NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

May 17, 2011

MATERIALS LABORATORY FACTUAL REPORT Report No. 11-049

A. ACCIDENT INFORMATION

Place : San Bruno, California
Date : September 9, 2010
Vehicle : Pacific Gas & Electric Natural Gas Transmission Pipeline
NTSB No. : DCA10MP008
Investigator : Ravindra Chhatre, RPH-20

B. COMPONENTS EXAMINED

One 6-foot 10.12-inch long section of 30-inch diameter pipe from Line 132, Section 180, 881 Glenview Drive, San Bruno, California.

C. DETAILS OF THE EXAMINATION

During an internal camera inspection of Line 132, Segment 180 (the same segment that ruptured on September 9, 2010), a 10-inch length of pipe was observed approximately 719 feet upstream (south) of the rupture site for which no identifiable internal seam could be visually detected. The 10-inch length, with 3-foot lengths of pipe on either side, was cut from the segment and shipped to a National Transportation Safety Board (NTSB) facility in Ashburn, Virginia. On April 7 and 8, 2011, the following individuals examined the pipe:

Donald Kramer, Ph.D., Materials Engineer, NTSB
Paul Tibbals, P.E., Sr. Materials Technology Engineer, Pacific Gas & Electric Co.

The pipe was received in the condition shown in Figure 1. The pipe was covered by a protective asphalt coating, which was chipped off in the field using brass hammers and scrapers prior to shipment, except for two 1-foot by 1-foot sections on the bottom. Top dead center, the north/south orientation of the pipe, and the direction of gas flow were labeled in the field. The two 1-foot by 1-foot sections of coating were chipped off at the Ashburn facility using a brass hammer and a metal scraper. There were no visual indications of deformation or corrosion on the outer or inner diameter surface of the pipe. After visual examination, the outside of the pipe was grit blast using olivine blast media to near-white (SSPC–SP 10/NACE No. 2). For convenience, the three lengths of pipe were labeled A1, A2, and A3 in the typical direction of gas flow (south to north). The 10-inch length for which no internal seam was detected during camera inspection was labeled A2, the length of pipe upstream from A2 was labeled A1, and the length of pipe downstream from A2 was labeled A3. The girth welds joining the lengths of pipe were labeled A1/A2 and A2/A3 for the girth weld joining A1 to A2 and the girth weld joining A2 to A3, respectively.

The pipe's outer and inner surfaces were examined for identifier markings. There were no observable stamp, stencil, or paint marks on the outer diameter surface of A1, A2, or A3 (the outer surface was examined for stencil and paint marks prior to abrasive blasting). The number "31" followed by other indiscernible numbers was painted on the inner diameter surface of A1 and A2, consistent with partial joint footage markings (not shown).[1] A painted symbol, similar to a "6" or "9" was observed on the inner diameter surface of A1, as shown in Figure 2a. The alphanumeric code "P24795" and the number "22" were stamped on the inner diameter surface of A3, as shown in Figure 2b, approximately 20 inch from girth weld A2/A3. Pacific Gas & Electric Co. (PG&E) was unfamiliar with these markings or their meaning (PG&E, 2011a, b).

The length and circumference of each length of pipe were measured by steel tape. The section of pipe measured 82.12 inch from end to end along the top. A1 was 36.12 inch long, A2 was 10.00 inch long, and A3 was 36.00 inch long. The length values are listed in Table 1. Four chord length measurements of A2 were taken at 90° intervals around the pipe starting at the top and continuing clockwise, defined relative to the typical direction of gas flow. The chord lengths were 10.00 inch, 10.12 inch, 10.25 inch, and 10.12 inch for the 0°, 90°, 180°, and 270° positions, respectively. The circumference of each length of pipe is listed in Table 1 and each was within the tolerance limits for 30-inch diameter pipe.

The wall thickness of each length of pipe was measured with an ultrasonic thickness gage and each was consistent with nominal 0.375-inch wall thickness pipe. The wall thickness was measured mid-chord at 90° intervals starting at the top of the pipe. The average wall thickness was 0.366 inch ± 0.002 inch, 0.371 inch ± 0.002 inch, and 0.376 inch ± 0.002 inch for A1, A2, and A3, respectively.[2] The wall thickness data are shown in Table 2.

Longitudinal seam welds were visible on the outer and inner surfaces of the three lengths of pipe. Except near the ends, the weld caps were rounded, of uniform width and height, and exhibited little to no visible ripple pattern, consistent with a double submerged arc welding (DSAW) process. The distance of each weld from the top along the outer circumference of the pipe was measured by steel tape and is listed in Table 1. The circumference of each length of pipe and the distance of its corresponding seam from the top were used to calculate the angle between the top of the pipe and the seam. The angles were 49°, 74°, and 40°, defined clockwise relative to the typical direction of gas flow, for A1, A2, and A3, respectively. The angle values are listed in Table 1 and shown schematically in Figure 3.

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[1] Pipe from Consolidated Western of this vintage, diameter, and wall thickness was typically provided in nominal 31.17-foot lengths.

[2] All confidence intervals are reported as one standard deviation.

The outer and inner seam welds on A1 were of uniform width and height except near girth weld A1/A2. The outer seam weld became irregular in shape starting 4.6 inch from the girth weld, consistent with a “squirt” weld,[3] as shown in Figure 4a. The inner seam weld was ground flush with the inner diameter surface of the pipe starting 12 inch from the girth weld, as shown in Figure 4b.

