ACUREN

Acuren Group Inc.
Bay 3, 1411 25 Avenue NE
Calgary, AB, Canada T2E 7L6
www.acuren.com

Phone: 403.291.3126
Fax: 403.250.1015

NDT, Inspection and Engineering

ISO 9001:2008 QUASAR REGISTERED
Acuren: An ISO 9001 certified company

PIPELINE METALLURGICAL FAILURE ANALYSIS

16TAN LICENSE 802177-001

Prepared for

Husky Energy Inc.

Prepared by

Brian Wilson, M.Eng., P.Eng.
Senior Materials Engineer

Reviewed by

Ken Magee, M.A.Sc., P.Eng.
Senior Engineering Technical Advisor

October 24, 2016
Acuren Project No.: 306-0087829-1-R1

TABLE OF CONTENTS

ACUREN

LIST OF FIGURES

LIST OF TABLES

PREFACE

This document and all services and/or products provided in connection with this document and all future sales are subject to and shall be governed by the "Acuren Standard Service Terms" in effect when the services and/or products are ordered. THOSE TERMS ARE AVAILABLE AT WWW.ACUREN.COM/SERVICETERMS, ARE EXPRESSLY INCORPORATED BY REFERENCE INTO THIS DOCUMENT AND SHALL SUPERSEDE ANY CONFLICTING TERMS IN ANY OTHER DOCUMENT (EXCEPT WHERE EXPRESSLY AGREED OTHERWISE IN THAT OTHER DOCUMENT).

The Client Representative who receives this report is responsible for verifying that any acceptance standards listed in the report are correct, and promptly notifying Acuren of any issues with this report and/or the work summarized herein. The owner is responsible for notifying Acuren in writing if they would like their samples returned or placed into storage (at their cost) otherwise, all samples/specimens associated with this report will be disposed of 60 days after the report date.

1.0 INTRODUCTION

A length of steel pipe, shown in Figure 1, was submitted to Acuren. This pipe had been cut from a diluted bitumen pipeline (16TAN, License 802177-001), identified by location as Celtic Junction to East Till Junction (02-32-51-24 to 10-01-50-28 W3M) after a failure was detected on July 21, 2016. The failure location was reported to be adjacent to a river bank at 04-20-51-24 W3M.

The pipe material was reported to be nominal 406.4 mm OD by 7.9 mm WT CSA Z245.1 Grade 359 Cat. II line pipe. This pipeline has reportedly been in service since 1997 and was transporting about 273 m^3/hr of blend crude at 5500 kPa and at a temperature of up to 53°C. The line was understood to have been pigged on a monthly basis and was being continuously treated with Cortron RU-166 corrosion inhibitor and batch treated with Bactron K-48 biocide. The outside surface of the pipe was reportedly covered with Yellow Jacket™ YJ2 extruded polyethylene coating, overlaid with polyurethane foam insulation, which in turn was covered with a black polyethylene outer coating. There has reportedly been five in-line inspections performed on this line over its history, with the most recent ILI being in January 2015. There have reportedly been no previous failures associated with this pipeline.

Figures 2 and 3 are site photographs taken at the time of excavation of the failed pipeline, prior to removal of the failure segment. As noted, the leak site was found to be associated with buckling deformation in the pipe and there was a second buckled location found in this line immediately upstream of the leak site. Also noted in Figure 2, there was a nominal 219.1 mm OD condensate line adjacent to the 16TAN line in the same right-of-way and this condensate line also exhibited buckling deformation at approximately the same location as the buckled leak site in the 16TAN line. Samples were also cut from the non-failed buckled locations of these two pipelines and submitted to Acuren for examination and testing. The results of this work have been addressed in a supplemental Acuren report to Husky Energy.

Acuren was requested to perform a metallurgical failure analysis on the supplied pipe shown in Figure 1. This report documents our findings and conclusions.

FIGURE 1 AS-RECEIVED PIPELINE FAILURE SAMPLE

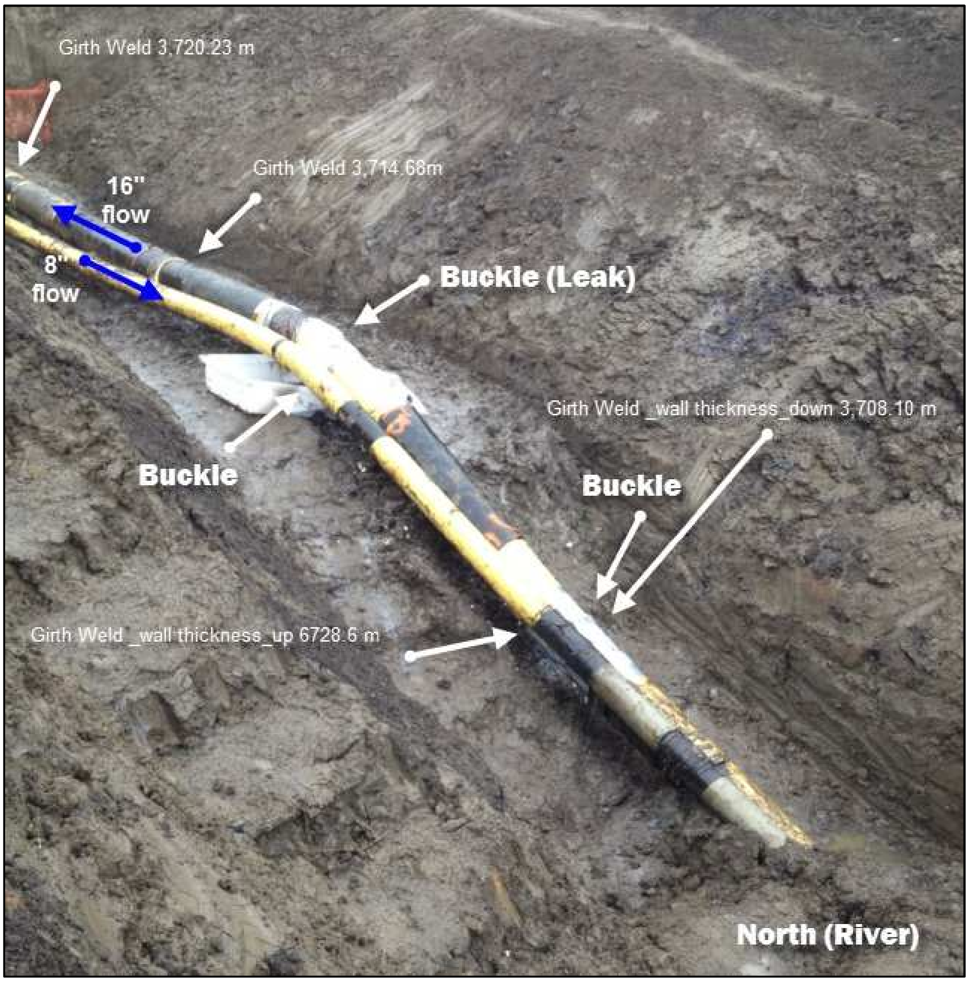


FIGURE 2 OVERVIEW OF EXCAVATED PIPELINES SHOWING BUCKLED LOCATIONS AND LEAK SITE

FIGURE 3 BUCKLING DEFORMATION AT 16TAN LEAK SITE

2.0 INVESTIGATION

2.1 VISUAL EXAMINATION

Figure 4 shows the as-received appearance of the buckled leak location at approximately mid-length on the supplied pipe sample after removal of the pipe from its steel shipping frame. As can be seen, the failure zone had been wrapped with clear plastic, held in place with duct tape. Black polyethylene tape had then been wrapped over the plastic sheet over top of the buckled zone. The foam insulation and outer polyethylene coating had been removed from this sample prior to shipment to Acuren.

The pipe sample consisted of two relatively straight segments with an inflection point coincident with the pronounced buckling at the leak location. Figure 5 shows a side view of the as-received failed pipe sample and illustrates the approximately 21° deflection angle in the vertical downward direction in the pipe, centred on the buckle.

The tape and plastic wrap were removed from the failure zone and Varsol was used to remove the oily residue on the OD surface of the pipe. Figure 6 shows the buckled and fractured failure region of the pipe after Varsol cleaning. As shown previously in Figure 3, a portion of the Yellow Jacket on one side of the buckle had been removed from the pipe on site prior to shipment to Acuren. Visual examination of the exposed external steel surface did not reveal any evidence of corrosion damage.

FIGURE 4 AS-RECEIVED TAPE AND PLASTIC WRAPPING ON FAILED BUCKLE ZONE

ACUREN

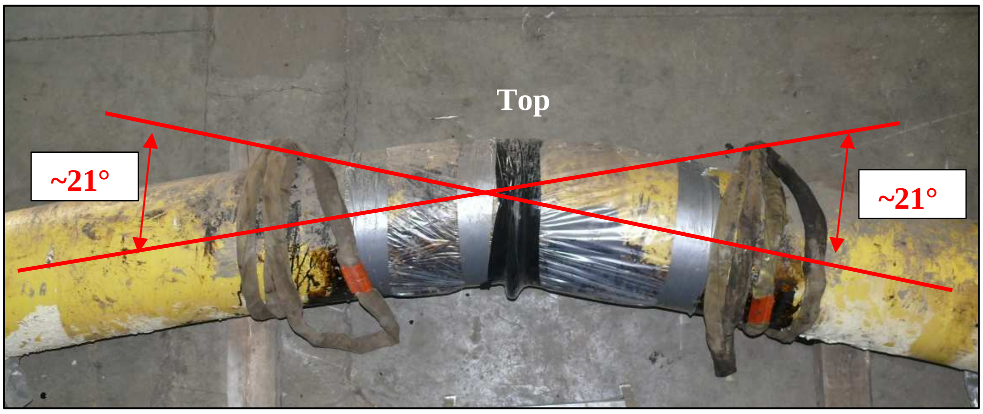


FIGURE 5 BEND ANGLE ON PIPE PROFILE

FIGURE 6 BUCKLE AND THROUGH-WALL FRACTURE AFTER CLEANING OD SURFACE WITH VARSOL

The failed segment of the pipe was extracted from the submitted sample by making circumferential cuts approximately 600 mm on either side of the buckled fracture location. The remainder of the YJ2 coating was then removed from the extracted failure segment in preparation for 3D laser scanning around the full circumference of the failure segment. The results of this laser scan have been documented by Acuren separately and the scan file submitted to Husky Energy.

As noted previously, the external surface of the pipe, including the buckled zone, did not exhibit any evidence of corrosion damage. The ID surface of the as-received pipe was covered with oily hydrocarbons, as shown by example in Figure 7. The ERW seam was located just above the 9 o'clock position (i.e. approx. 10 o'clock), near one end of the circumferential buckle. The buckle extended around about 50% of the circumference, centred at approximately the 6 o'clock position. The through-wall fracture at the apex of the buckle was also centred at the 6 o'clock position and extended around about 30% of the circumference (approx. 380 mm fracture length).

The cut ends of the failed pipe segment remote from the buckle exhibited a round profile, with a measured internal diameter of about 392 mm. This is approximately equivalent to the nominal ID (i.e. 390.6 mm) for 406.4 mm OD by 7.9 mm WT line pipe. The pipe exhibited a slightly oval cross section immediately adjacent to the buckle, with the minimum diameter being in the 6 to 12 o'clock direction (i.e. centred at the mid-length point of the buckle). The minimum ID on the upstream side of the buckle was found to be approximately 370 mm, while the minimum ID on the downstream side of the buckle was about 380 mm.

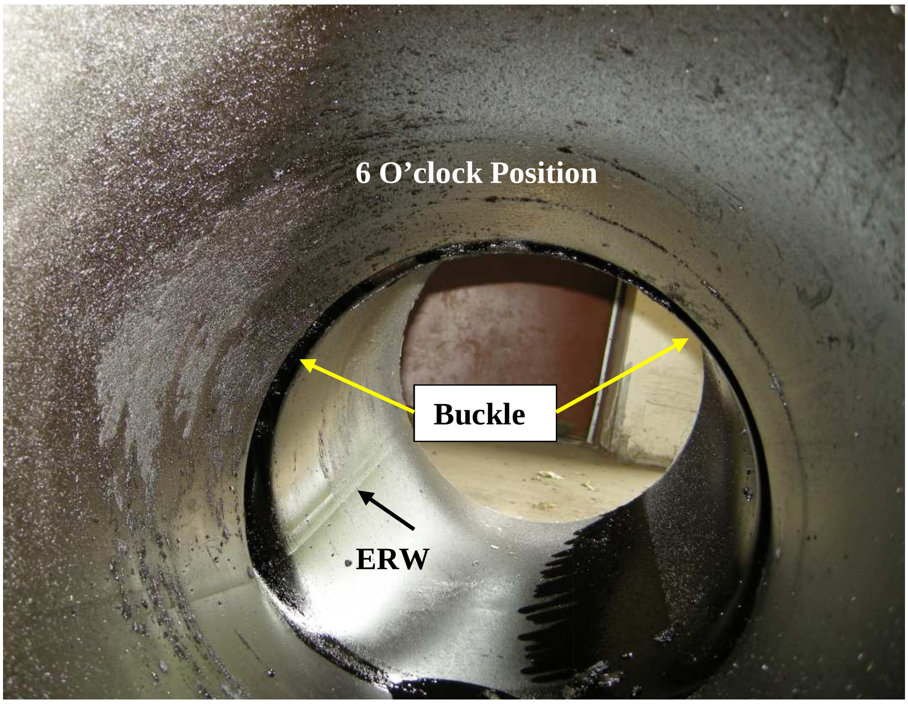


FIGURE 7 OILY FILM ON AS-RECEIVED ID SURFACE AS VIEWED FROM DOWNSTREAM END

Axial cuts were made to intersect the two ends of the 380 mm long fracture, resulting in separation of the two through-wall fracture faces and the exposure of the internal surface for more detailed examinations. Figure 8 illustrates the location of the saw cut lines, while Figure 9 shows two views of the separated fractured material in the as-received condition after cutting. A sample of the oily scale deposits that were present on the buckled ID surface was collected for chemical analysis, as described later in this report.

