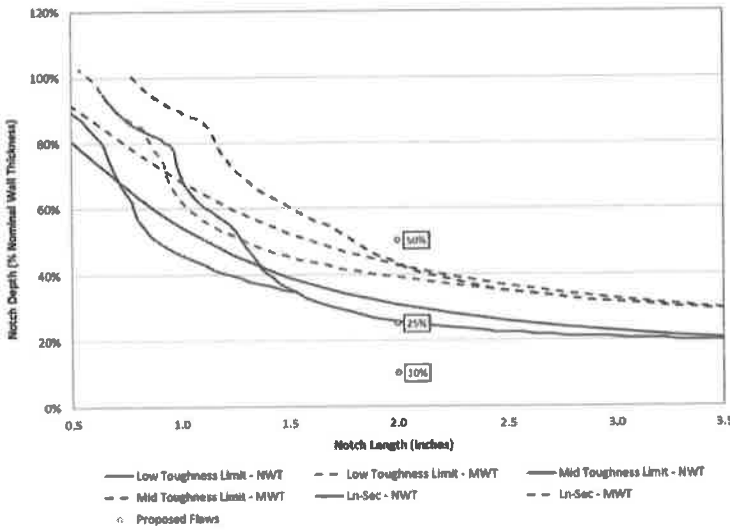

Figure 2-1: Limiting flaw size for surge pressures.

Table 2-2: Crack growth estimates.

Notch Depth (in)	Curve	Growth After 100 Cycles (in)	Growth After 1,000 Cycles (in)
10% WT	BS 7910 Mean	None	None
25% WT			0.6%
10% WT	API 579		None
25% WT			2.5%

Test methodology

Three (3) samples received EDM notches as part of this test program. The methodology behind their placement is listed below and summarized in
Table 2-3.

Table 2-3: Test methodology summary.

Sample ID	Depth	Testing	Purpose
1	In-Service Anomaly	Surge and Cycles	Alternate pressure surge/cycles to simulate in-service conditions for all three operational periods. Burst sample following fatigue cycles and examine in-service anomaly for fatigue growth after 97 years of simulated pressure surge/cycles. Compare initial defect size to NDE.
2	50%	Surge until Burst	Demonstrate a 50% wall thickness flaw would not survive a pressure surge of 106% SMYS. Indicate that there should not be any 50% flaws in the pipeline.

		(Predicted 106% SMYS)	
3	10%, 25%	Surge and Cycles (5 years of service)	Initially surge sample to demonstrate a 10% and 25% WT flaw would survive 106% SMSY pressure surge. Pressure cycle sample for five (5) years of simulated service (representative inspection interval). Metallurgical examine flaw surface for evidence of crack growth
4	10%, 25%	Surge and Cycles	Alternate pressure surge/cycles to simulate in-service conditions for all three operational periods. Burst sample following fatigue cycle and examine 10% and 25% WT flaws for evidence of crack growth after 97 years of representative pressure surge/cycles.

Test setup and procedure

The pipe samples were subjected to combinations of pressure surges and cycles to simulate past and future operation of the pipeline. The samples were then pressurized to failure following the pressure cycling. The below sections describe the test samples and procedure used in the full-scale testing.

The HF ERW pipe sections provided for this test program were sectioned into four (4) 80-inch length test samples. Figure 3-1 illustrates the sample dimensions and instrumentation. Each sample had locations for three (3) notches per sample (at most each sample only had two notches). The notches were placed in the center of the HF ERW seam on the bond line (seams polished and etched). The EDM notches were 2-inch in length, 0.02-inch in width, and either 10%, 25%, or 50% of the wall thickness in depth. Two biaxial strain gages were placed 10-inches from the notch locations on the ERW seam and in the base pipe 90° from the seam. The notch crack opening displacement during each pressure cycle and surge was measured by clip gages pictured in
Figure 3-2. Internal pressure was continually monitored with calibrated pressure transducers.

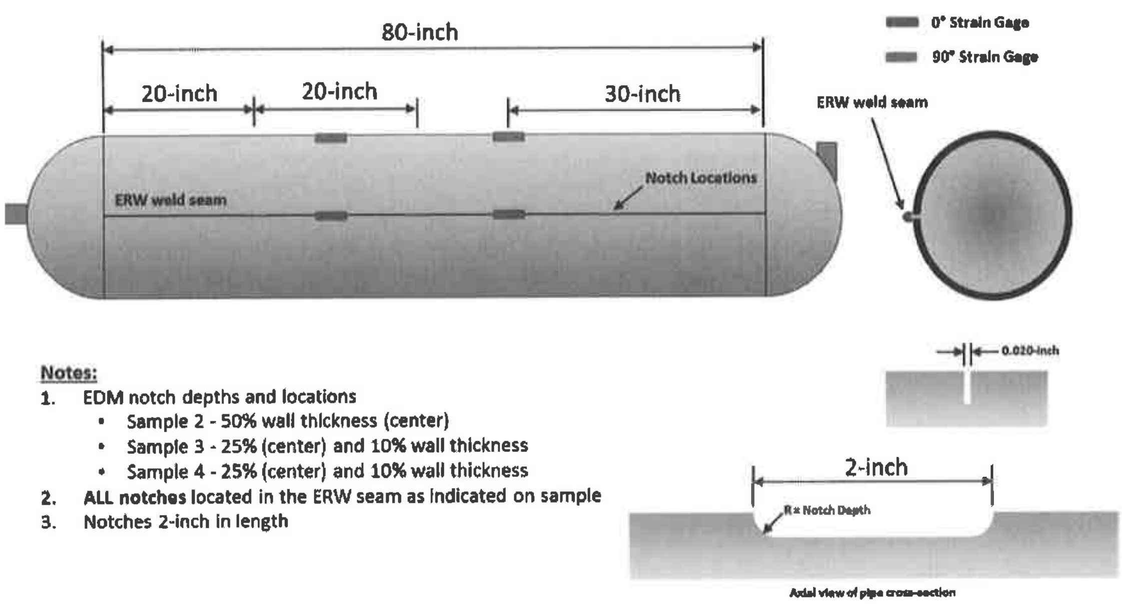

Figure 3-1: Test sample details and instrumentation locations.

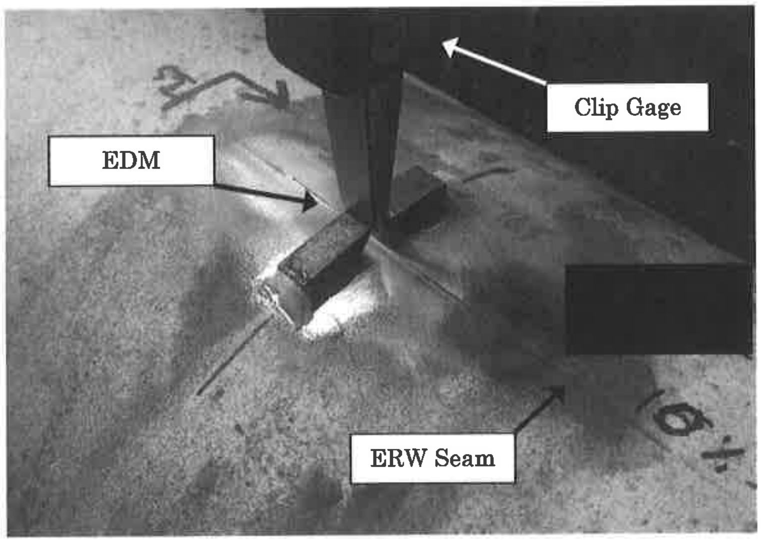

Figure 3-2: Example clip gage installation on Sample 3.