The outer and inner seam welds on A2 were of similar appearance. The outer seam weld was of uniform width and height, except near girth weld A1/A2. Starting 4.2 inch from the girth weld, the seam weld became irregular in shape, consistent with a “squirt” weld, as shown in Figure 5a. The inner seam weld was ground flush with the inner diameter surface over the entire 10-inch length of the pipe, except for a 1-inch length near girth weld A2/A3, where the weld was partially ground, as shown in Figure 5b.

The outer and inner seam welds on A3 were of uniform width and height, except near girth weld A2/A3. The profile of the outer seam weld changed shape starting 5.2 inch from the girth weld, as shown in Figure 6a, but did not have the irregular appearance of a “squirt” weld, as compared with A1 and A2. The inner seam weld was ground flush with the inner diameter surface starting 4.5 inch from the girth weld, as shown in Figure 6b. The length of each notable outer and inner seam weld feature is summarized in Table 1 for A1, A2, and A3.

Girth welds A1/A2 and A2/A3 were examined on the outer surface, inner surface, and on etched cross sections. The appearance of both welds was consistent with welding from the outer surface only. The appearance of the weld bead on girth weld A1/A2 was consistent with a start position 61° clockwise from the top of the pipe. Ripple marks on the weld bead were consistent with two weld paths emanating in opposite directions from the start position, with one path traversing the top of the pipe, the other path traversing the bottom of the pipe, and the two paths meeting 180° from the start position. The appearance of the weld bead on girth weld A2/A3 was consistent with a start position on the top of the pipe at approximately 0°. Ripple marks on the weld bead were consistent with two weld paths emanating in opposite directions from the start position and the two paths meeting at the bottom of the pipe, 180° from the start position.

Various weld discontinuities were observed on the girth welds.[4] Arc strike clusters were observed at approximately six locations, distributed around the outer circumference of girth weld A1/A2. Each cluster contained multiple individual arc strikes. Approximately six arc strike clusters of similar appearance were also observed on girth weld A2/A3. Undercutting was observed on the outer circumference of girth weld A2/A3 along an 8-inch length, a second separate 8-inch length, and a 12-inch length. High/low offset was observed along some regions that exhibited undercutting. Figure 7 shows undercutting

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[3] Early vintage DSAW pipe from Consolidated Western was subject to cracks in the longitudinal seams 5 inch to 8 inch from the end of the pipe after automated welding. As part of the standard process, cracked ends were chipped out and the end of the pipe was welded using a handheld Lincoln welding unit that produced a weld of comparatively irregular appearance referred to as a “squirt” weld.

[4] A discontinuity is an interruption of the typical structure of a material. A discontinuity may be classified as a defect if its size and concentration exceed certain acceptance criteria (such as API Std. 1104) when evaluated using an accepted method such as visual or radiographic inspection.

and arc strikes on girth weld A2/A3. Figure 8 shows the inner surface of the pipe with the girth welds in profile. Both girth welds exhibited occasional spot-sized regions (0.75 inch or less) where weld metal did not melt through the inner diameter surface. In addition, girth weld A1/A2 exhibited three such locations 2 inch in length between 0° and 90°. Girth weld A2/A3 exhibited a 12-inch long region of internal concavity (i.e., weld suck back) between 180° and 240°, as shown in Figure 9a, and a 2-inch lack of fusion defect (API, 1956) between 30° and 60°, as shown in Figure 9b.

Cross sections through the welds were taken at approximately 270° (90° counterclockwise) from the top of the pipe. The cross sections were prepared in accordance with ASTM E3–01 (ASTM, 2001) through 6-μm diamond abrasive and etched in accordance with ASTM E407–99 (ASTM, 1999). The cross section through girth weld A1/A2 is shown in Figure 10, and the cross section through girth weld A2/A3 is shown in Figure 11.

Girth weld A1/A2 was sectioned through a region with an undercutting discontinuity on the A1 side of the weld. Multiple porosity/inclusion discontinuities were visible in the weld as well. A 3° angle was measured between the A1 and A2 pipe walls on the cross section macrograph in Figure 10.

The region where girth weld A2/A3 was sectioned exhibited high/low offset, as shown in Figure 11. The offset was 0.088 inch, exceeding the maximum offset of 0.062 inch allowed for pipe of the same diameter according to API Std. 1104 (API, 1956). An inclusion discontinuity was visible in the weld. Cold lap was visible on the inner diameter surface on the A3 side of the weld where weld metal had not fused to the base metal.

The rolling direction of A2 was determined by evaluating the orientation and relative length of manganese sulfide inclusions (stringers) on longitudinal and transverse metallographic cross sections. The samples were mounted, ground, and polished according to standard metallographic procedures (ASTM, 2001). Elongated stringers were observed in the longitudinal direction, as shown in Figure 12a, consistent with plate rolled in the longitudinal direction. By contrast, the stringers, when viewed in the transverse plane, were flattened but not elongated, as shown in Figure 12b.

The yield strength, tensile strength, and elongation of A1, A2, and A3 were measured on plates cut from each length of pipe. Plates were taken 90° from the longitudinal seam in accordance with PG&E specifications for pipe (PG&E, 1948a, b). The plates were removed using a plasma cutter and were 11.0 inch in the transverse direction by 8.5 inch in the longitudinal direction. Tensile testing was conducted in accordance with ASTM A370–10 (including Annex A2) (ASTM, 2010). For each length of pipe, three tensile specimens were tested. The tensile specimens had the following characteristics:

1) The samples were full thickness (nominally 0.37 inch) transverse strip test specimens. The specimens were flattened at room temperature with no post flattening heat treatment. The tensile specimen dimensions conformed to ASTM A370–10 — Annex A2.