Figure 10 shows the remainder of the failed pipe segment after removal of the fracture zone, including close-up views of the saw cut buckled profile at each end of the through-wall fracture. As can be seen, the ID surface at the apex of this bulge on either side of the through-wall fracture exhibited a relatively deep crack. This cracking was an extension of the through-wall fracture.

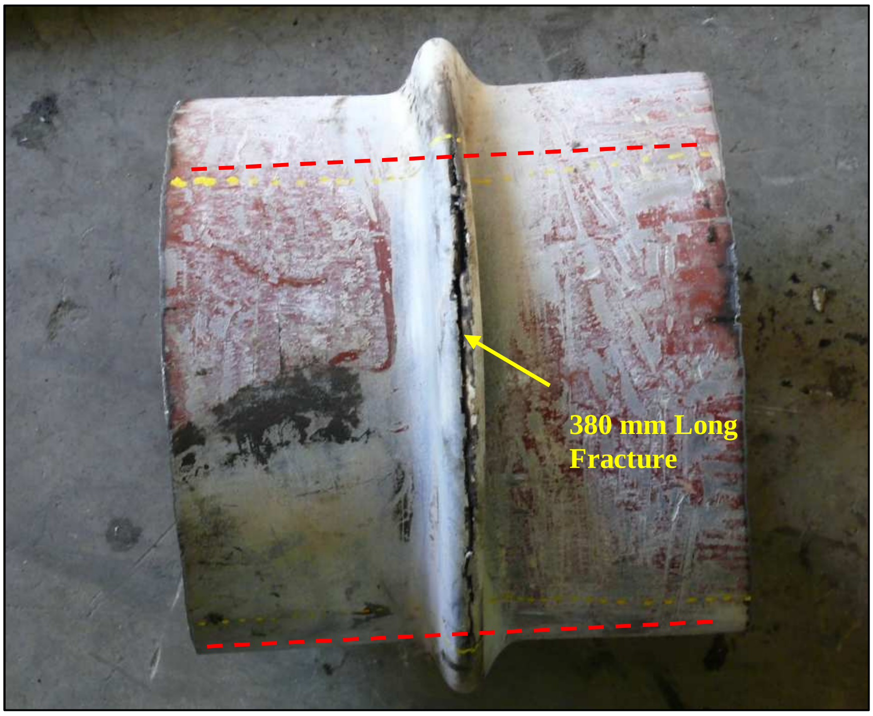
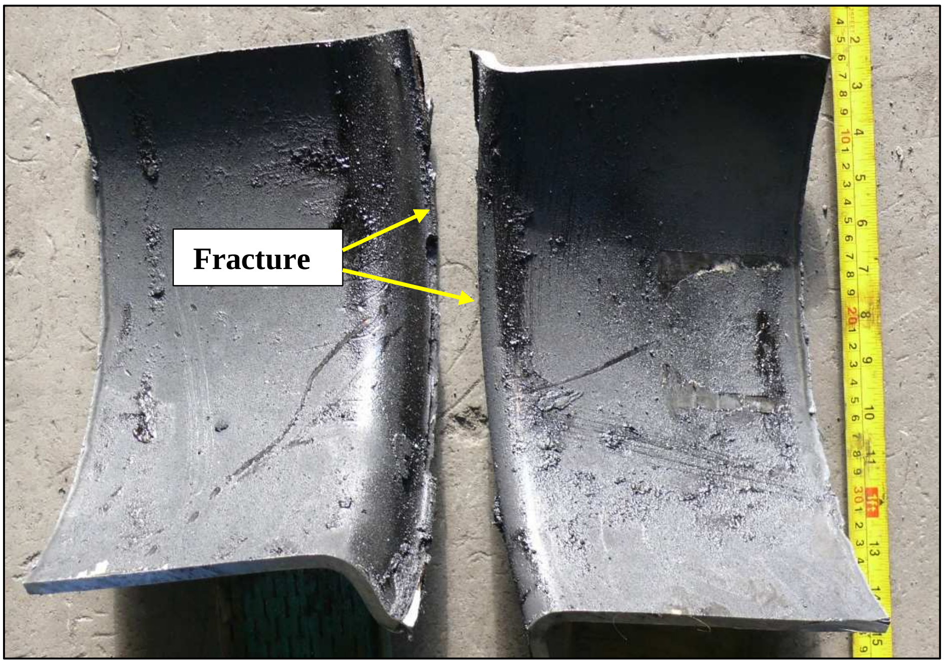


FIGURE 8 LOCATION OF AXIAL SAW CUTS



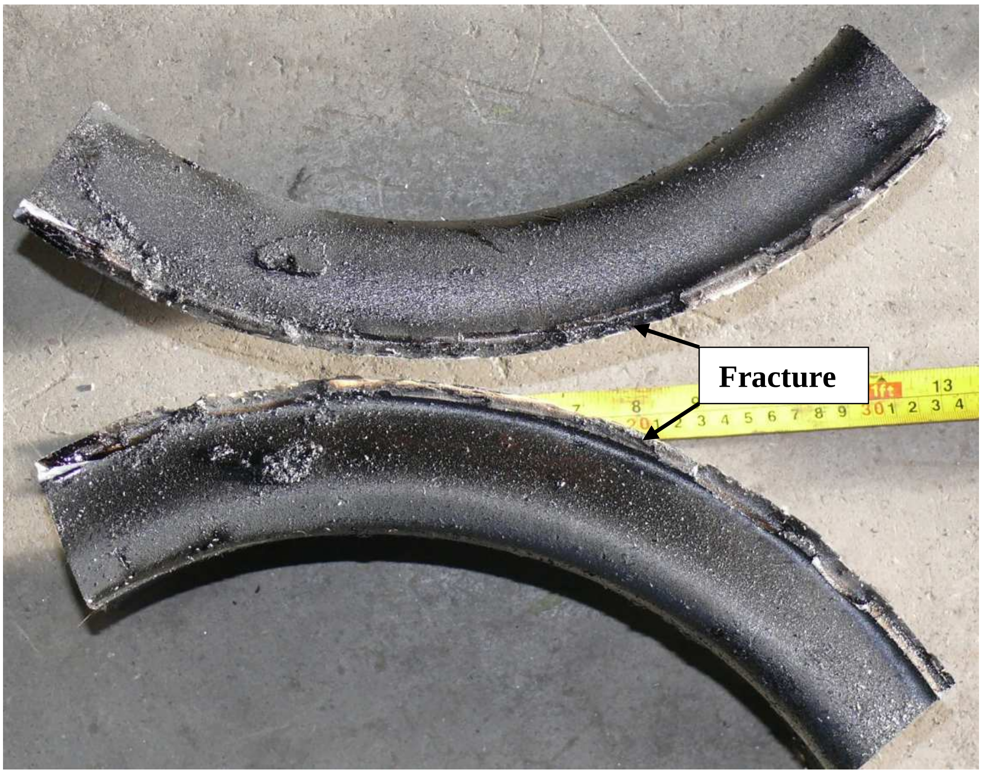


FIGURE 9 SEPARATED FRACTURE FACES, AS-RECEIVED CONDITION

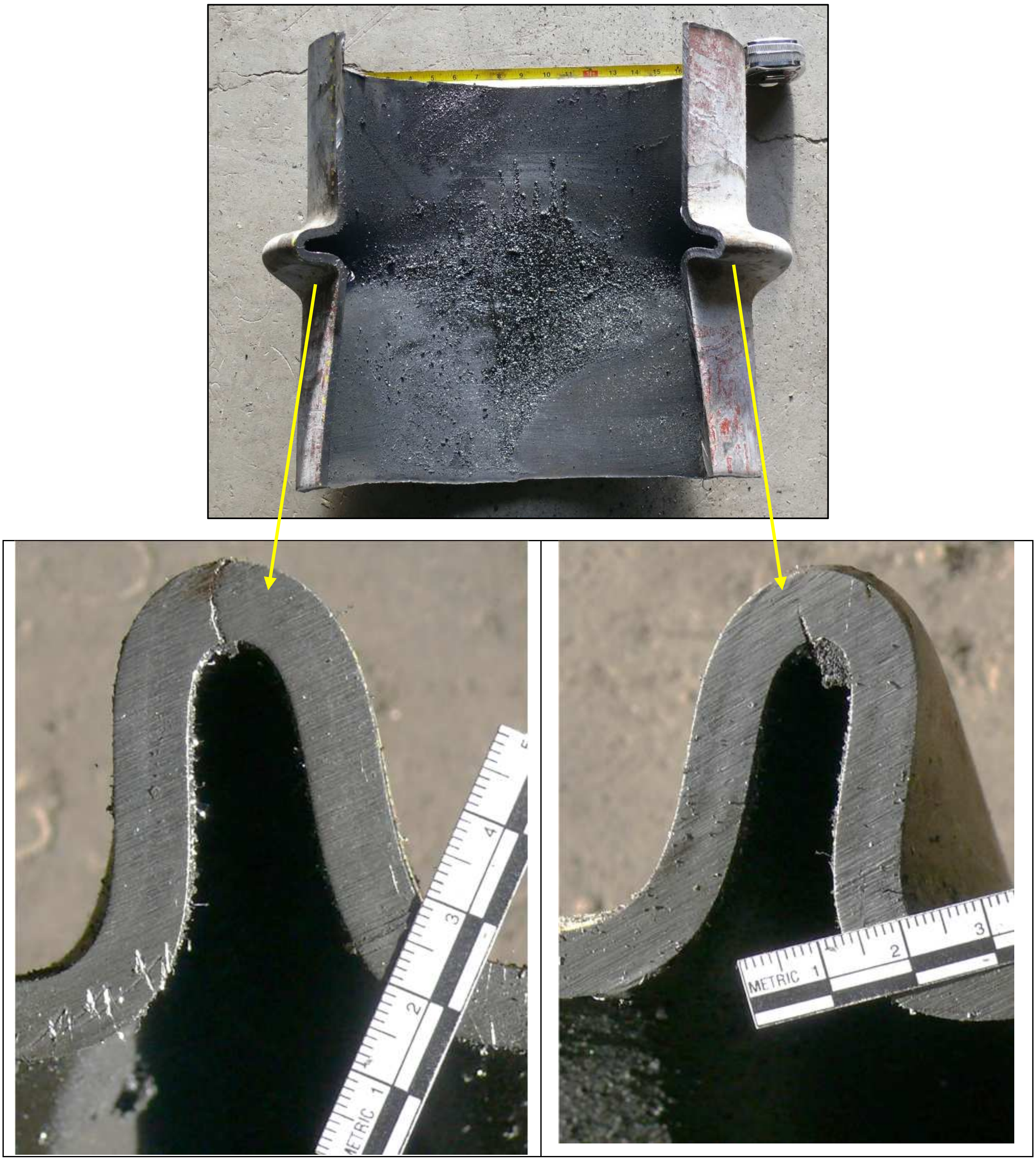


FIGURE 10 BUCKLE PROFILE AT SAW CUT FRACTURE ENDS OF INTACT SEGMENT

ACUREN

The internal surface of the extracted buckled and fractured pipe segment was washed with Varsol to remove the black oily deposits and permit a more detailed visual examination of the fracture faces. This examination revealed two distinct fracture zones: Several areas along the inner edge of the fracture exhibited a brittle planar fracture morphology, with evidence of small step-like ratchet marks. The remainder of the fracture was predominantly ductile in appearance, exhibiting a dull satiny finish with a slanted or curved fracture profile. There was no evidence of a difference in colour or scale build-up between the inner brittle zones and the outer ductile zones.

Based on the observed fracture features, two locations were selected as being representative of the typical fracture features present along the full length of the fracture. The locations of these two locations (numbered 1 and 2) are shown in Figure 11, while Figure 12 shows these two fracture zones in detail. These fracture locations were subsequently cut out for detailed examination by scanning electron microscopy (SEM) followed by metallographic examination, as described later in this report.

The internal surface of the buckled and fractured pipe segment was lightly sandblasted to remove the thin film of black scale. As shown in Figure 13, the sandblasted surface revealed a number of randomly distributed shallow corrosion pits within an approximately 150 mm wide axial band along the bottom quadrant of the line. These pits were very shallow, exhibiting depths that were estimated to be no more than about 0.2 mm. A few of these pits were also present within the buckled zone, in close proximity to the fracture. However, the fracture did not appear to have been influenced in any way by this localized corrosion.