Test procedure

SES completed the test program in the order listed below.

- Sample 2 (50% Notch)
  - Rapidly pressurize sample to failure to simulate pressure surge (reach 106% SMYS in less than 10 seconds)
  - Sample 3 (10% and 25% Notch)
- Rapidly pressurize sample to 106% SMYS for one cycle to simulate pressure surge
  - Perform 220 pressure cycles to simulate 5-year of service (44 cycles per year)
  - Pressure range from 10% to 72% SMYS
  - Remove sample from testing for metallographic examination of notches
- Sample 4 (10% and 25% Notch)
  - Alternate one pressure surge of 106% SMYS and pressure cycles at a range of 10% to 72% SMYS for the below cycle counts and representative years
    a. 44 cycles for 34 years
    b. 19 cycles for 13 years
    c. 37 cycles for 50 years
  - Pressurize sample to failure with 5-minute holds at the following pressures
    a. 72% SMYS
    b. 100% SMYS
- Sample 1 (In-Service Anomaly)
  - Alternate one pressure surge 106% SMYS and pressure cycles at a range of 10% to 72% SMYS for the below cycle counts and representative years
    a. 44 cycles for 34 years
    b. 19 cycles for 13 years
    c. 37 cycles for 50 years
  - Pressurize sample to failure with 5-minute holds at the following pressures
    a. 72% SMYS

b. 100% SMYS

Test results

Surge test – 50% defect

The purpose of the surge-only test was to demonstrate that a 50% wall thickness notch would not survive rapid pressurization to 106% SMYS in less than 10 seconds.
Figure 4-1 illustrates that Sample 2 reached the failure pressure of 119% SMYS in 4.53 seconds. The seam (0°) and base pipe (90°) hoop strain gages in
Figure 4-2 recorded mostly linear behavior until approximately 106% SMYS. There was a clear difference between the seam weld and base pipe strain response, which is expected due to the properties of the seam weld.

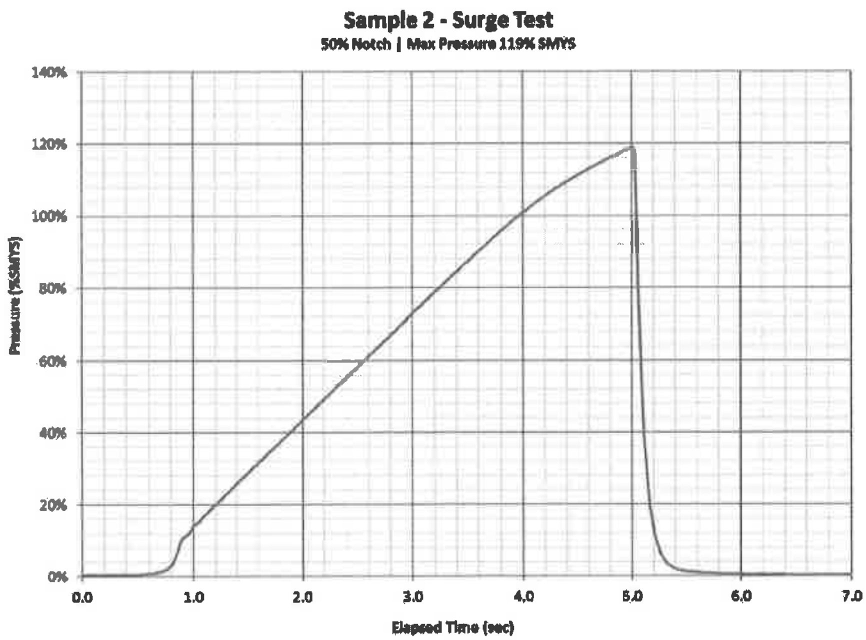

Figure 4-1: Pressure vs. elapsed time for surge test of Sample 2 – 50% WT notch.

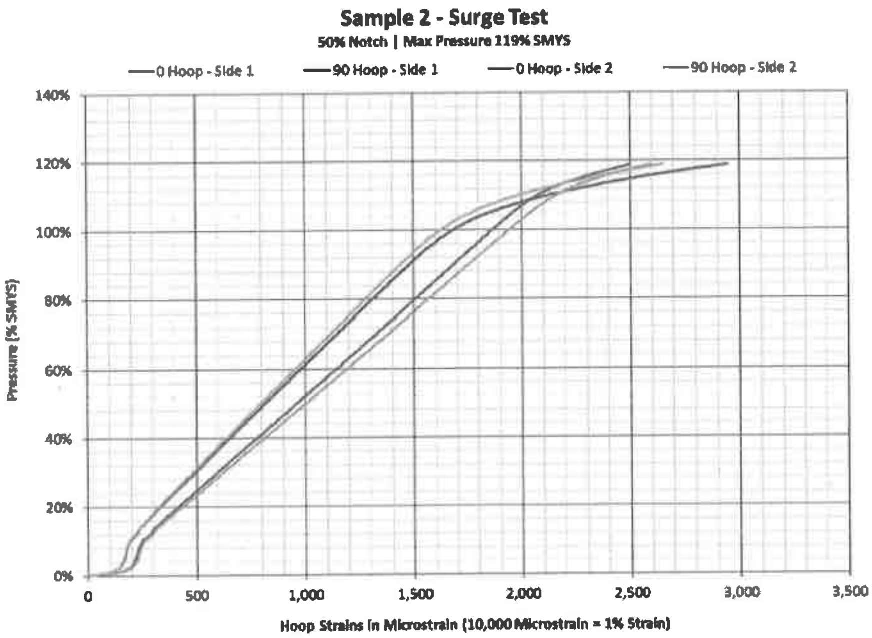

Figure 4-2: Pressure vs. hoop strains for surge test of Sample 2 – 50% WT notch.

Surge/cycle over one representative inspection interval – 10% and 25% defect

Initial surge

The 10% and 25% WT notches in Sample 3 were subjected to an initial pressure surge followed by 220 simulated pressure cycles. The purpose of the initial surge was to show that 25% and 10% WT defects could survive at 106% SMYS. The total time required for the surge to occur was 5.5 seconds. The seam and base pipe strains from the surge indicated that the seam behaves linear-elastically while the base pipe experiences a small amount of plastic strain. This is to be expected since the surge is over 100% SMYS and the seam has higher yield/tensile properties than the base pipe. The notch displacement measured by the clip gage in Figure 4-3 indicated the 10% notch experienced no change from the surge while the 25% notch experiences approximately 1.75 mils of displacement. Later samples indicated this notch displacement continued to increase with subsequent surges, but this portion of the test program only included one (1) surge.