2) The tensile sample gage length was 2.000 inch ± 0.005 inch.
3) The yield strength was measured using the 0.5% extension under load (EUL) method and the 0.2% strain offset (SO) method.
4) The crosshead rate of separation conformed to the requirements of ASTM A370–10.

Tensile test data were compared to mechanical property requirements from PG&E pipe specifications (PG&E, 1948a, b). Material codes for pipe on material procurement orders for the 1956 relocation project corresponded to X52 DSAW pipe,[5] the same grade as in the above mentioned materials specifications (NTSB, 2011a, b). Table 3 lists the mean and one standard deviation for 0.5% EUL yield strength, 0.2% SO yield strength, tensile strength, and elongation. According to the 0.5% EUL method, the mean yield strength of A1, A2, and A3 fell below the specified minimum yield strength (SMYS) requirement for X52 pipe by 2.2 ksi, 1.0 ksi, and 0.7 ksi, respectively. According to the 0.2% SO method, A2 and A3 met the SMYS requirement and A1 fell below the requirement by 3.2 ksi. Figure 13 graphically represents the 0.5% EUL and 0.2% SO yield strength data. A dashed line is plotted on the graph representing the X52 SMYS. All lengths of pipe exceeded PG&E specification requirements for minimum tensile strength of 72.0 ksi and minimum elongation of 22%. Complete mechanical property data are presented in Appendix A and the test lab report is contained in Materials Laboratory Report 11-059 (NTSB, 2011c).

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[5] High-test line pipe is referred to by the “X” prefix followed by a number that represents the specified minimum yield strength (SMYS) for that grade of pipe in ksi. For example X52 would indicate a SMYS of 52 ksi.

D. REFERENCES

API. (1956). *API Std. 1104 — Standard for Field Welding of Pipe Lines, 4th Ed*. Washington, DC: American Petroleum Institute.

ASTM. (1999). *ASTM Standard E407, 1999, Standard Practice for Microetching Metals and Alloys*. DOI: 10.1520/E0407-99, West Conshohocken, PA: ASTM International.

ASTM. (2001). *ASTM Standard E3, 2001, Standard Practice for Preparation of Metallographic Specimens*. DOI: 10.1520/E0003-01, West Conshohocken, PA: ASTM International.

ASTM. (2010). *ASTM Standard A370, 2010, Standard Test Methods and Definitions for Mechanical Testing of Steel Products*. DOI: 10.1520/A0370-10, West Conshohocken, PA: ASTM International.

NTSB. (2011a). *Docket No. SA-534—Exhibit No. 2–AZ—NTSB_011-010 PG&E 1956 Journal Voucher, Material Codes and Pipeline Survey Sheet*. Washington, DC: National Transportation Safety Board.

NTSB. (2011b). *Docket No. SA-534—Exhibit No. 2–DV—1956 Relocation Source of Pipe Material*. Washington, DC: National Transportation Safety Board.

NTSB. (2011c). *Docket No. SA-534—Materials Laboratory Report 11-059*. Washington, DC: National Transportation Safety Board.

PG&E. (1948a). *Pacific Gas and Electric Specifications for Pipe — Purchase Order 7R-61963*. San Francisco, CA: Pacific Gas & Electric Co.

PG&E. (1948b). *Pacific Gas and Electric Specifications for Pipe — Purchase Order 7R-66858*. San Francisco, CA: Pacific Gas & Electric Co.

PG&E. (2011a). *San Bruno GT Line Incident_DR_NTSB_065-001*. San Francisco, CA: Pacific Gas & Electric Co.

PG&E. (2011b). *San Bruno GT Line Incident_DR_NTSB_070-001*. San Francisco, CA: Pacific Gas & Electric Co.

Donald Kramer
Materials Engineer

Table 1: Dimensional attributes of the three lengths of pipe. Direction of rotation and angle values are defined clockwise relative to the typical direction of gas flow (south to north).

Pipe Length	Chord Length along Top of Pipe, inch	Outside Circumference, inch	Seam Distance from Top Along Outer Surface, inch	Angle Between Top and Seam	Length of Differentiated Profile on Outer Longitudinal Seam Weld, inch	Length of Grinding on Inner Longitudinal Seam Weld, inch
A1	36.12	94.44	13.00	49°	4.6	12.0
A2	10.00	94.38	19.50	74°	4.2	10.0
A3	36.00	94.50	10.62	40°	5.2	4.5

Table 2: Mid-chord ultrasonic wall thickness data for A1, A2, and A3. The angle values are defined clockwise relative to the typical direction of gas flow.

Position	A1 Wall Thickness, inch	A2 Wall Thickness, inch	A3 Wall Thickness, inch
0°	0.365	0.370	0.378
90°	0.369	0.369	0.374
180°	0.364	0.372	0.376
270°	0.366	0.372	0.377

Table 3: Mechanical testing data for A1, A2, and A3. The confidence interval is given as one standard deviation. The yield strength was measured using the 0.5% extension under load (EUL) method and the 0.2% strain offset (SO) method.