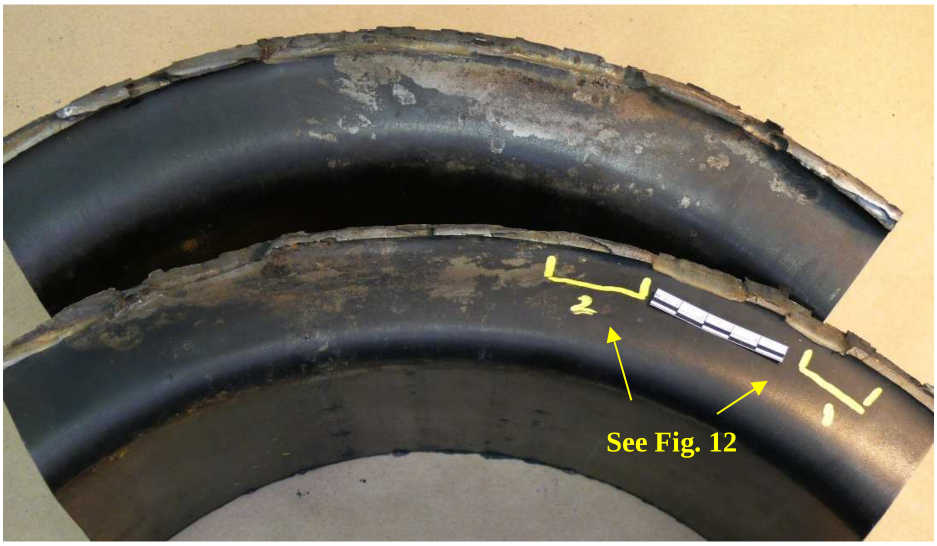
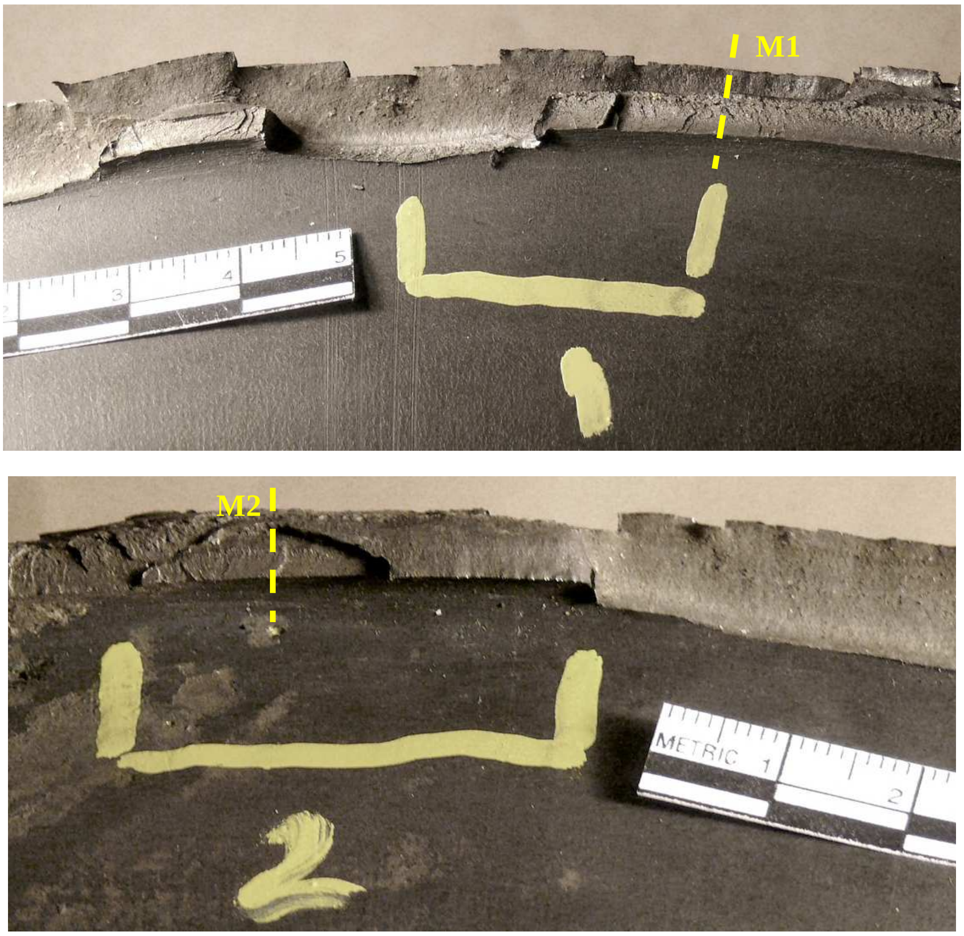


FIGURE 11 DEGREASED FRACTURE SURFACES



Note: Dashed Lines M1 & M2 Show Subsequent Metallographic Specimen Locations

FIGURE 12 CLOSE-UP VIEWS OF FRACTURE ZONES SELECTED FOR SEM EXAMINATION

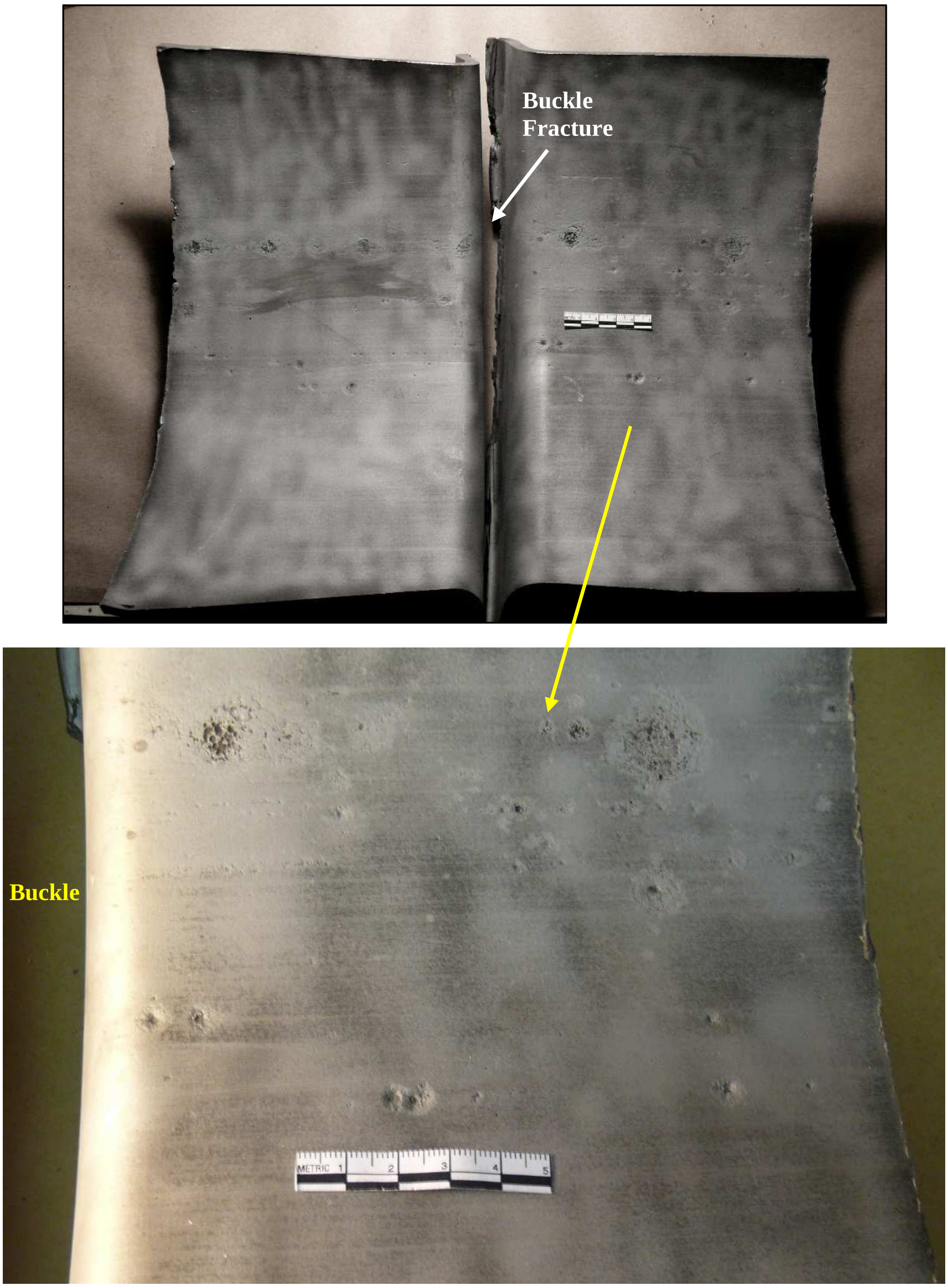


FIGURE 13 PITTING ON SANDBLASTED BOTTOM QUADRANT

2.2 Non-Destructive Examination

The cleaned external and internal surfaces of the failed segment of pipe were examined for evidence of secondary surface cracking by wet fluorescent magnetic particle inspection (MPI).

Inspection of the ID surface of the pipe on either side of the through-wall fracture zone revealed a single linear crack following the internal surface at the apex of the buckle, which extended for a distance of about 150 mm on either side of the through-wall fracture zone. Figure 14 shows this internal cracking on one side of the through-wall fracture zone for illustration purposes. This cracking did not extend through the pipe wall to the outside surface.

Figure 15 shows the brittle secondary cracking that was observed on the internal surface, parallel to and immediately adjacent to the main fracture within the apex of the buckle. As can be seen, this cracking was readily visible to the naked eye. This internal secondary cracking did not extend through the pipe wall to the OD surface.

The only cracking detected on the external surface of the remainder of the failed pipe segment was at the apex of the buckle immediately adjacent to the saw cut edges, as shown in Figure 16. The MPI indication in the lower image of this figure appear to be an extension of the end of the through wall fracture, while the small intermittent indications in the upper image appear to be small surface tears.

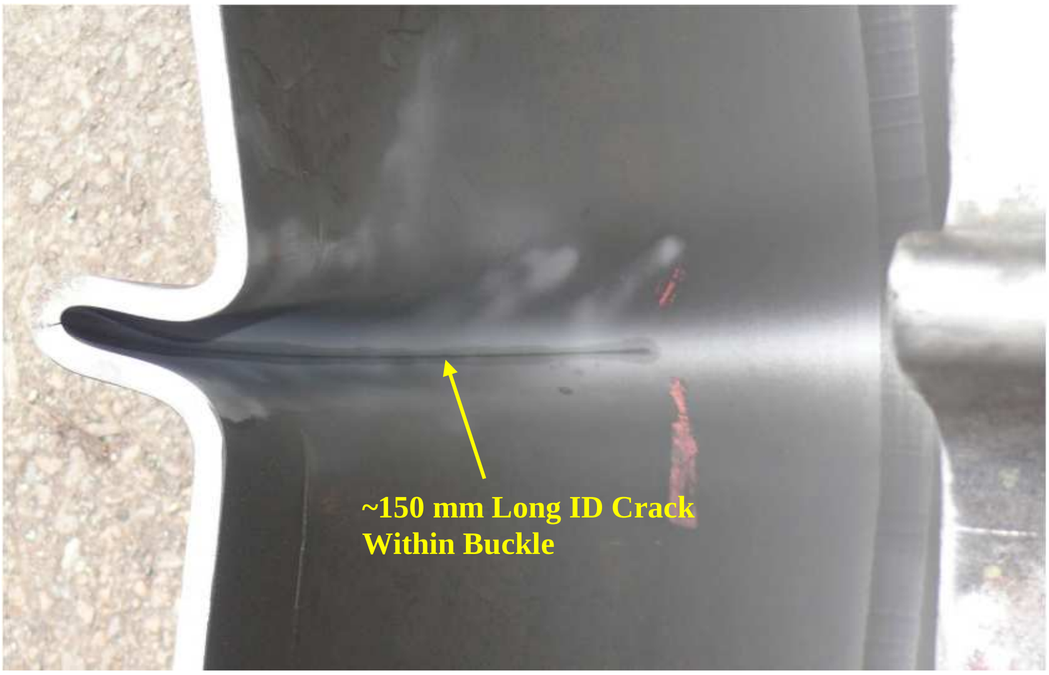


Figure 14 Internal Cracking Within Apex of the Ends of the Buckle on Either Side of Fracture zone