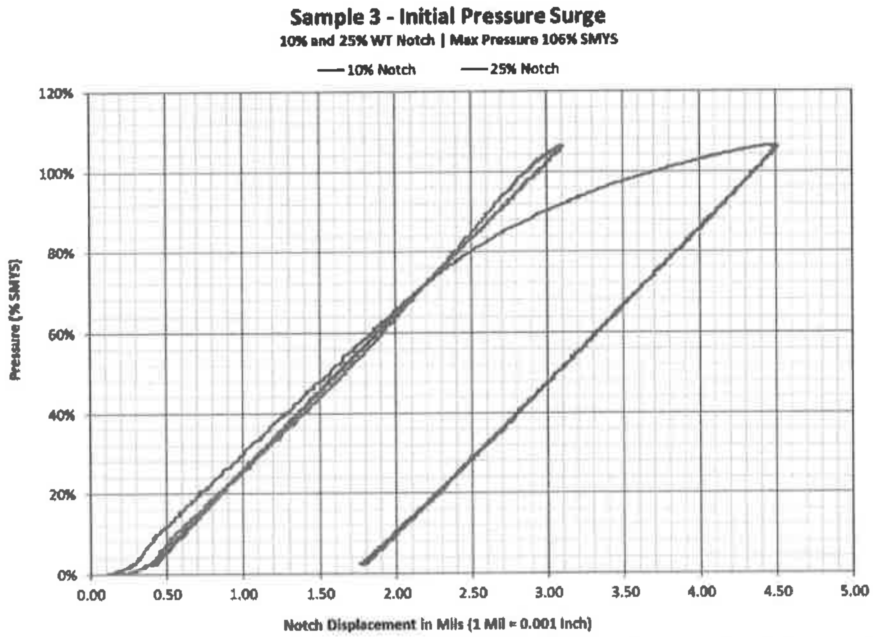

Figure 4-3: Pressure vs notch displacement in mils (1 mil = 0.001 inch) for surge test of Sample 3 – 10% and 25% WT notch.

Cycling – 5 years of service

Sample 3 was cycled for 220 cycles following the surge to represent 5 years of operation during operational period 1 in
Table 2-1 (44 cycles per year). Even though the base pipe experienced a small amount of plastic deformation in the initial surge, the same hoop strain gages indicate this strain did not grow with following cycles. These strains and notch displacement remained relatively constant over the 220 cycles (5 year operating period). . After the 220 cycles were completed, the two (2) notches were removed from the pipe body and broken open to examine for crack growth.

Surge/cycle – 10% and 25% defects

The 10% and 25% WT notch in Sample 4 underwent 97 years of simulated cycle/surges covering all three (3) operational periods in
Table 2-1. SES recorded the initial pressure surge and first few cycles of each operational year, since continuous data recording was unnecessary.
Figure 4-4 below displays the internal pressure vs. elapsed time for the first operational year (1 surge and 44 cycles at 10% to 72% SMYS) which is representative of the data taken for the other cycle/surge combinations.

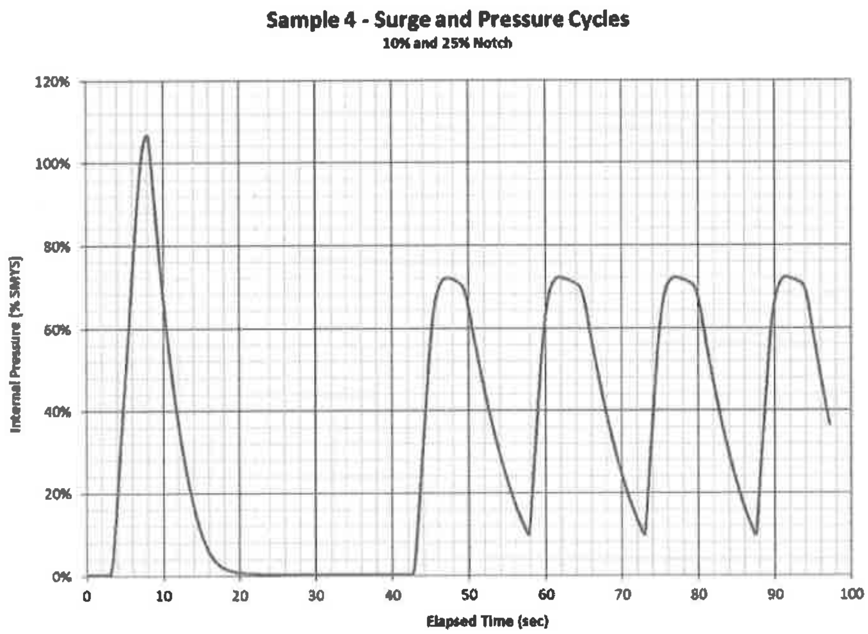

Figure 4-4: Internal pressure vs. elapsed time for representative operational year of the cycle-surge fatigue test for Sample 4.

The one indication of fatigue growth during testing was the notch opening displacement measured by the clip gages.

Figure 4-5 displays the notch displacement range for all 97 pressure surges in mils (1,000 mils = 1-inch). Note that the displacement range is the difference between the max and min displacement during the pressure surge, and the notch opening displacement is the opening of the notch (not measuring crack growth into the wall thickness). The 10% notch saw no increase in displacement range for all 97 surges. The 25% notch though experienced a steady increase in notch opening displacement after the initial 20 simulated years. The initial and final displacement range for the 25% notch was 3.13 mils (0.00313-inch) and 4.17 mils (0.00417-inch) respectively. Due to a technical issue with the data acquisition, data was not recorded for cycle 57.

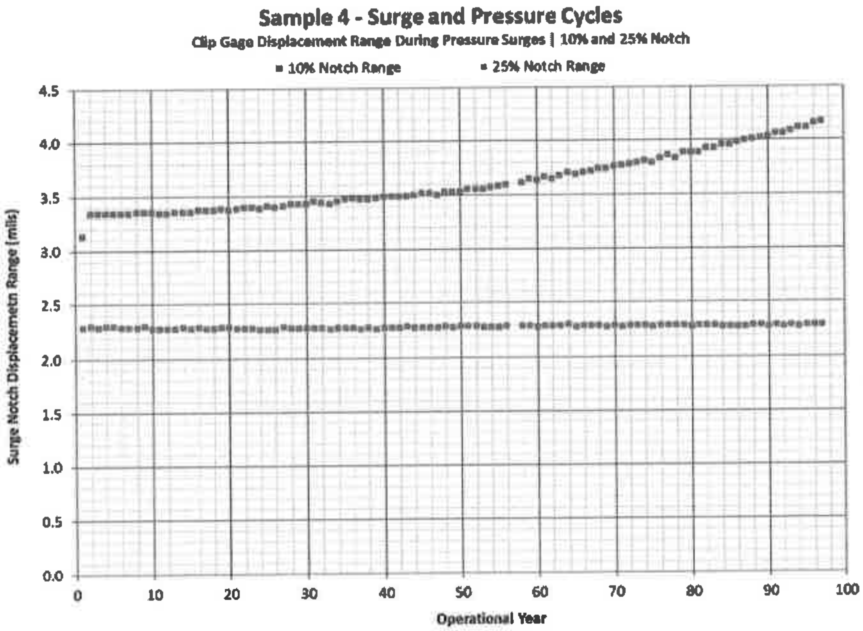

Figure 4-5: Notch displacement range (mils) vs operational year for the 97 pressure surges of Sample 4 (10% and 25% Notches).