Pipe Length	Yield Strength — 0.5% EUL, ksi	Yield Strength — 0.2% SO, ksi	Tensile Strength, ksi	Percent Elongation
A1	49.8 ± 1.9	48.8 ± 0.6	74.0 ± 0.5	34 ± 1
A2	51.0 ± 1.0	52.7 ± 0.8	80.3 ± 0.3	32 ± 0
A3	51.3 ± 1.0	52.5 ± 2.2	82.2 ± 0.3	30 ± 1

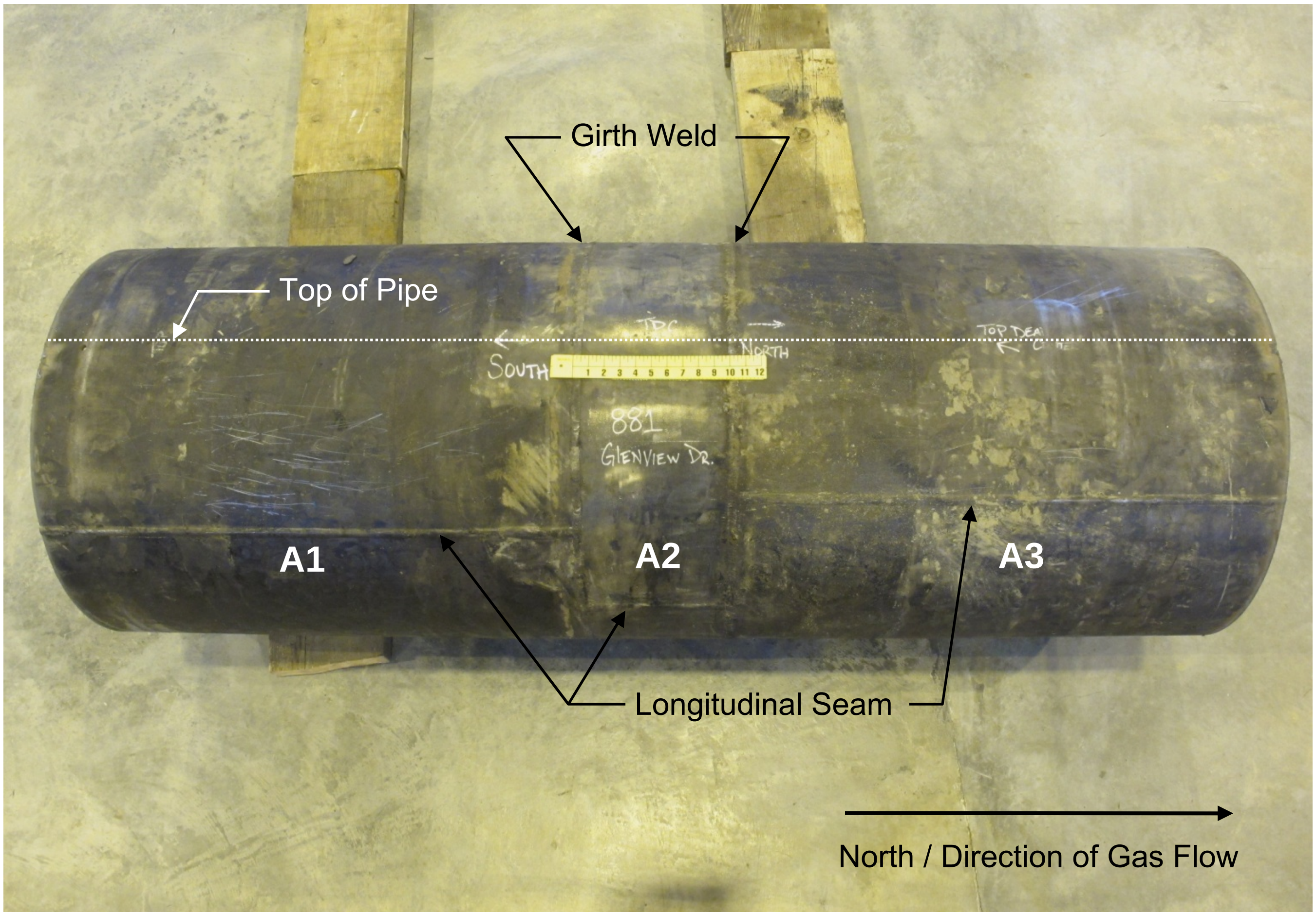


Figure 1: Overview of the as-received pipe from Line 132, Segment 180, 881 Glenview Drive.