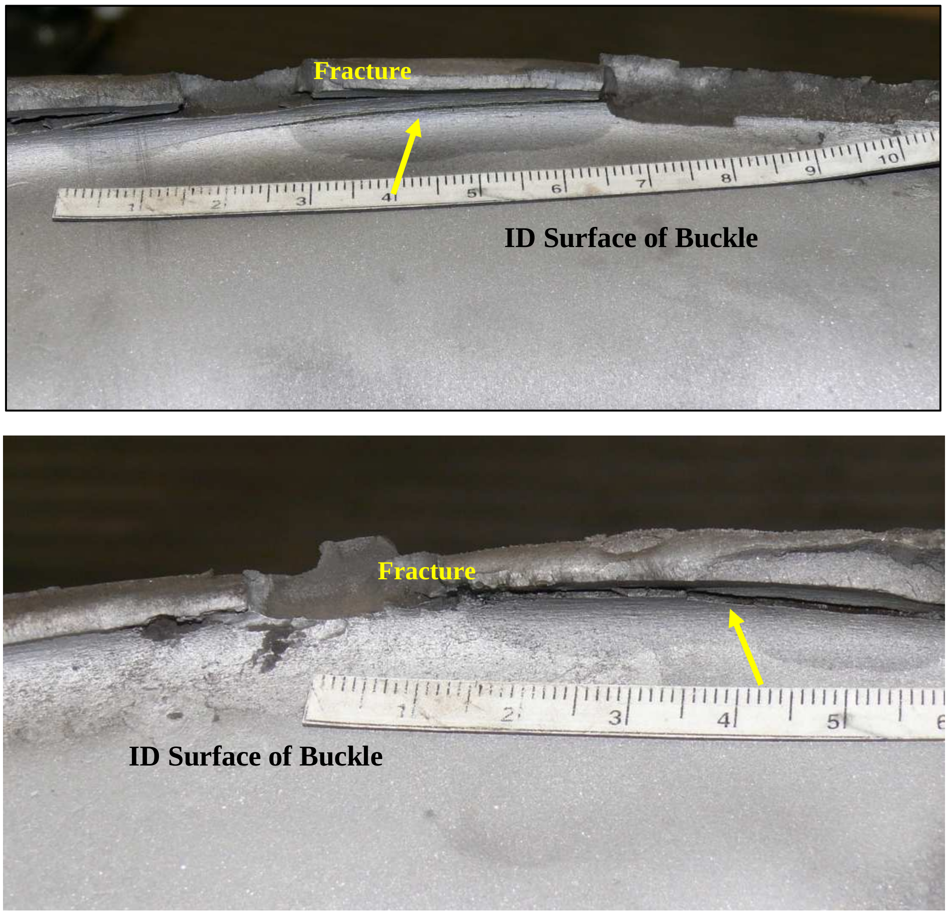


FIGURE 15 SECONDARY INTERNAL CRACKING ADJACENT TO FRACTURE

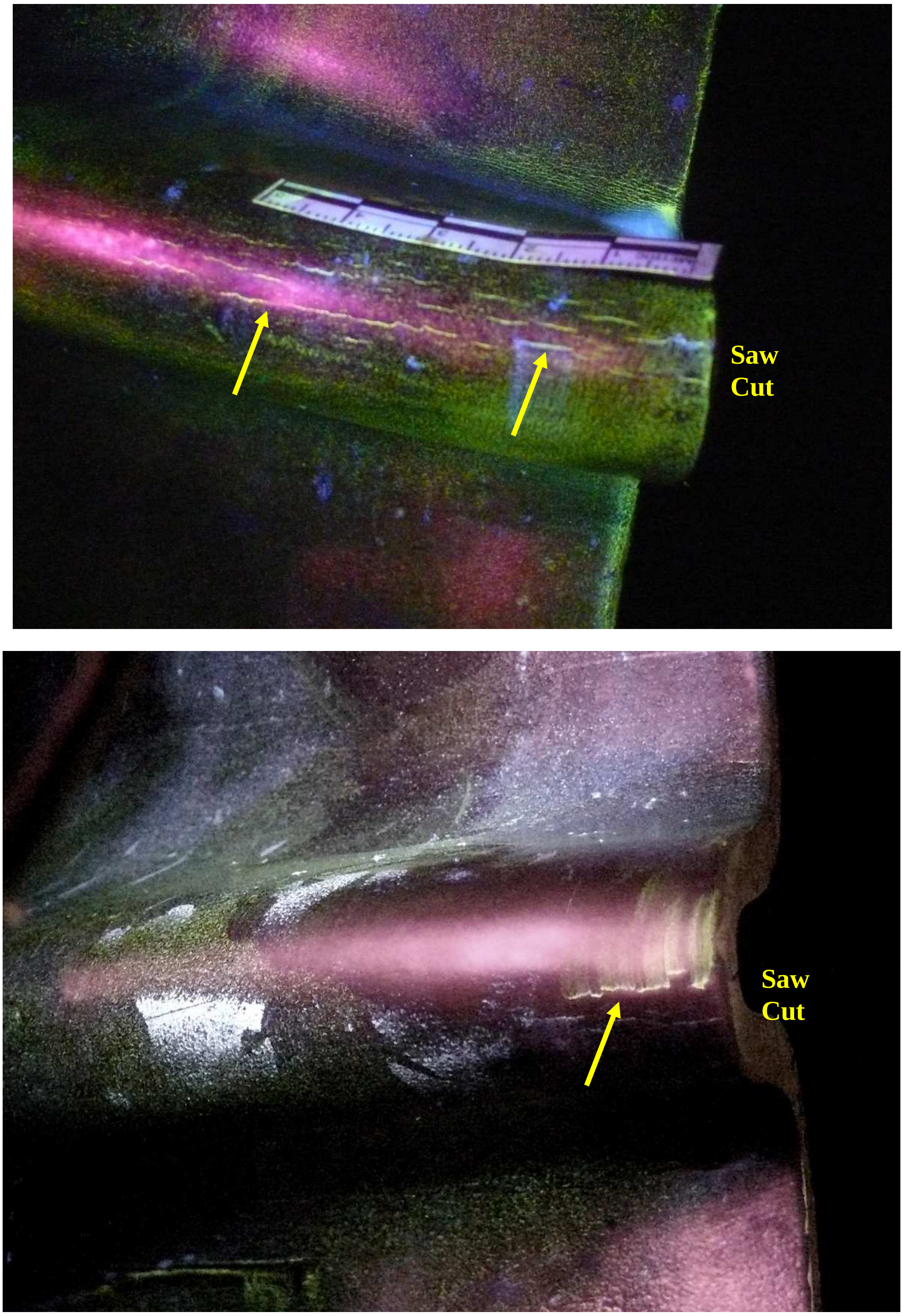
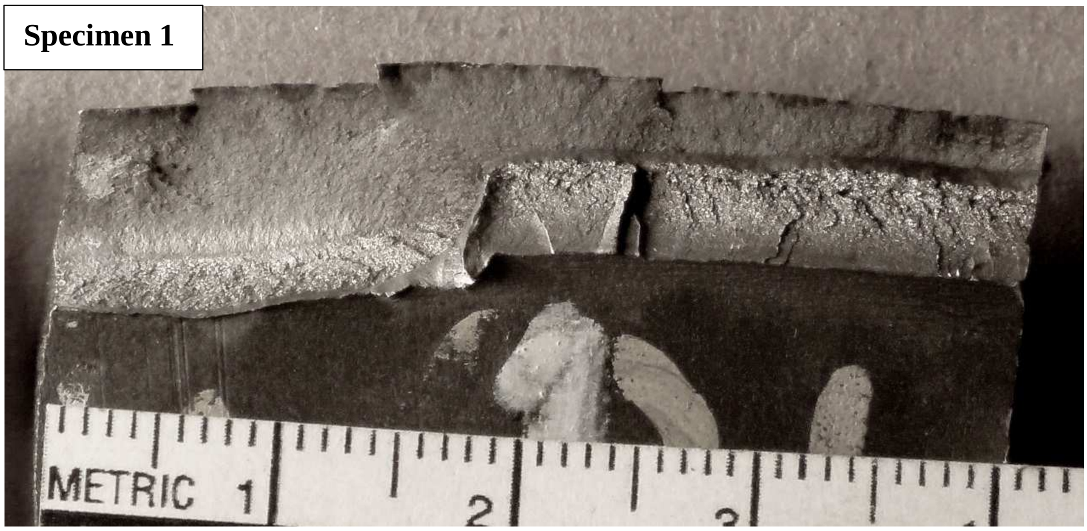


FIGURE 16 ENDS OF EXTERNAL CRACKING AT APEX OF BUCKLE

2.3 SCANNING ELECTRON MICROSCOPY

As noted previously in Figures 11 and 12, based on detailed visual examinations of the fracture surface, two locations were selected as being representative of the various fracture features observed. These two specimens were cut from the fracture and ultrasonically cleaned in an Alconox detergent solution. The cleaned specimens (Specimen 1 and 2) are shown in Figure 17.



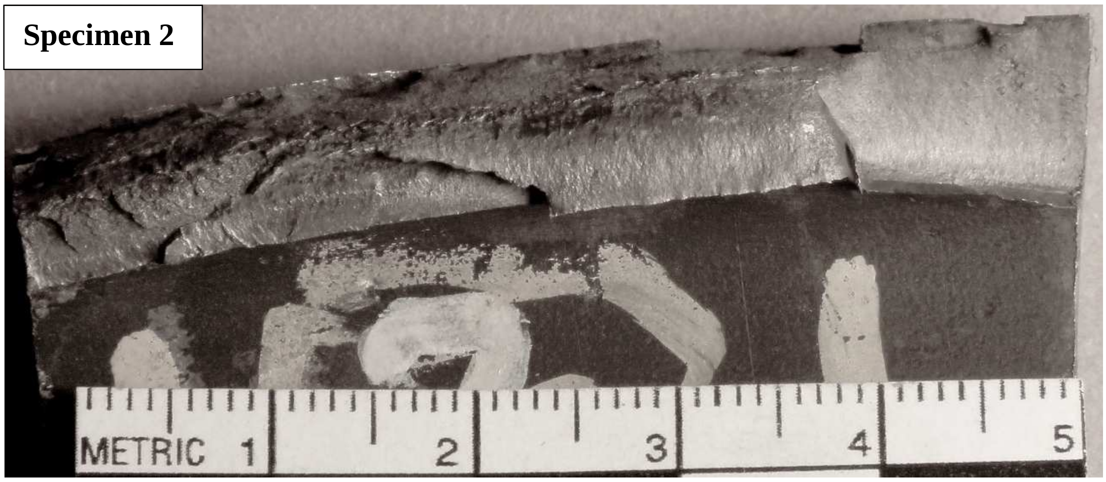
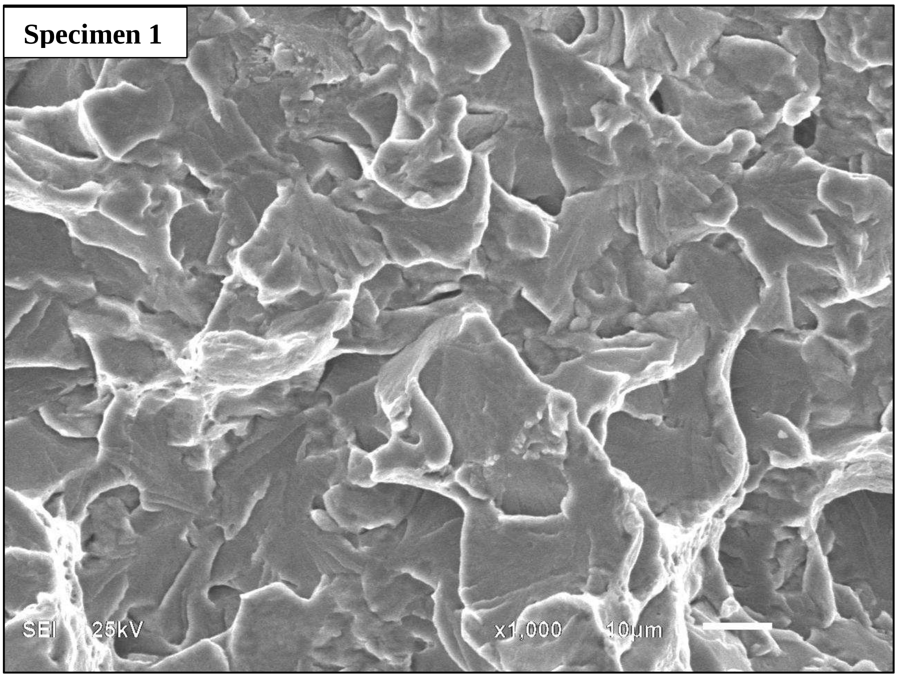


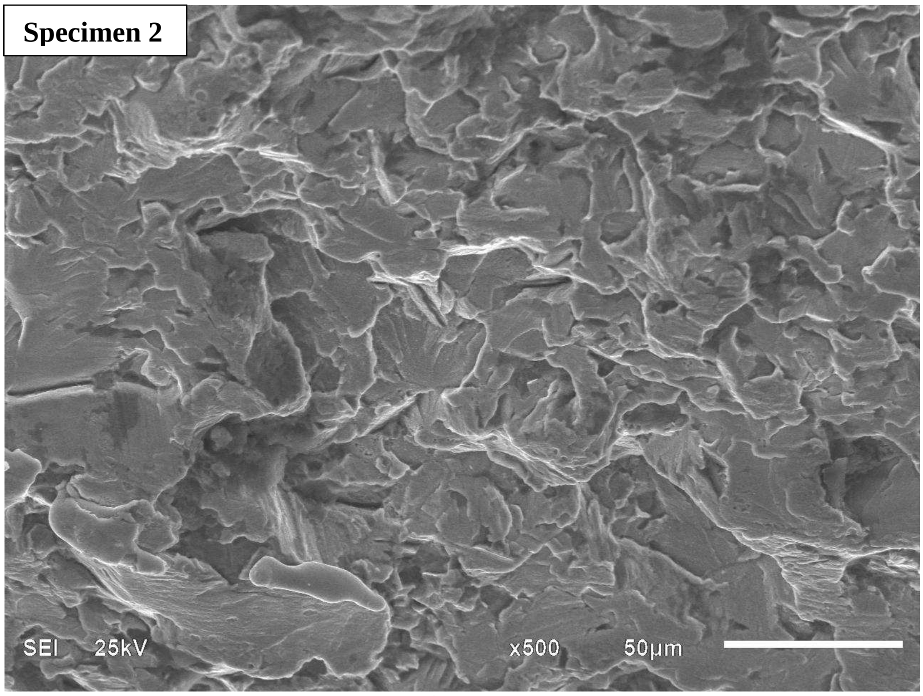
FIGURE 17 CLEANED SEM FRACTURE SPECIMENS

Examinations of the planar fracture regions near the internal surface of the pipe for both Specimens 1 and 2 revealed a brittle cleavage morphology, as shown by example with the SEM images in Figure 18. These brittle cleavage zones were found to transition to a more ductile morphology towards the external surface of the pipe. The SEM images in Figure 19 show examples of the ductile fracture morphology observed in these outer regions of the fracture on both specimens. There was no evidence of striation marks or other features associated with fatigue cracking found on either specimen.