Figure 4-6 displays the same notch opening displacement for the pressure cycles over the simulated 97 year operational period. In this figure, the data represents the maximum notch displacement range over the recorded cycles in each operational period. In other words, the 19 to 44 equivalent cycles during each operational period were compressed to one maximum displacement range. This was done because the notch displacements during the cycling only portion of the fatigue test showed no signs of increasing. The steady increase in the 25% notch displacement range in
Figure 4-6 is due to growth achieved during the pressure surges, and not from any growth during the cycles.

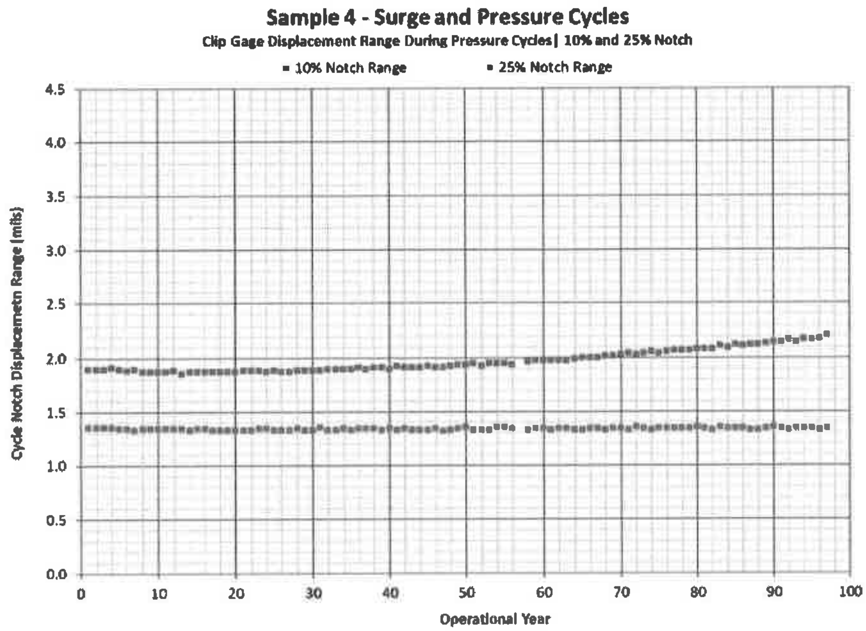

Figure 4-6: Maximum notch displacement range (mils) for the pressure cycles of each operational year of Sample 4 (10% and 25% Notches).

The ERW seam and base pipe hoop strain ranges (difference between max and min hoop strains) for the surges and cycles showed relatively no increase during the 97 year operational period. The only increase occurred in the initial surges where the surge pressure exceeded the yield strength of the base pipe and caused the base pipe to strain harden.

Surge/cycle – in service anomaly

The in-service anomaly (Sample 1) underwent 97 years of simulated cycles/surges covering all three (3) operational periods in
Table 2-1. Since the in-service anomaly was an internal feature, it was not possible to measure crack opening displacements via clip gages. Hoop and axial strains on the HF ERW seam and base pipe were recorded during the surge/cycle test program. Strains measurements on the HF ERW seam and base pipe indicated that the strain ranges during cycling were much lower than during the pressure surges. All strain ranges remained constant though during the 97 years of simulated operation.

Burst tests

At the completion of the pressure surge/cycle fatigue phase of the test program, burst tests were performed on Sample 1 (in-service anomaly) and Sample 4 (25% and 10% notch). Both these samples survived the 97 pressure surges and the equivalent number of 10% to 72% SMYS pressure cycles for each of the operational years.

Sample 4 burst at a pressure of 132% SMYS at the 25% notch location as shown in
Figure 4-7. Strains in the base pipe and HF ERW seam remained stable during two five minute holds at 72% and 100% SMYS . The two (2) base pipe strain gages located at 90° both reached 5,500 microstrain (0.55% strain) at failure. The HF ERW seam strains at failure were lower the base pipe at 4,000 and 4,600 microstrain.

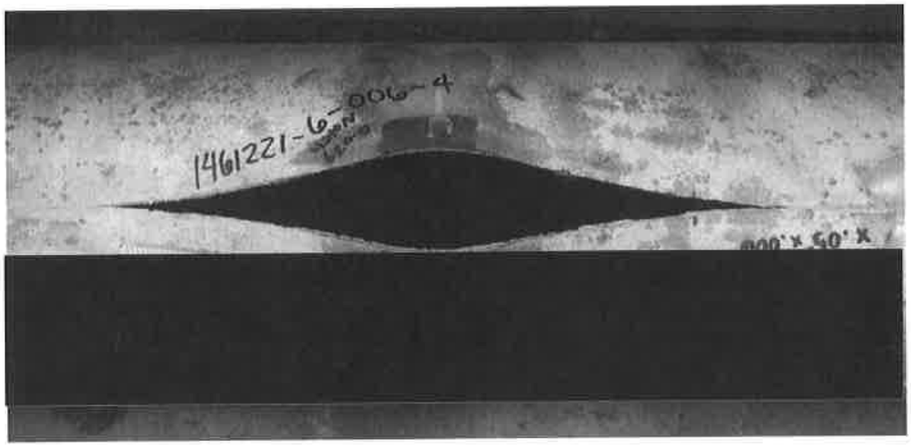

Figure 4-7: Sample 4 (10% and 25% notch) failure surface at the 25% notch in the HF ERW seam.

The in-service anomaly in Sample 1 failed at an internal pressure of 161% SMYS at the anomaly location as shown in Figure 4-8. Strains in the base pipe and HF ERW seam remained stable during two five minute holds at 72% and 100% SMYS. The anomaly, which was thought to be 73% of the wall thickness at the time of failure, did not significantly reduce the strength of the HF ERW seam even after the fatigue test program. The base pipe at the time of failure reached over 22,000 to 23,000 microstrain (2.2% to 2.3% strain). The gages located on the HF ERW seam disbonded from the pipe at approximately 12,500 microstrain (1.25% strain).