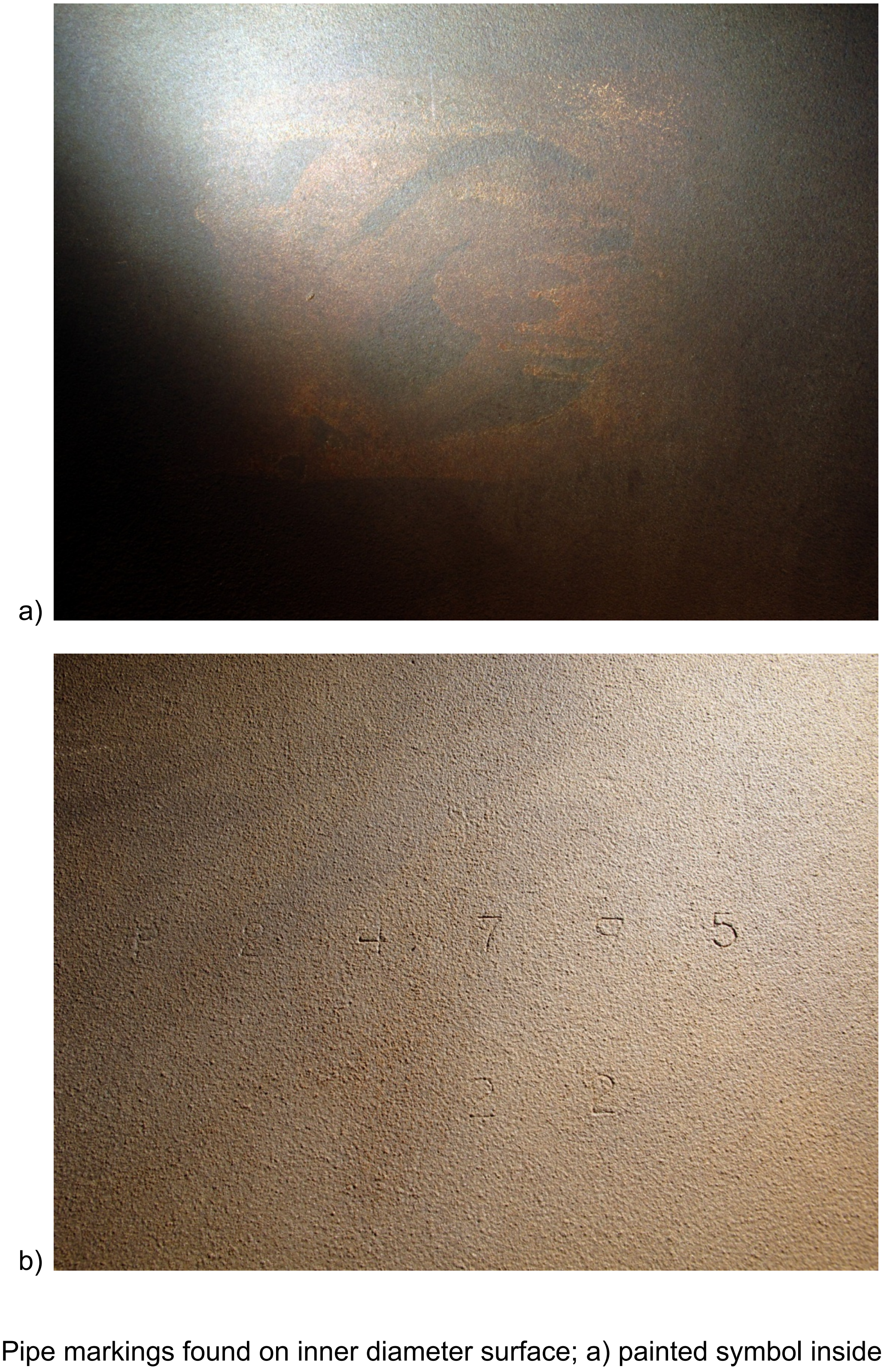


Figure 2: Pipe markings found on inner diameter surface; a) painted symbol inside A1, similar to a “6” or “9”; b) stamp inside A3 reading “P24795” and “22”.

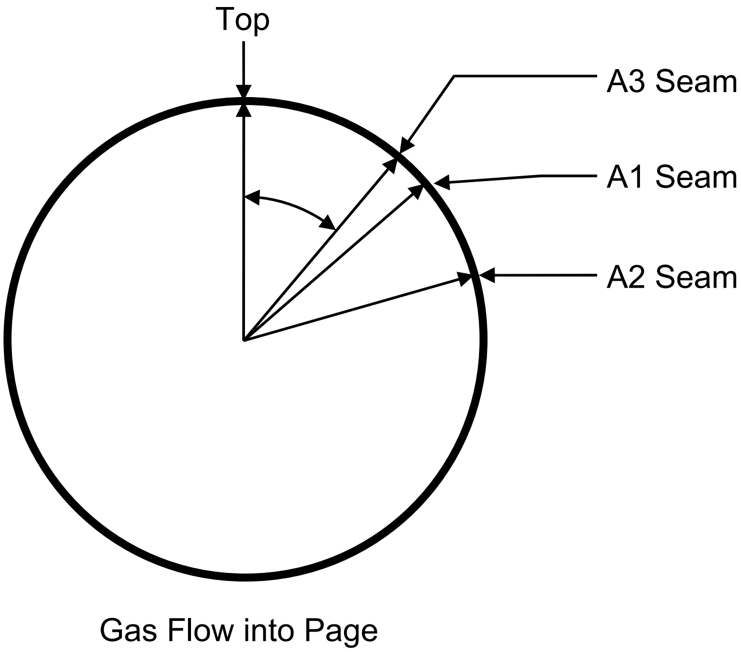
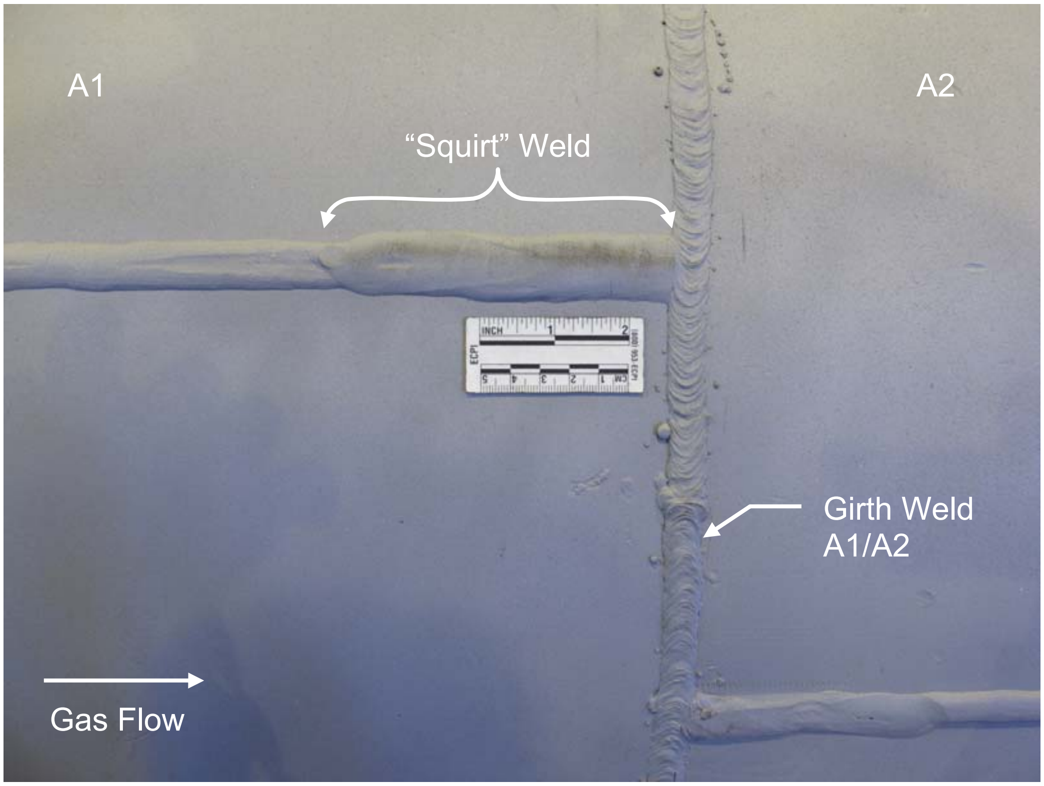