ACUREN

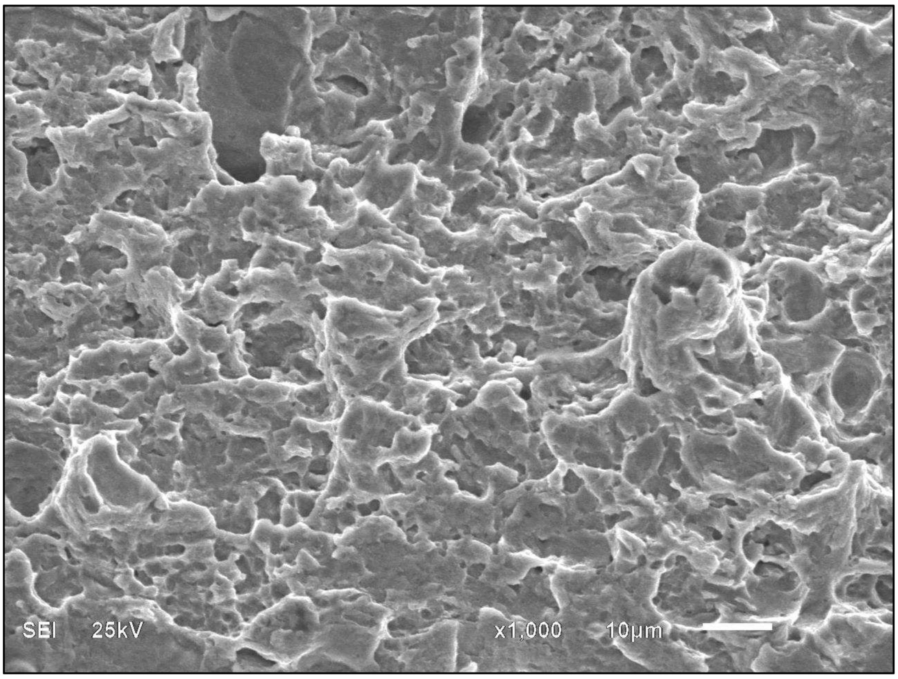


Mag. Approx. X1000

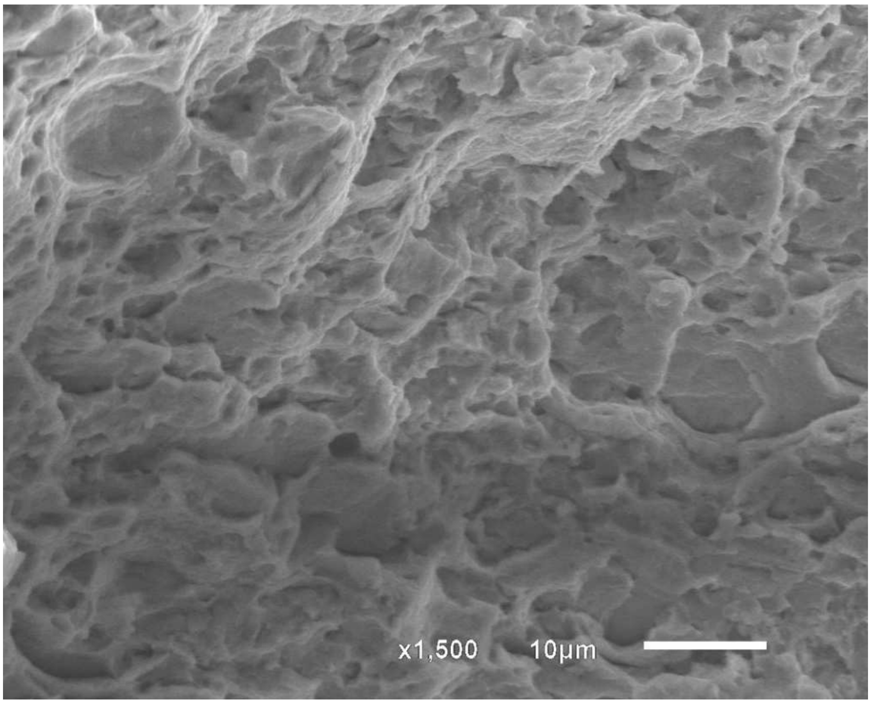


Mag. Approx. X500

FIGURE 18 EXAMPLES OF BRITTLE CLEAVAGE FRACTURE NEAR ID SURFACE



Mag. Approx. X1000



Mag. Approx. X1500

FIGURE 19 EXAMPLES OF DUCTILE FRACTURE NEAR OD SURFACE

2.4 METALLOGRAPHIC EXAMINATION & HARDNESS TESTING

Cross sections (M1 and M2) were cut from each of the two SEM specimens through matching locations on either side of the through-wall fracture and prepared for metallographic examination. The fracture locations where these two metallographic specimens were cut from are as noted previously in Figure 12. A third metallographic specimen (M3) was cut and prepared from the intact buckled zone beyond the end of the fracture, where internal cracking was observed (i.e. Fig. 14). For comparison purposes, a fourth specimen (M4) was cut and prepared from the body of the pipe, remote from the buckled zone. The polished and etched specimens are shown in Figure 20.

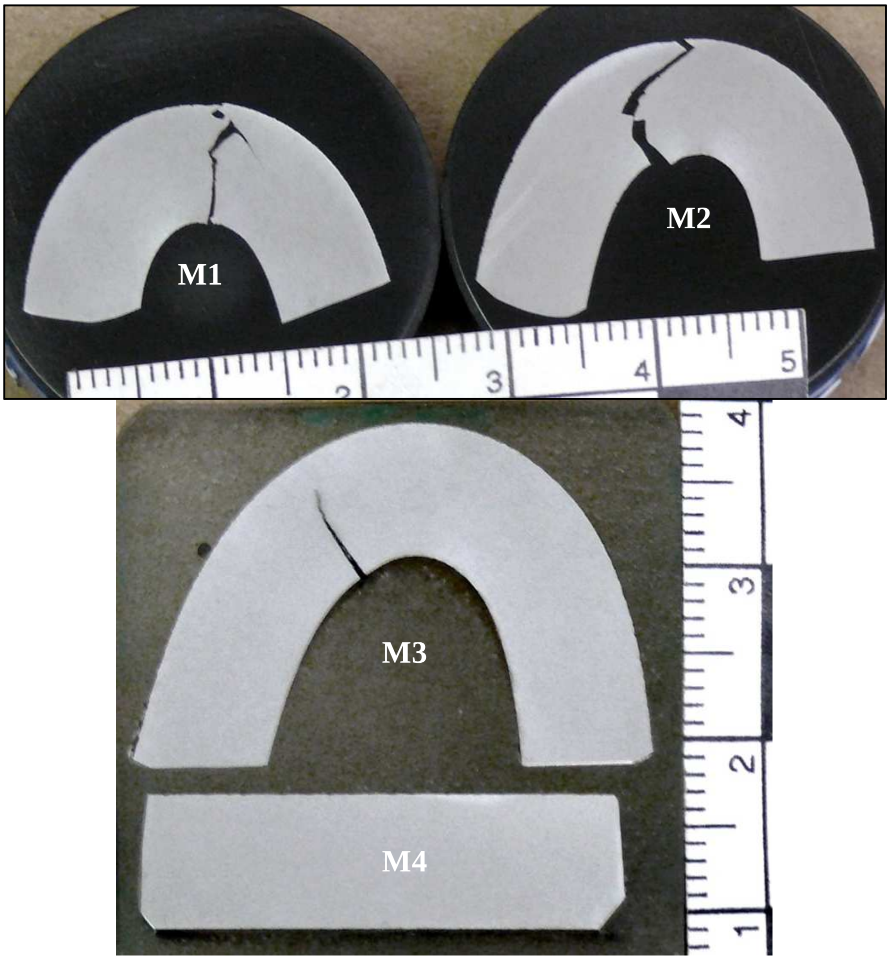


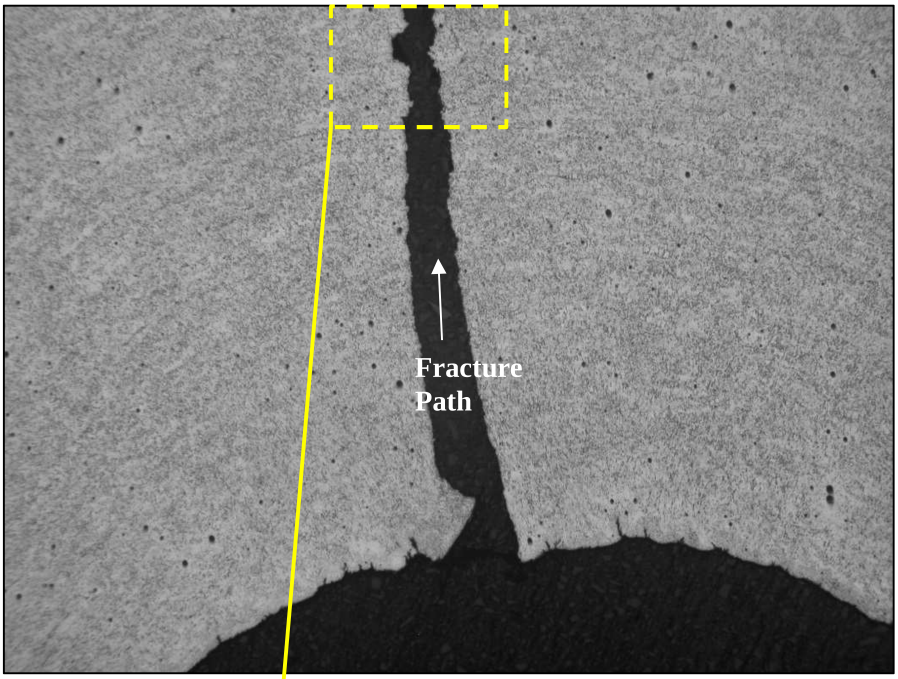
FIGURE 20 PREPARED METALLOGRAPHIC SPECIMENS

Figure 21 shows the brittle fracture profile near the inner surface at the apex of the buckle for specimen M1, while Figure 22 shows the brittle fracture profile near the inner surface of M2. As noted in Figure 22, M2 exhibited a secondary brittle crack (approx. 1 mm deep) adjacent to the main through-wall fracture. As shown in the higher magnification photomicrographs in Figure 23, both M1 and M2 exhibited a very fine-grained ferritic microstructure with small localized colonies of pearlite, as is typical of control-rolled line pipe product. The inner surface of the apex of the buckle in both specimens exhibited small crease-like folds, as a result of the plastic deformation which took place when the buckle was formed. As shown in the photomicrographs in Figure 24, the outer portions of the through-wall fracture in M1 and M2 exhibited plastic grain deformation along the fracture edges, indicative of a ductile shear fracture mechanism in this outer wall region. The metallographic observations described above are consistent with the findings of the SEM examinations.

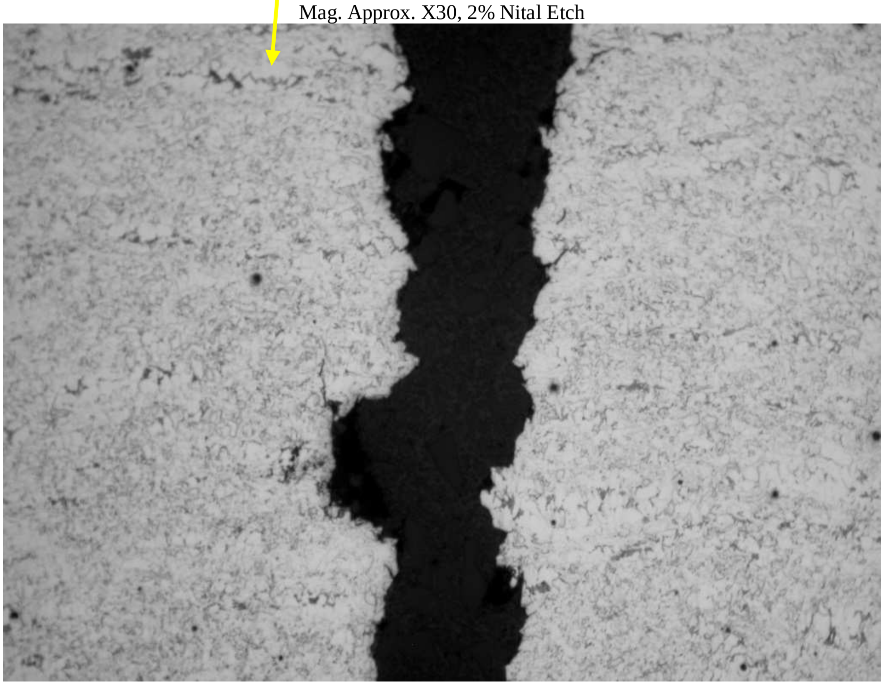
Figure 25 shows the crack initiation zone at the inner surface of the apex of the buckle in specimen M3, while Figure 26 is a higher magnification image taken at the tip of this brittle crack. The depth of the crack at this location was approximately 6 mm or 75% of the wall thickness. Figure 27 is a high magnification photomicrograph of the typical microstructure observed in the buckled region of M3. The microstructure and brittle crack morphology of M3 were similar to that observed for specimens M1 and M2.

Figure 28 is a low magnification photomicrograph of non-buckled specimen M4, taken near the ID surface. Figures 29, 30 and 31 are high magnification images of the typical microstructure taken near the ID surface, mid-wall and OD surface of M4, respectively. The fine-grained ferritic microstructure with isolated pearlite colonies was similar to that observed in specimens M1, M2 and M3. No metallurgical anomalies or defects were observed in this specimen.