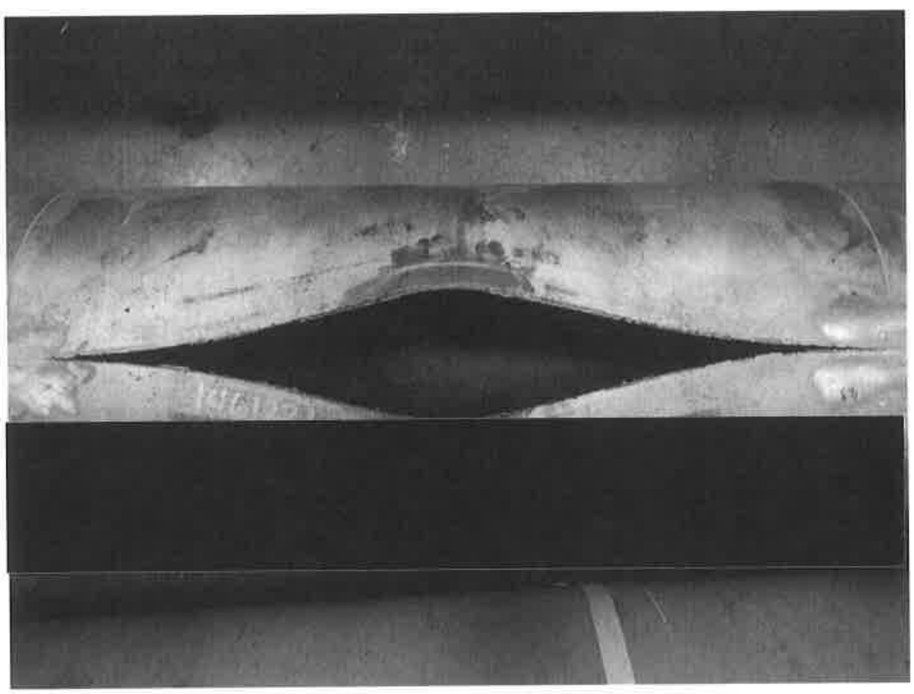

Figure 4-8: Sample 1 (in-service anomaly) failure surface at the anomaly in the HF ERW seam.

Metallurgical examination

Fractography

SES sectioned and removed the in-service anomaly from Sample 1 and the notches from Samples 2, 3, and 4. Samples 1, 2, and 4 were subjected to a burst test; therefore the fracture surface was exposed after testing. Sample 3 did not fail during the surge test; and the notch was broken open by chilling the sample in liquid nitrogen.

The fracture surfaces for Samples 1 through 4 are shown in
Figure 5-1 through
Figure 5-4, respectively. The in-service anomaly present in Sample 1 (
Figure 5-1) appears to have a discontinuity that runs along the circumference of the pipe, parallel and close to the internal surface. Metallurgical examination of this sample will provide greater detail to the type of flaw present.

The notch present in Sample 2 (
Figure 5-2) and Sample 3 (
Figure 5-3) did not show signs of fatigue growth during the cycle and surge tests. However, the notch present in Sample 4 (
Figure 5-4) shows signs of fatigue growth during the cycle and surge test. Up-close examination of the fracture surface, shown in Figure 5-5, displays three distinct regions – the EDM notch, notch growth by fatigue during pressure surges, and final overload fracture. These regions were also examined via scanning electron microscopy below.

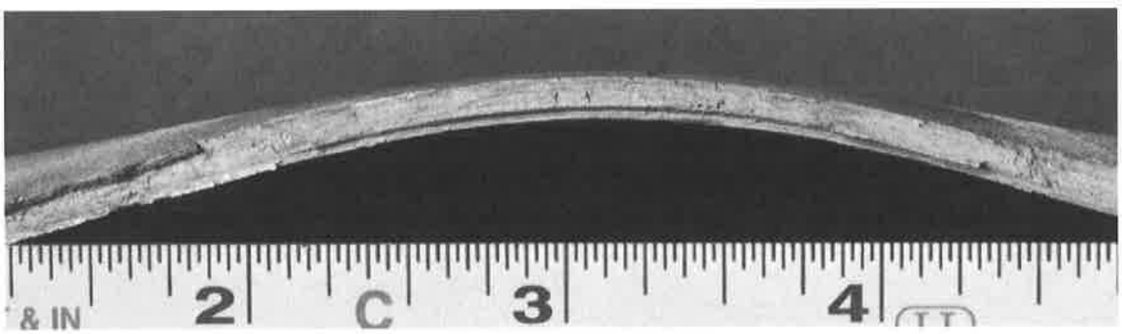

Figure 5-1: Photograph of Sample 1 fracture surface containing the in-service anomaly. Numbered scale divisions are inches.

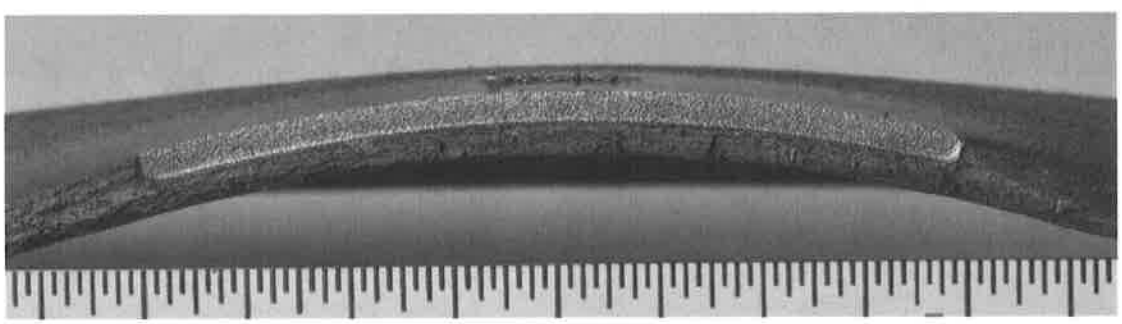

Figure 5-2: Photograph of Sample 2 fracture surface containing a 50% notch. Scale divisions are 1/32 inch.

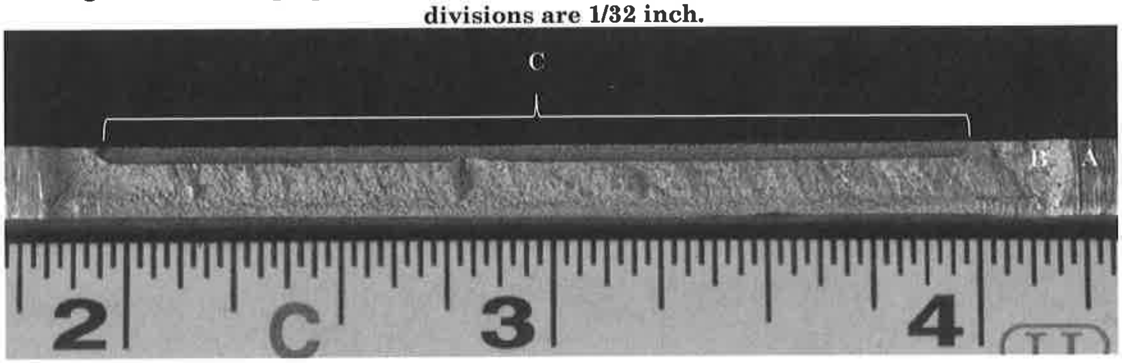

Figure 5-3: Photograph of Sample 3 fracture surface containing a 25% notch. Region A is the saw cut, region B is lab fracture, C is the EDM notch. Numbered scale divisions are inches.