Figure 3: Schematic of pipe viewed in the typical direction of gas flow illustrating the orientation of the longitudinal seams relative to the top of the pipe.

a)



b)

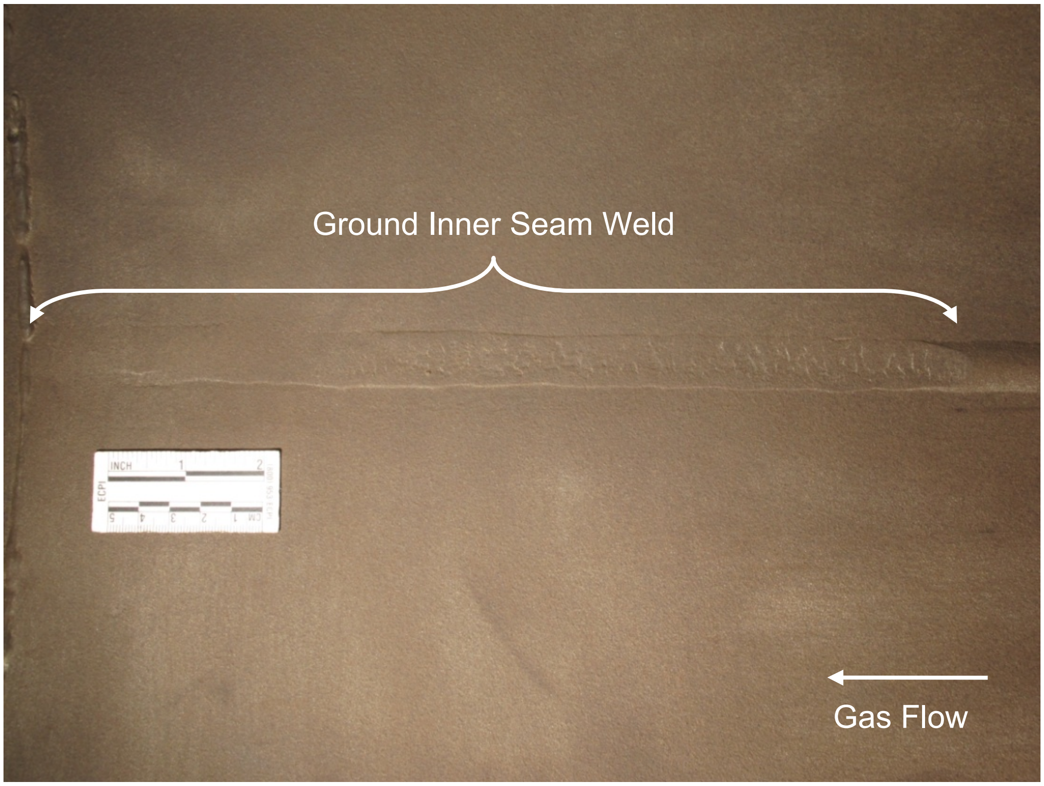


Figure 4: Photographs of DSAW longitudinal seams on A1 near girth weld A1/A2; a) outer seam; b) inner seam.