Vickers microhardness testing was performed on the polished surfaces of the four specimens using a 500g test load. The results of this testing are summarized in Figure 32. The original pipe hardness, represented by specimen M4, ranged from about 165 to 181 HV500gf, with the material near the surfaces being slightly harder than at mid-wall. These results are consistent with common line pipe material, such as CSA Gr. 359. As expected, the hardness within the buckled zone of all three specimens, particularly near the inner apex, was significantly higher than the M4 non-deformed pipe material, as a result of the work hardening generated by the severe plastic deformation introduced during the buckling event.

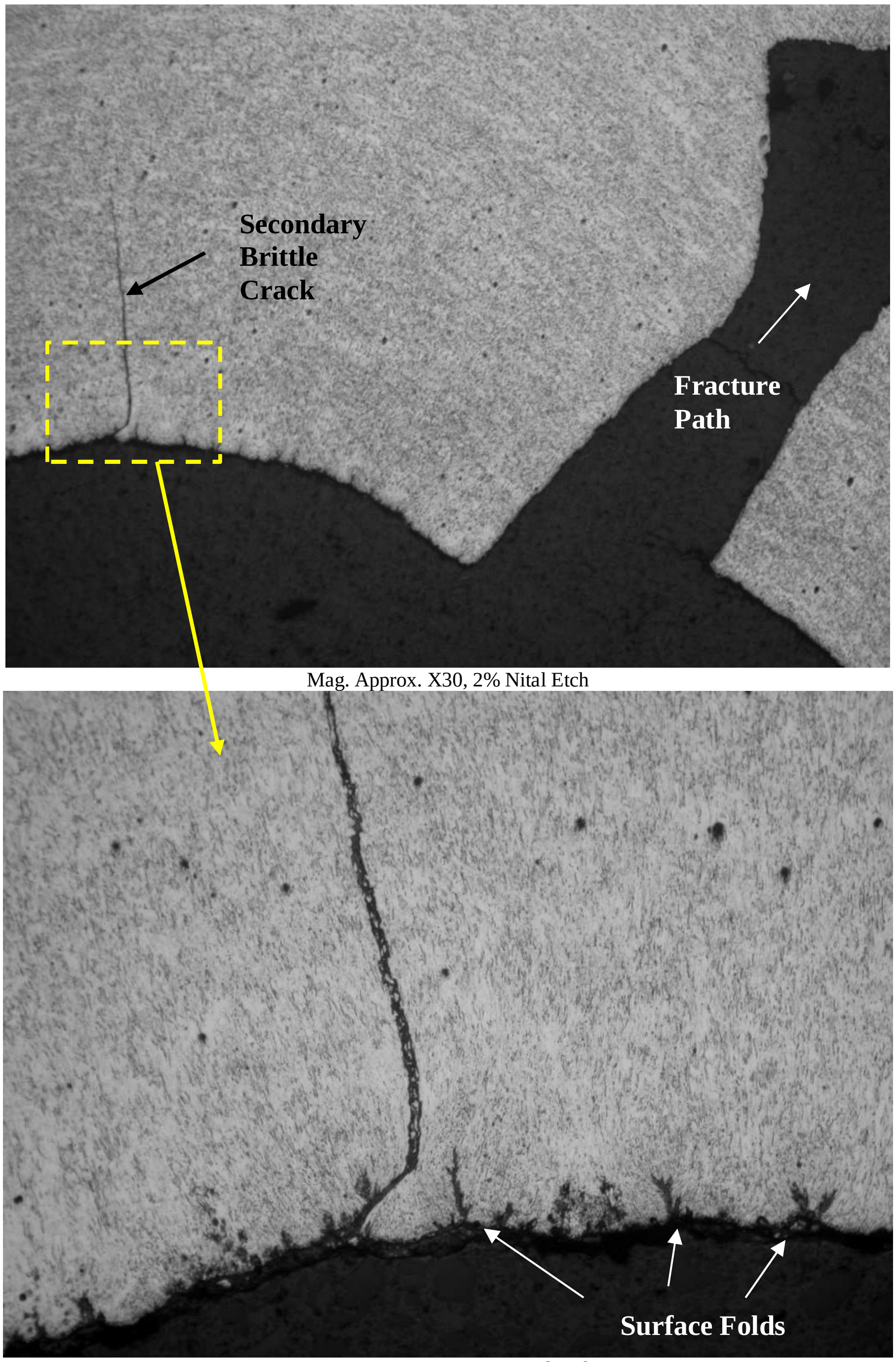


Mag. Approx. X30, 2% Nital Etch



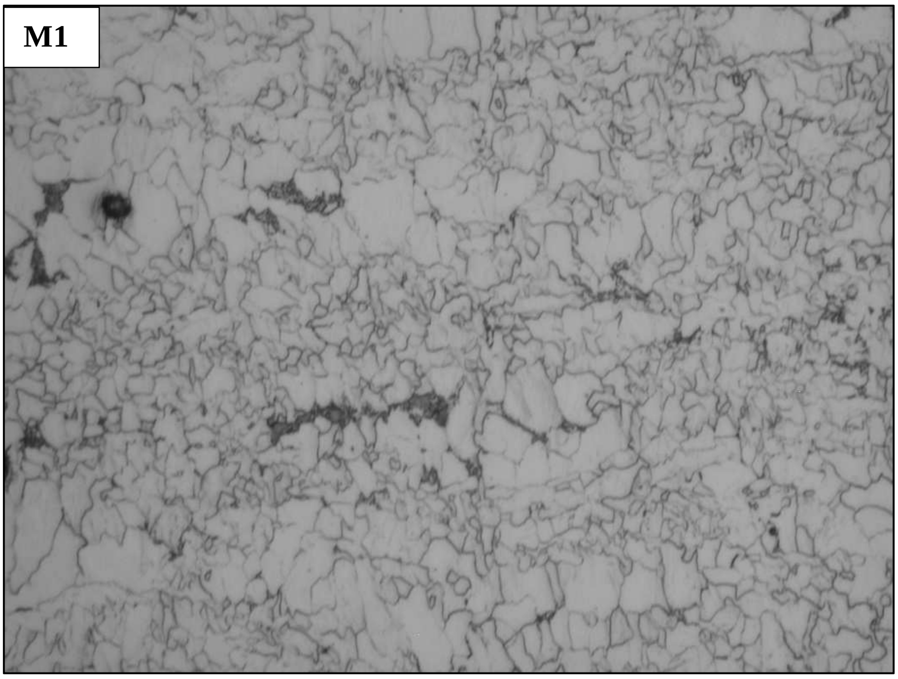
Mag. Approx. X100, 2% Nital Etch

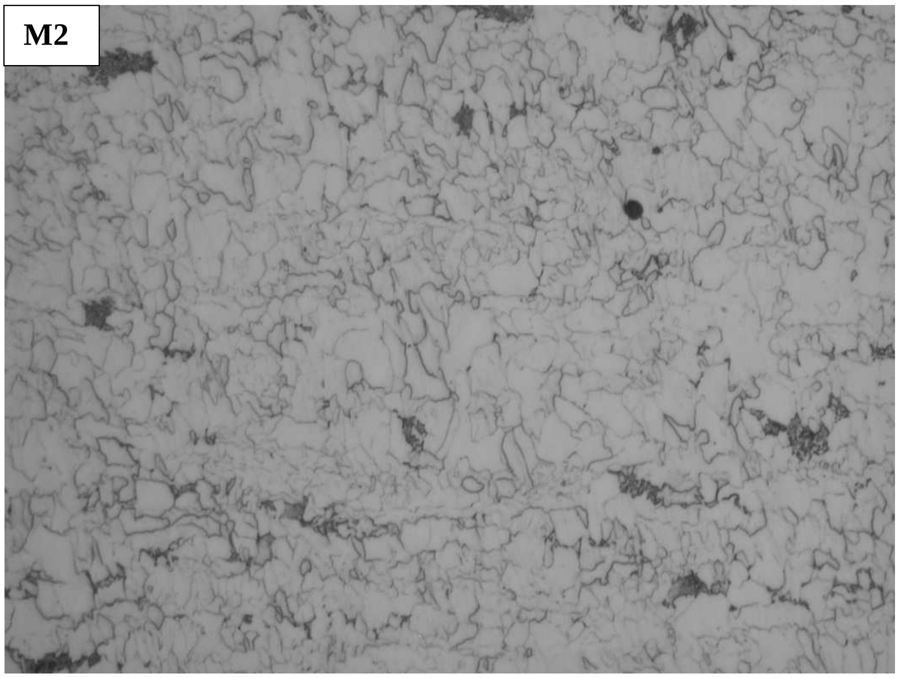
FIGURE 21 BRITTLE FRACTURE PROFILE (M1)