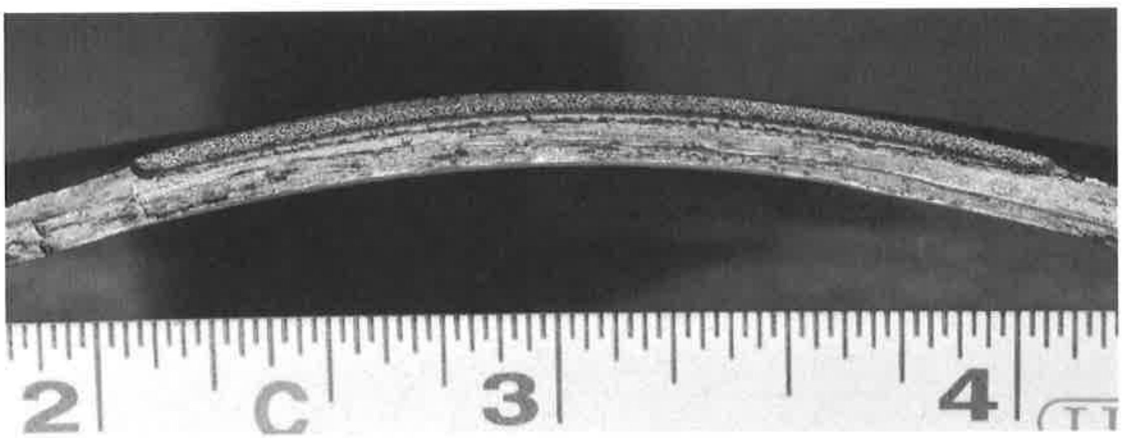

Figure 5-4: Photograph of Sample 4 fracture surface containing a 25% notch. Numbered scale divisions are inches.

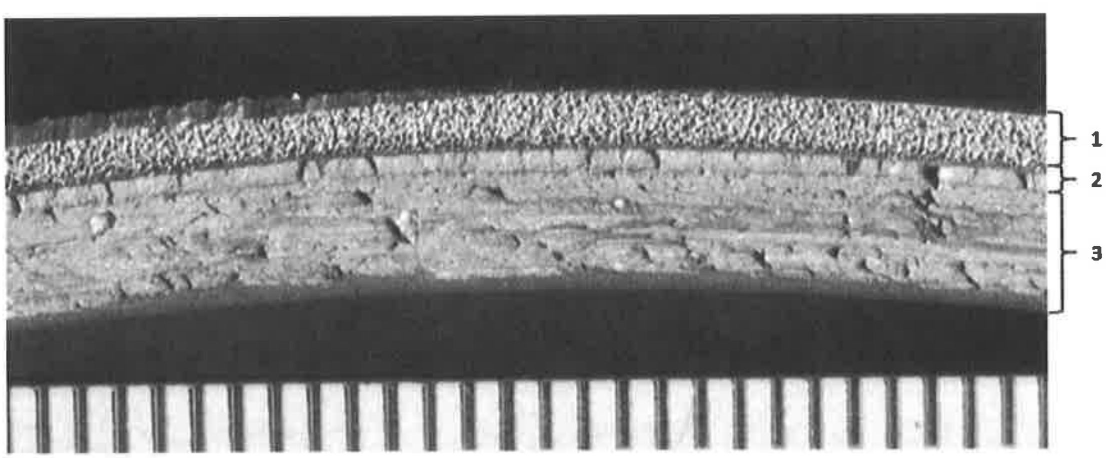

Figure 5-5: Up-close photograph of Sample 4 fracture surface containing a 25% notch. Region 1 is the original EDM notch, region 2 is the fatigue growth, and region 3 is the final overload fracture. Scale divisions are 1/32 inch.

Metallography

SES prepared a matched fracture metallurgical cross section across the in-service anomaly present in Sample 1, as shown in
Figure 5-6. The in-service anomaly appears to be consistent with a downturned fiber, i.e. an entrapped inclusion turning toward the pipe internal surface. The non-uniform fracture surface, especially at the ID, indicates the flaw likely did not connect to the inner pipe surface, as shown in
Figure 5-7. An inclusion appears to be present on the ERW bond line at approximately 1/3 of the wall thickness from the pipe OD. Ferrite banding along the downturned fiber interface supports the conclusion the flaw is a downturned fiber, as shown in
Figure 5-8.

SES prepared a metallurgical cross section of the long seam weld from a pipe section not used in testing Based on the microstructure of the body of the pipe, heat-affected zone, and bond line of the weld, it appeared that the pipe examined was likely produced using the high frequency ERW process. The arrow in Figure 5-9 represents the approximate bond line.

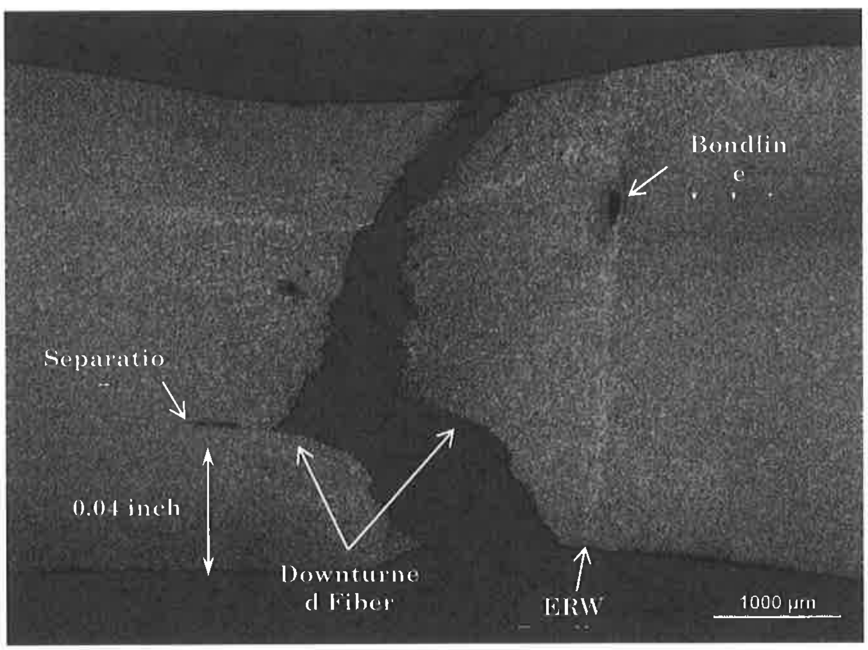

Figure 5-6: Matched fracture photomicrograph of in-service anomaly present in Sample 1. Etchant is 2% Nital, original magnification is 25x.