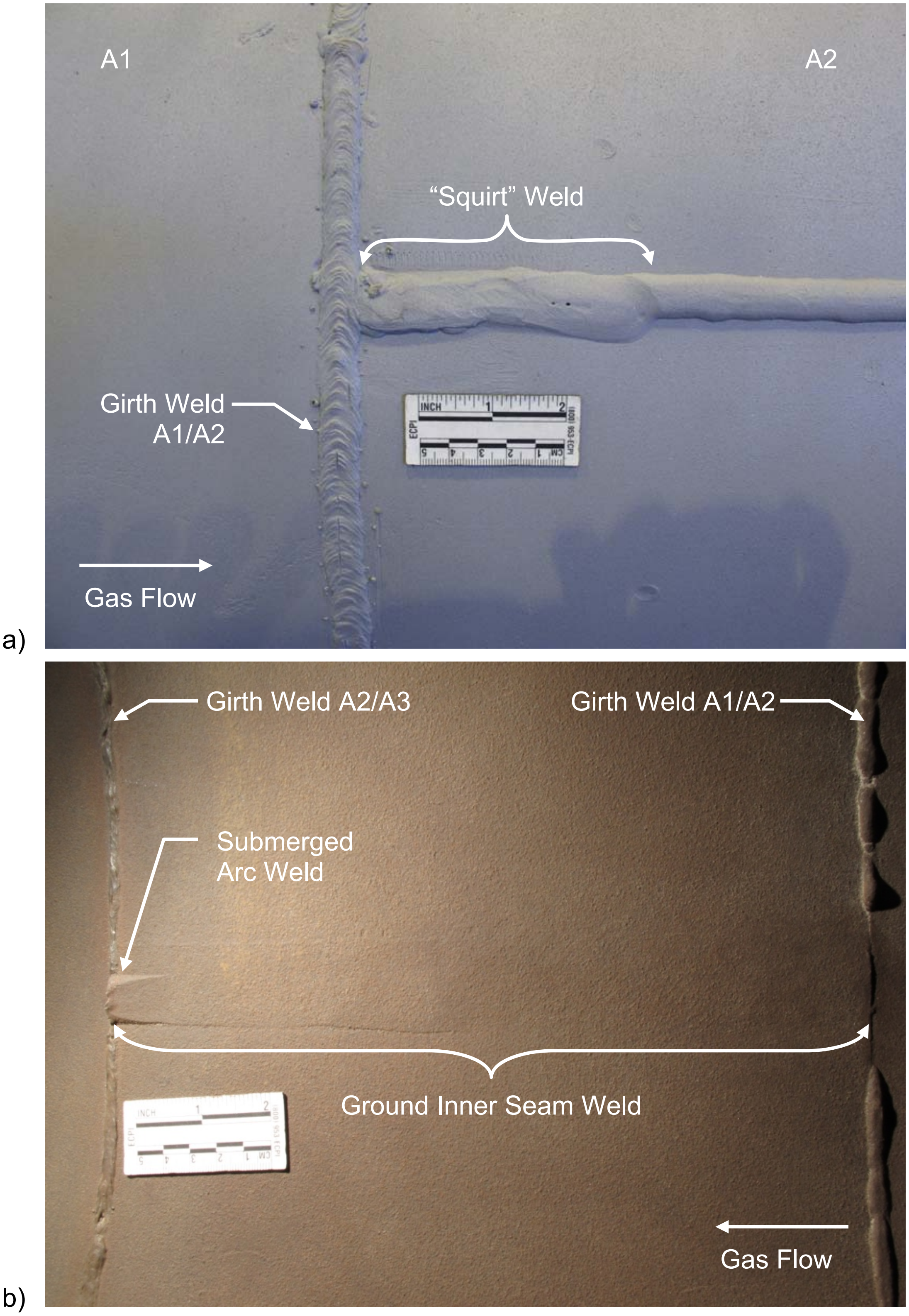
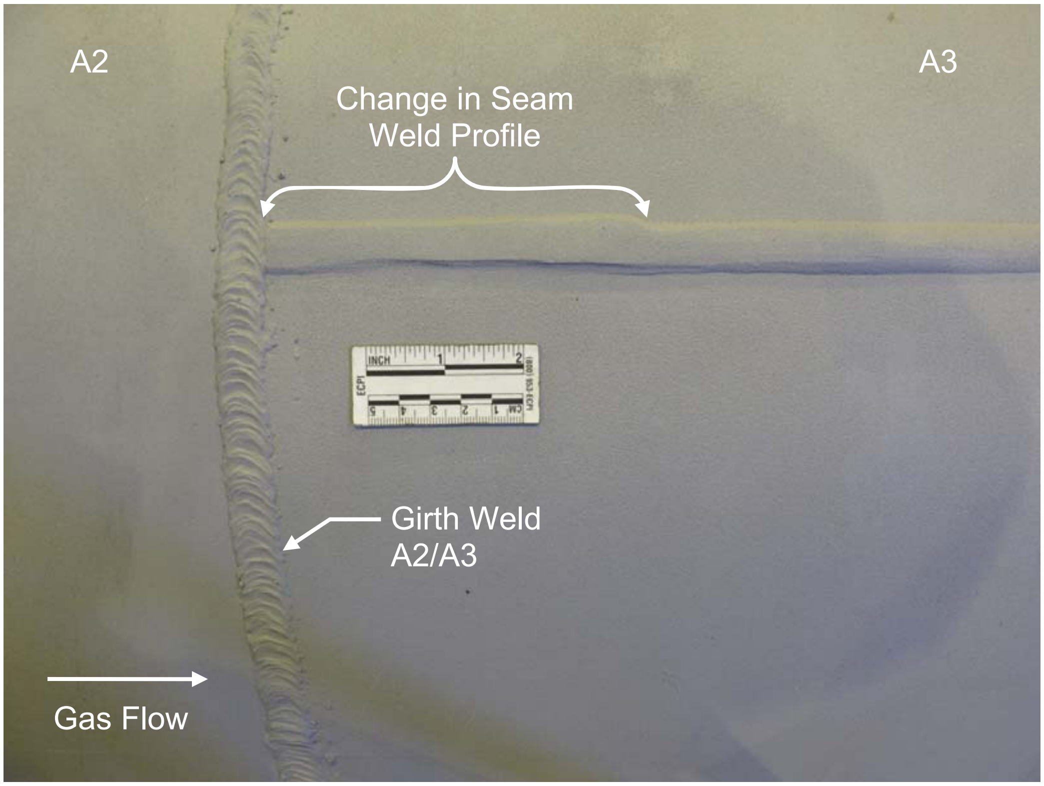