Mag. Approx. X100, 2% Nital Etch

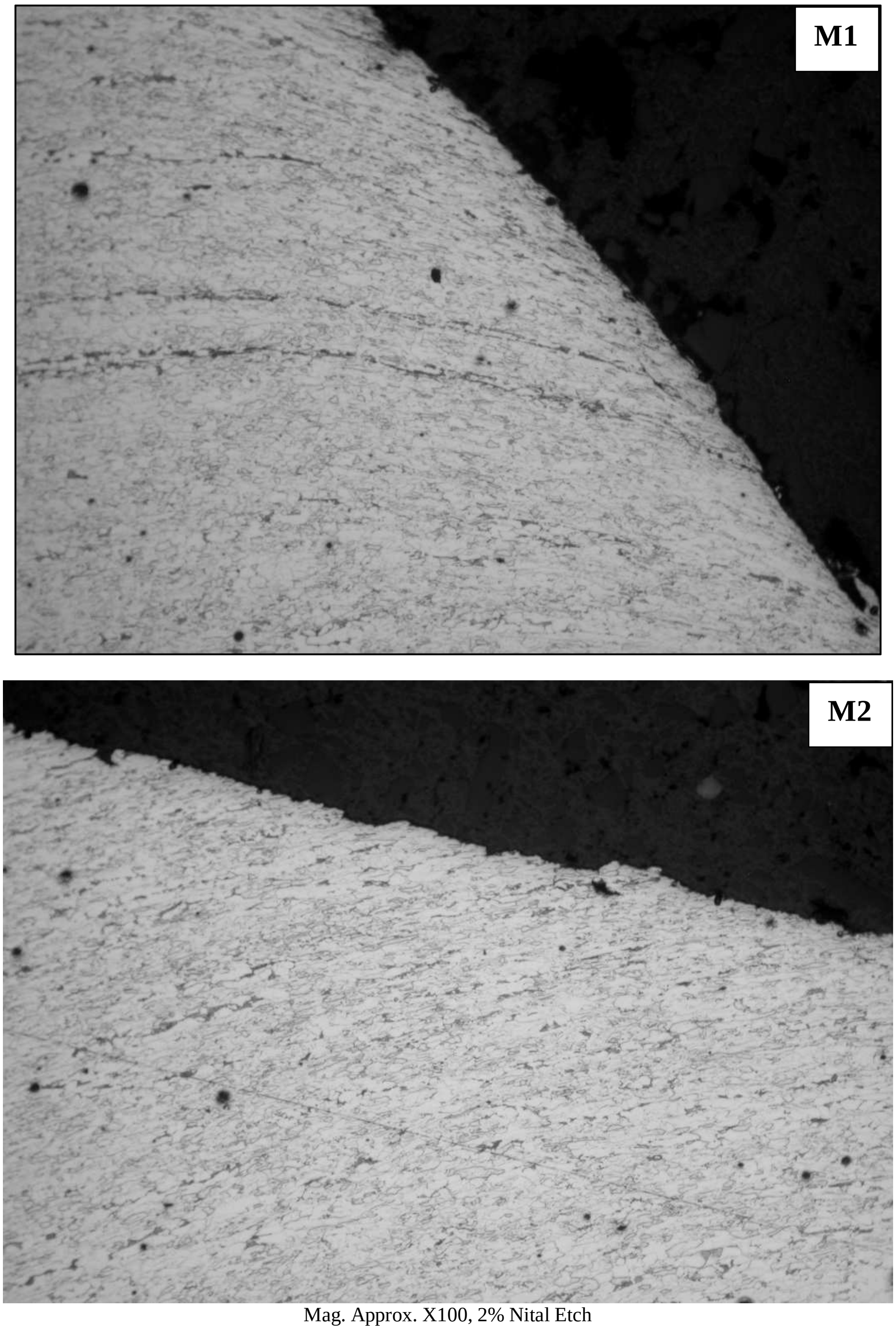
FIGURE 22 BRITTLE FRACTURE AT INSIDE SURFACE OF THE BUCKLE APEX OF M2





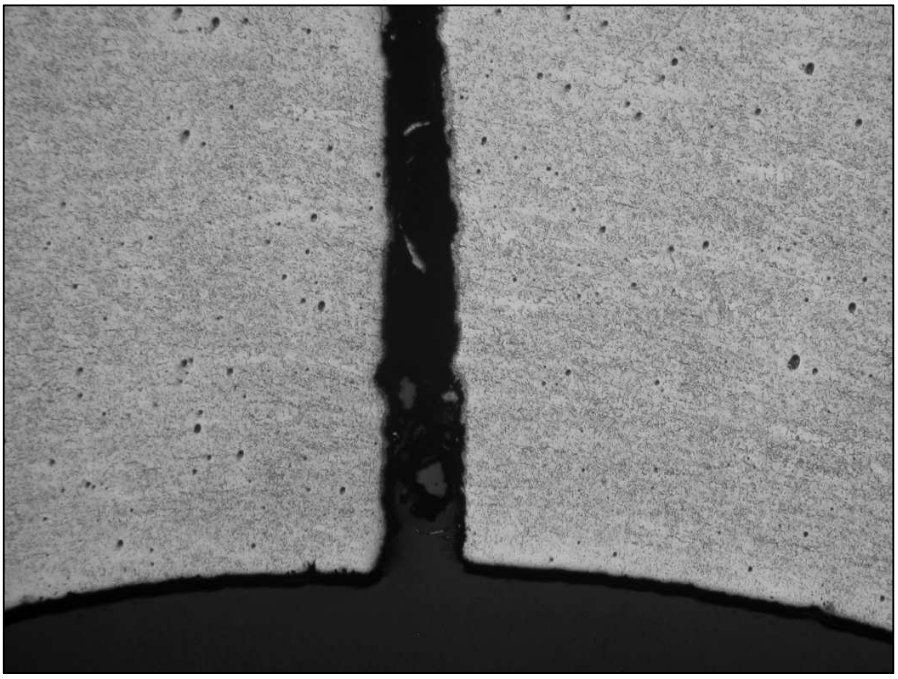
Mag. Approx. X500, 2% Nital Etch

FIGURE 23 PHOTOMICROGRAPHS OF TYPICAL MID-WALL MICROSTRUCTURE FOR M1 AND M2



Mag. Approx. X100, 2% Nital Etch

FIGURE 24 DUCTILE SHEAR FRACTURE PROFILES NEAR OUTER SURFACE OF M1 AND M2 THROUGH-WALL FRACTURES

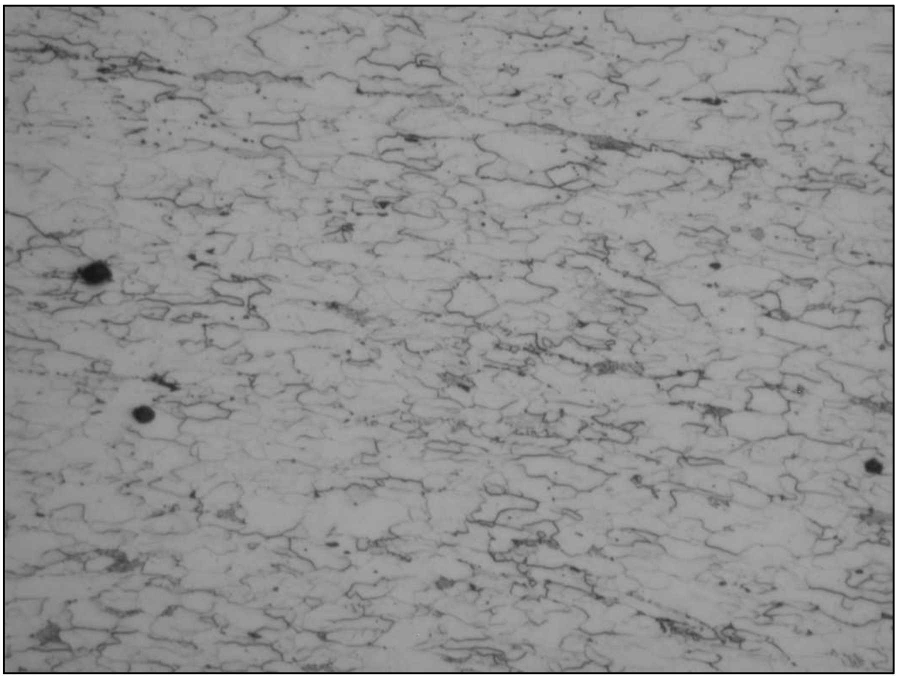


Mag. Approx. X30, 2% Nital Etch

FIGURE 25 BRITTLE CRACK AT INSIDE SURFACE OF THE BUCKLED APEX OF SPECIMEN M3

Mag. Approx. X100, 2% Nital Etch

FIGURE 26 TIP OF BRITTLE CRACK IN M3

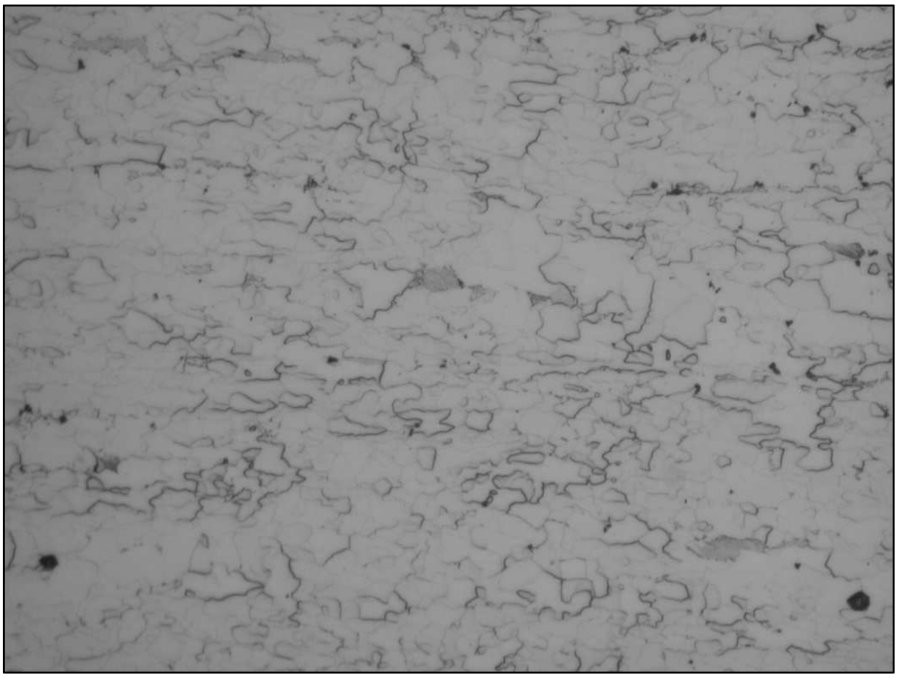


Mag. Approx. X500, 2% Nitel Etch

FIGURE 27 TYPICAL MICROSTRUCTURE OF M3 IN BUCKLE MID-WALL ZONE

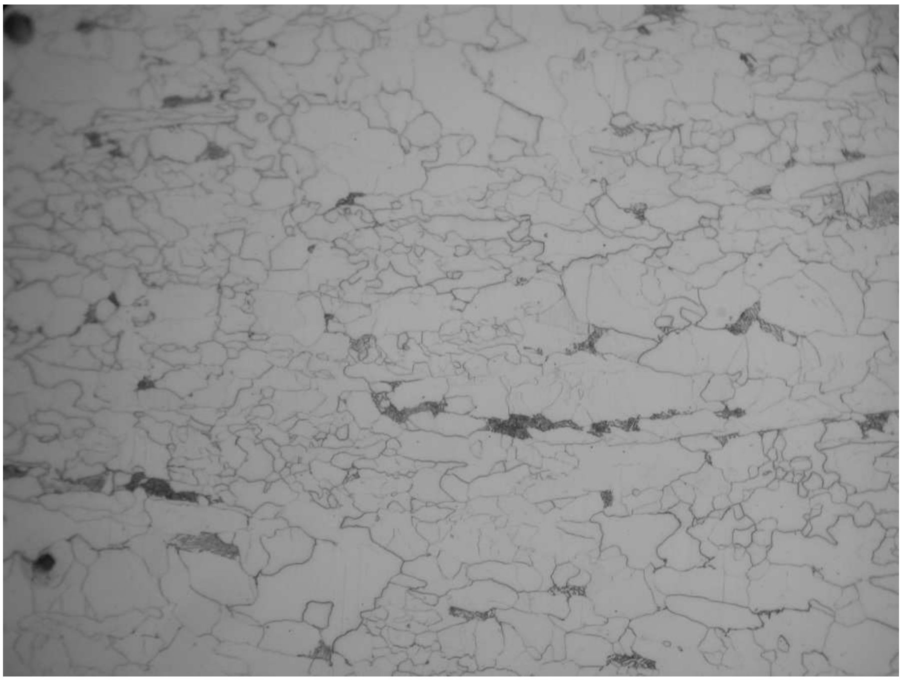
Mag. Approx. X100, 2% Nital Etch

FIGURE 28 PHOTOMICROGRAPH AT ID SURFACE OF M4



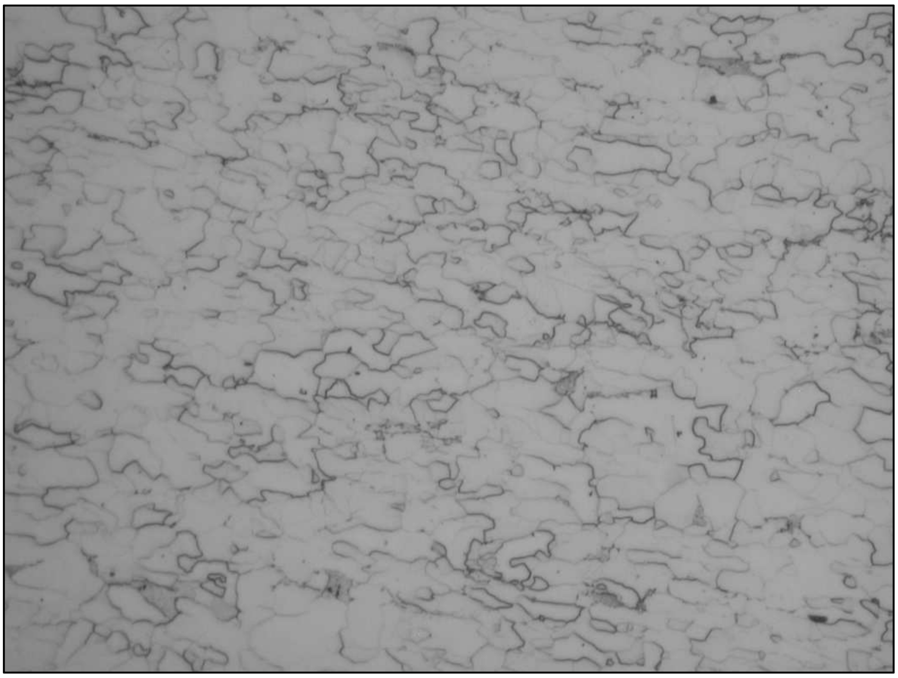
Mag. Approx. X500, 2% Nital Etch

FIGURE 29 M4 MICROSTRUCTURE NEAR ID SURFACE



Mag. Approx. X500, 2% Nital Etch

FIGURE 30 M4 MICROSTRUCTURE AT MID-THICKNESS



Mag. Approx. X500, 2% Nital Etch

FIGURE 31 M4 MICROSTRUCTURE NEAR OD SURFACE

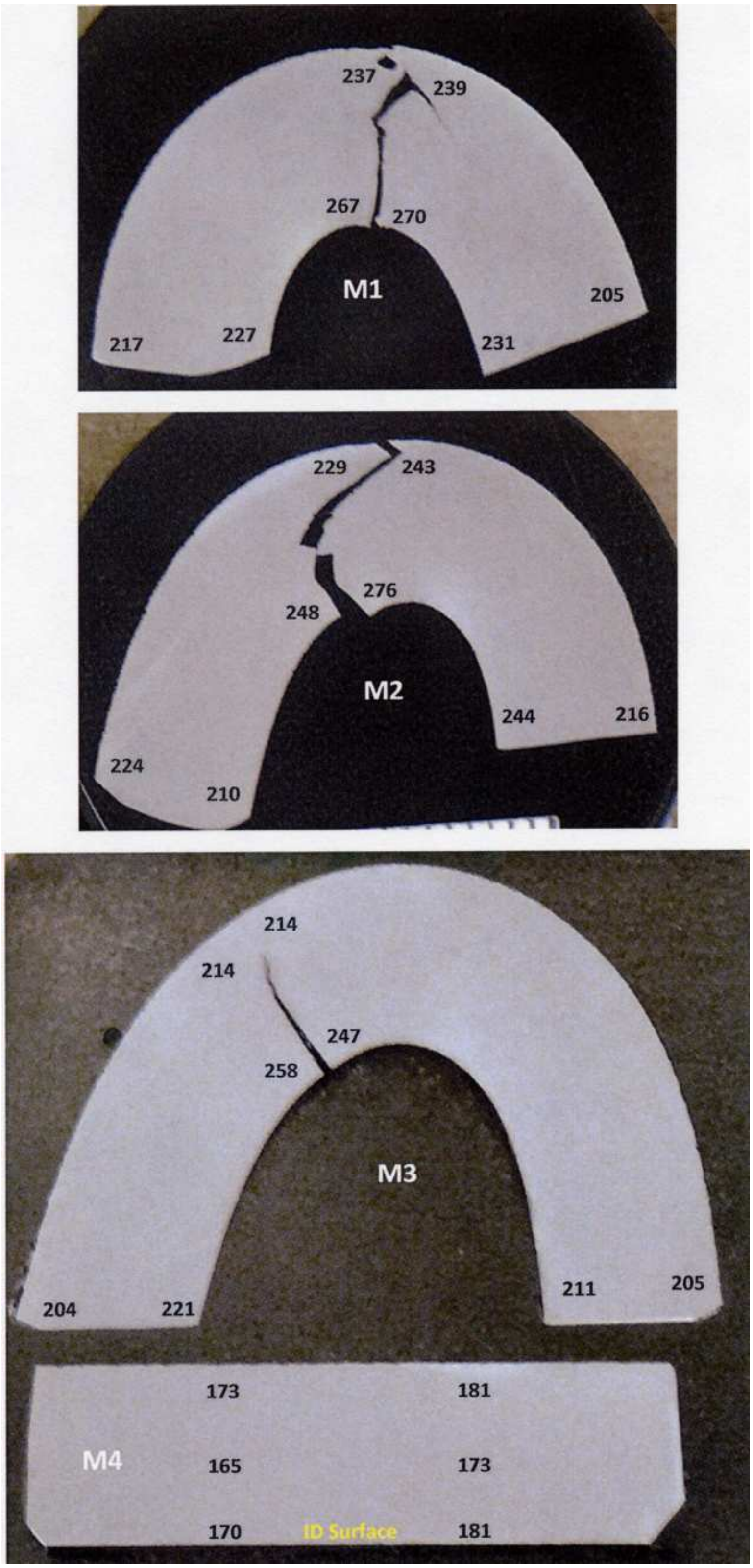


FIGURE 32 VICKERS MICROHARDNESS RESULTS (HV500GF)

2.5 PIPE TESTING

2.5.1 Tensile Testing

Both a pipe body transverse (‘T’) and longitudinal (‘L’) tensile sample were cut from the non-deformed pipe, just upstream of the buckled failure location. The longitudinal sample was cut from the bottom quadrant of the pipe. Although CSA Z245.1 does not specify testing line pipe of this size in the longitudinal direction, this test was used to measure the pipes strength in the orientation of the buckling deformation. A transverse tensile sample was also cut across the pipe ERW seam, which was located at approximately the 10 o’clock position. The results of this tensile testing are summarized in Table 1. The pipe met the tensile requirements for CSA Gr. 359.