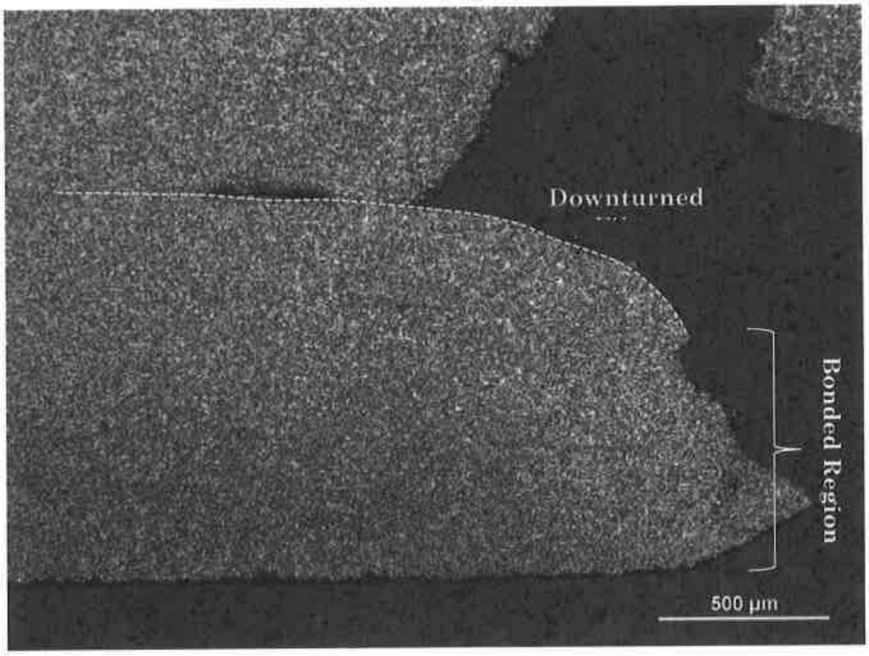

Figure 5-7: Photomicrograph of in-service anomaly present in Sample 1 showing downturned fiber. Etchant is 2% Nital, original magnification is 50x.

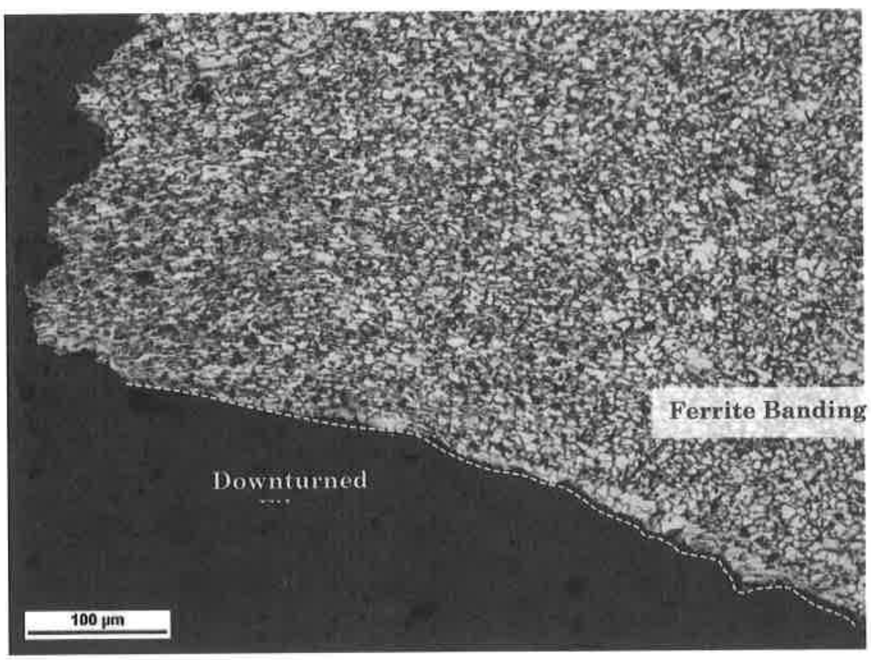

Figure 5-8: Photomicrograph of in-service anomaly present in Sample 1 showing ferrite banding near downturned fiber. Etchant is 2% Nital, original magnification is 200x.

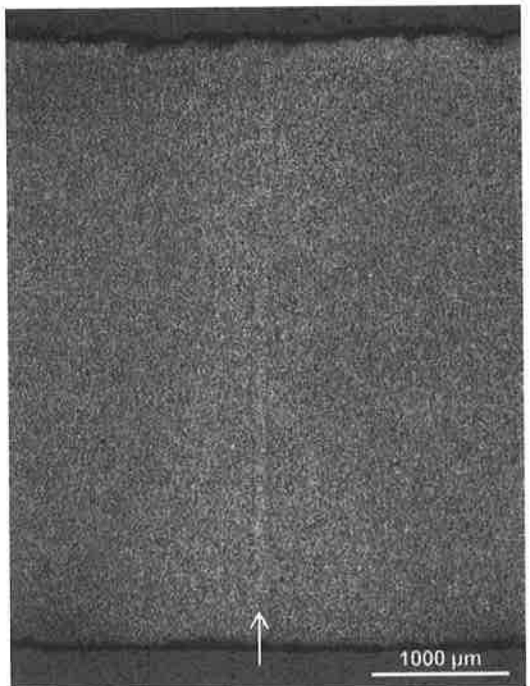

Figure 5-9: Photomicrograph of ERW long seam weld present in a fabrication drop from P66 Sample 5. White arrow indicates ERW bondline. Etchant is 2% Nital, original magnification is 25x.

Scanning electron microscopy

The fracture surface of Sample 4 was examined with scanning electron microscopy (SEM). Figure 5-10 shows an overall secondary electron image displaying three distinct regions. Areas for up-close examination are indicated by letters A, B, and C. Location A displays some indication of fatigue as slight striations are visible. Location B is an area of transition from fatigue to overload fracture. Location C was is an area of overload fracture displaying ductile dimpling. The fracture surfaces are consistent with the testing program, i.e. melting due to EDM notching, fatigue during pressure cycling, and final overload fracture during burst testing.