TABLE 1 TENSILE TEST RESULTS

Specimen	Yield, MPa	Ultimate, MPa	Elongation, %	Y/T Ratio
Body ‘T’	478	524	32	0.91
Body ‘L’	370	498	35	0.74
ERW	--	544	--	--
CSA Gr. 359	359 - 530	455 - 760	25 min.	0.93 max.

2.5.2 Charpy Impact Testing

A set of Charpy specimens were cut from the pipe in the transverse direction, consistent with the test methodology specified in CSA Z245.1. A second set of Charpy specimens were cut from the pipe in the axial direction to create a circumferential fracture path in the same orientation as the through-wall fracture. Both sets of Charpy specimens were cut from the bottom quadrant of the line just upstream of the buckle and were limited to two-thirds size (i.e. 6.67 mm x 10 mm) due to wall thickness constraints. As requested by Husky, all specimens were tested at -18°C. Both sets of results, summarized in Table 2, exceeded the specified minimum requirements in CSA Z245.1 for Category II line pipe, with the exception of the average percent shear for the transverse specimens (i.e. fracture path in the axial direction). CSA requires individual specimens to exhibit at least 50% shear, with an average value of at least 60%. It is noted that the CSA-specified minimum absorbed energy for full size Charpy specimens is 27 J.

TABLE 2 CHARPY IMPACT TEST RESULTS (-18°C)

Specimen Orientation	Absorbed Energy, J*		Percent Shear	
	Results	Average	Results	Average
Transverse	67, 71, 69	69	55, 55, 55	55
Longitudinal	68, 79, 76	74	70, 85, 85	80

(*) Actual absorbed energy results for two-thirds size specimens

2.5.3 Flattening Tests

As requested, flattening test coupons were cut from the pipe just upstream of the buckled failure zone and tested in accordance with CSA Z245.1. The ERW seam in one coupon was aligned with the compression (i.e. flattening) direction, while the ERW seam in the second coupon was oriented at 90° to the compression direction. The pipe samples passed the CSA flattening test (i.e. compression to 50% of diameter) and were then further flattened until the diametrically opposite ID surfaces came in contact. There was no evidence of cracking observed after this complete flattening process. Figure 33 shows the final flattened test coupons and the absence of cracking.

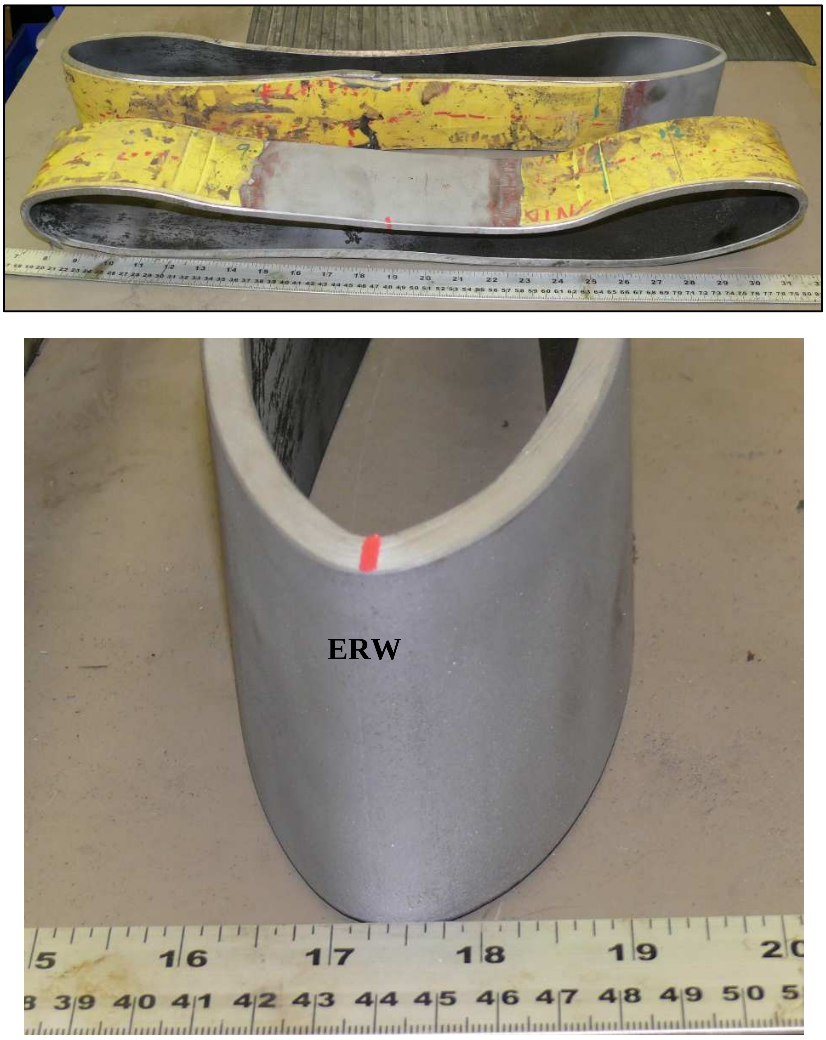


FIGURE 33 RESULTS OF FLATTENING TESTS

2.5.4 Chemical Analysis

A sample of the pipe material was subjected to chemical analysis and the results of this analysis are summarized in Table 3, along with the specified maximum limits in CSA Z245.1. The pipe was a fully killed plain carbon-manganese steel, with a low carbon content. The pipe chemistry was typical of common line pipe materials and met the requirements of CSA Z245.1.

TABLE 3 PIPE CHEMISTRY RESULTS

Element	Concentration (Weight Percent)	
	Pipe Sample	CSA Z245.1 (max.)
C	0.07	0.26
Mn	0.99	2.00
P	<0.010	0.030
S	0.006	0.035
Si	0.16	0.50
Ni	<0.01	--
Cr	0.02	--
Mo	<0.01	--
Cu	<0.01	--
Nb	0.030	0.11
V	<0.010	0.11
Ti	<0.010	0.11
Al	0.028	--
B	<0.0005	0.001
CE	0.17	0.40

2.6 SCALE ANALYSIS

As noted previously in this report, a sample of the oily scale products that were present on the internal surface of the pipe in the buckled zone was collected for chemical analysis. This sample was washed with Varsol to remove the oily residue and is shown in Figure 34. This scale sample was subjected to chemical analysis by x-ray diffraction (XRD), supplemented by energy dispersive x-ray spectroscopy (EDS). The results of the XRD analysis, summarized in Table 4, revealed a high concentration of non-metallic compounds, with silica being the most predominant. Trace amounts of iron-based corrosion products (iron carbonate, iron oxide and iron sulphide) were also detected. The EDS results were in good agreement with the XRD data.

FIGURE 34 SCALE SAMPLE COLLECTED FROM INTERNAL SURFACE OF BUCKLE

TABLE 4 SCALE X-RAY DIFFRACTION ANALYSIS RESULTS

Formula	Name	Approximate Percentage
SiO_2	Quartz	87
Other non-metallic compounds (microcline, calcite, albite, etc.)		8
$FeCO_3$	Siderite	2
$FeSO_4.H_2O$	Szomolnokite	<1
Fe_3O_4	Magnetite	<1
Fe_3S_4	Greigite	<1
FeS_2	Pyrite	<1

ACUREN

3.0 DISCUSSION

The submitted nominal 406.4 mm OD by 7.9 mm WT pipeline sample exhibited severe circumferentially-oriented localized buckling deformation in the bottom half of the line, approximately centred at the 6 o'clock position. The apex of this buckle contained a through-wall fracture, again approximately centred at the 6 o'clock position, which extended in the circumferential direction for a total distance of about 380 mm, or 30% of the circumference. The cracking on the internal surface of the buckle extended beyond the ends of the through-wall fracture for a total distance of about 680 mm, or about 50% of the circumference (i.e. 3 to 9 o'clock position). The buckle had created a local inflection point in the line, with an approximately 21° angle of deflection in the vertically downward direction.

Based on detailed visual and microscopic examinations of the fracture and internal cracking extending beyond the ends of the fracture within the buckled zone, it is concluded by Acuren that the through-wall fracture initiated as brittle cracking on the internal surface of the pipe at the apex of the buckle, followed by ductile overload fracture (i.e. shear) through the remainder of the wall thickness at the apex of the bulge. The brittle fracture exhibited a non-branching cleavage morphology, indicative of a sudden one-time event (as opposed to a time-dependent progressive cracking mechanism). There was no evidence of post-cracking surface scale or corrosion on the brittle fracture faces, which indicates that this brittle cracking had most likely occurred very recently. There was therefore no evidence found to indicate that a long-term brittle crack growth mechanism, such as fatigue, played a role in the failure process.

The severe plastic deformation of the pipe during the formation of the buckle created shallow creases and/or folds at the internal apex of the buckle. It is reasonable to assume that some of these shallow folds acted as stress risers for the subsequent initiation of the brittle overload cracks. The buckle forming process would have generated compressive stress on the ID surface at the apex of the buckle. Therefore, for the brittle cracking to have initiated at this location, the axial stress would have had to have been reversed at some point after the buckling event to generate tension at the internal surface of the apex of this buckle.

Testing and metallographic examination of the pipe material gave results consistent with CSA Gr. 359 Cat. II line pipe, with the exception that the average Charpy percent shear was slightly below the specified 60% limit. Flattening testing of ring samples from the pipe revealed that the pipe material was highly ductile. There was therefore no evidence found to suggest that pre-existing material deficiencies or defects contributed to the buckling or subsequent fracture of the pipe. Similarly, although shallow internal pitting corrosion was observed along the bottom of the line on both sides of the fracture, there was no evidence to suggest that corrosion contributed in any significant manner to the failure.

ACUREN

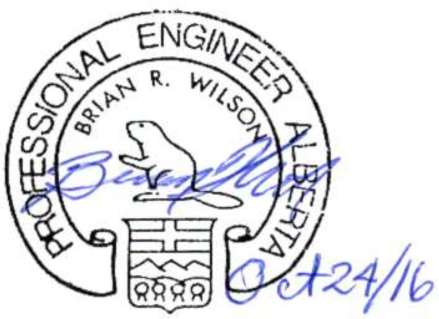
In summary, despite the demonstrated good strength properties and high degree of ductility and toughness associated with the original line pipe material, it is apparent that the severe plastic deformation and accompanying work-hardening of the pipe within the buckled region rendered the pipe material susceptible to brittle cracking on the ID surface of the apex of the buckle when a longitudinal tensile stress of sufficient magnitude was applied across the buckle. The small folds on the ID surface within the buckle that were formed during the buckling event most likely contributed to the eventual failure by acting as stress riser sites for the brittle crack initiation. Determination of the details pertaining to the origin(s) and nature of the loading conditions on the pipeline at this location necessary to cause the buckling and subsequent cracking within the buckle are beyond the scope of this metallurgical failure analysis.

4.0 CONCLUSIONS

Based on the findings of this investigation, it is Acuren's opinion that the submitted nominal 406.4 mm OD by 7.9 mm WT pipeline sample failed as a result of localized severe buckling deformation in the bottom half of the line, followed by brittle cracking on the ID surface of the pipe at the apex of the buckle and subsequent ductile overload fracture from these brittle cracks, resulting in a through-wall fracture within the buckle. There was no evidence of a progressive time-dependent cracking mechanism (e.g. fatigue) associated with the brittle fracture. The timing of the original buckling of the pipe could not be determined in our investigation and determination of the source(s) and nature of the applied loading conditions on the pipeline necessary to cause this buckling and the subsequent cracking within the buckle were beyond the scope of this metallurgical failure analysis.

There was no evidence found to indicate that substandard pipe material or corrosion contributed to the failure.

Prepared By,



Brian Wilson, M.Eng., P.Eng.
Senior Materials Engineer

Reviewed By,
Ken Magee, M.A.Sc, P.Eng.
Senior Engineering Technical Advisor

APEGA Permit Number: P5386 (Alberta)

0087952-report1R1
Please note that unless we are notified in writing, samples from this investigation will be disposed of after 60 days.