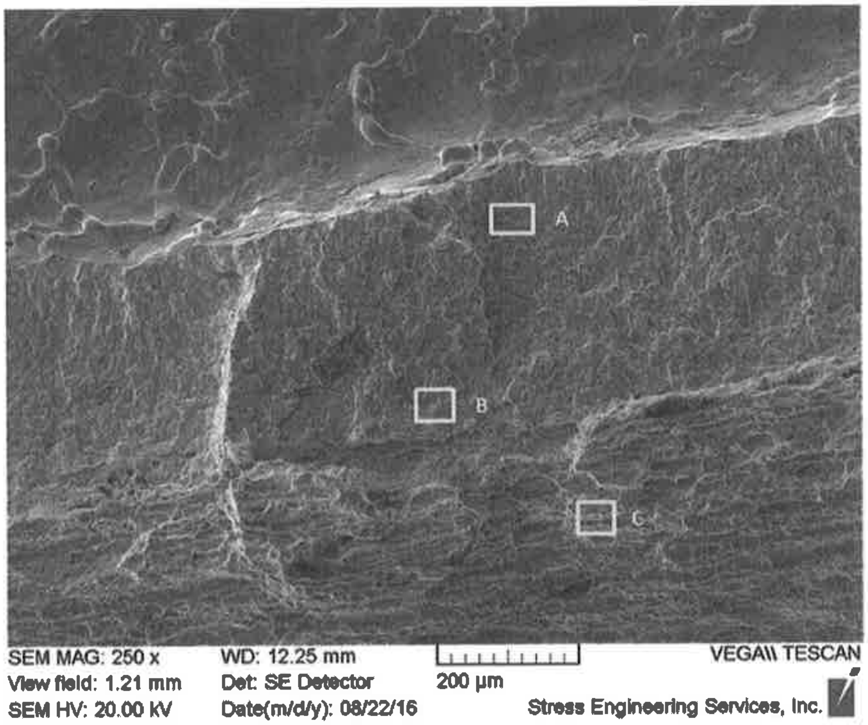

Figure 5-10: Secondary Electron SEM image at base of EDM notch in Sample 4.

Discussion

The fracture mechanics calculations predicted the 50% notch in Sample 2 would not survive a pressure surge of 106% SMYS. The sample actually surpassed this pressure though and failed at 119% SMYS. The difference between the fracture mechanics calculations and test results could be due to a number of factors. One likely cause is that fracture mechanics calculations require accurate material property information that is often not easily available for pipeline material in this study. Charpy V-Notch values are easily attainable, but do not provide a direct measure of fracture toughness (a number of correlations relate CVN to toughness values). Other times, constants are provided by industry standards and experience. For example, in this study the API 579 FAD calculations used what is commonly considered moderate fracture toughness values for Grade X52 pipe. This uncertainty in the material data often leads the calculations to have built in conservatism, which is also the case with the 50% notch.

Failure above the predicted 106% SMYS pressure is a conservative result, and preferred to failure below this predicted pressure. This test successfully demonstrated that the pipeline in question is unlikely to have defects in excess of 50% of the wall thickness, if the magnitude of past pressure surges was 119% SMYS or below. It is also important to note that EDM notches are not the same as cracks. Notches are close approximation to crack-like flaws, but initially do not have sharp crack tips. In other words, the stress riser at the tip of an EDM notch is smaller than that of an actual crack. This is another potential cause for the difference between the fracture mechanics predicted failure pressure and the test results.

Sample 3 was a short duration test of only five (5) operational years to identify if pressure cycles from the pipeline would cause detectable fatigue growth in 10% and 25% defects. Five (5) years is a representative inspection period for the pipeline. The initial pressure surge caused deformation of the base pipe and opening of the 25% crack tip (see Figure 4-3 and
Figure 4-4 for pressure vs. hoop strains and pressure vs notch displacement data). The Fractography in
Figure 5-3 indicate that no detectable flaw growth occurred in the 25% notch due to the five (5) years of equivalent cycles. This five year period did not include intermediate pressure surges (aside from the initial surge).

The 97 year surge/cycle fatigue test on Sample 4 did result in fatigue growth of the 25% notch. The growth is visible in
Figure 4-5 where the notch displacement range grows with each surge. This figure also indicates that the 10% notch did not experience any growth due to the constant displacement range. The Fractographic image seen in Figure 5-5 also has a clearly visible band of fatigue growth for the 25% notch. This growth is mostly likely due to the pressure surges and not cycles. This is supported by the 25% notch in Sample 3 (5-year representative inspection interval) not experiencing any fatigue growth during five simulated years of continuous cycling with no intermediate pressure surges. Also, the high magnitude pressure surge would blunt the crack tip by creating a localized area of plasticity at the tip. The initial 25% notch and subsequent crack growth from 97 years of equivalent cycles and surges did not greatly reduce the pipe strength though. The pipe burst at a pressure equivalent to 132% SMYS.

The in-service anomaly in Sample 1 was identified as a downturned fiber that did not connect with the inner pipe surface. Measuring from the inside surface, the downturned fiber initiated from a separation at 25.6% of the WT to 12.8% the WT (total through wall extent of approximately 13%). The ILI tool initially identified this anomaly as a 3.071-inch long crack in the lowest reporting bin of 0-40 mils. The phased array UT inspection identified the anomaly as a 1.5-inch and a 73% WT. The authors can only speculate on the discrepancy between the NDE measurements and the metallography, but it may be due to the shape, and physical features of the downturned fiber. This is unlike an actual crack where the NDE signal is likely more discernable. In that the bonding around the downturned fiber is typically good when no crack is present, the HF ERW seam retained much of its strength during the burst test and failed at 161% SMYS. Metallographic examination of the downturned fiber following the burst also did not find any indication of fatigue growth following the 97 year cycle/surge fatigue program.

Conclusions

This paper presented a testing program developed to evaluate the fatigue performance of manufacturing defects in HF ERW seams. The fatigue program included typical liquid line pressure cycles and occasional pressure surges over three (3) operational periods. The defect sizing methodology was based on fracture mechanics, and the line's operational characteristics. Findings of this test program include:

- A 2-inch long, 50% WT notch failed during a pressure surge at 119% SMYS. This pressure was higher than the fracture mechanics predicted, but acted as validation for the calculations. The higher failure pressure during testing was attributed to conservatism built into the fracture mechanics calculations, and/or a relatively blunt EDM notch, as compared to a crack tip.
- Five years of pressure cycling based on the first operational period did not produce any measurable fatigue growth in 10% and 25% WT defects. The five year length is a representative inspection interval for the pipeline in question.

The simulated 97 years of surge/cycles did produce measurable fatigue growth in 10% and 25% notches. The notch opening displacement data attributed this growth to the pressure surges, and not the pressure cycles. With the simulated 97 years of fatigue growth, the burst pressure was 132% SMYS.

The ILI tool call, phased array ultrasonic inspection, and metallurgical inspection of the in-service anomaly did not agree on the defect depth. The ILI tool was closest to the measured anomaly by placing the feature call in the 0-40mil depth bin. The phased array ultrasonic inspection indicated a significantly large defect depth of 73% the wall thickness.

The in-service anomaly that was initially identified as a long weld anomaly in the ILI dig sheet was in fact a downturned fiber that did not connect with the inner pipe surface. The total through wall extent of the downturned fiber was approximately 13% of the wall thickness. This was less than the phased array ultrasonic inspection measurement of 73% conducted prior to testing, but closer to the ILI tool call of 0-40mil. The downturned fiber did not experience any measurable fatigue growth during the cycle/surge fatigue program, and did not greatly reduce the failure strength of the pipe seam. The pipe burst at a pressure 161% SMYS and reached 2.2% to 2.3% strain in the base pipe.

addressed herein. Readers of this document are responsible for making their own assessment of the information and should verify all relevant information with their own advisors.