Figure 5 Photographs of DSAW longitudinal seams on A2; a) outer seam near girth weld A1/A2; b) inner seam between girth welds A1/A2 and A2/A3.

a)



b)

Figure 6: Photographs of DSAW longitudinal seams on A3 near girth weld A2/A3; a) outer seam; b) inner seam.

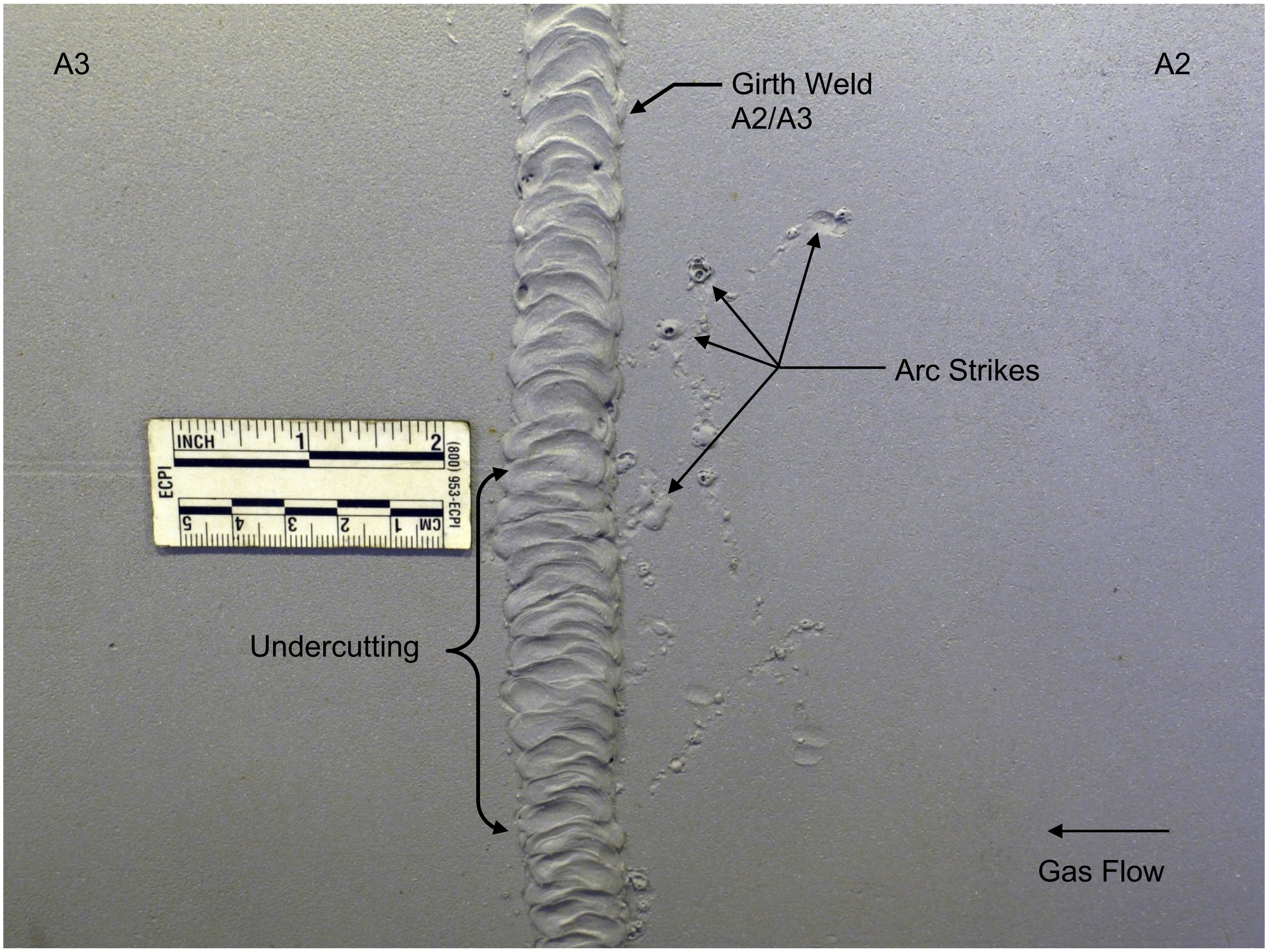


Figure 7: Photograph of outer surface of girth weld A2/A3 showing undercutting and arc strikes.

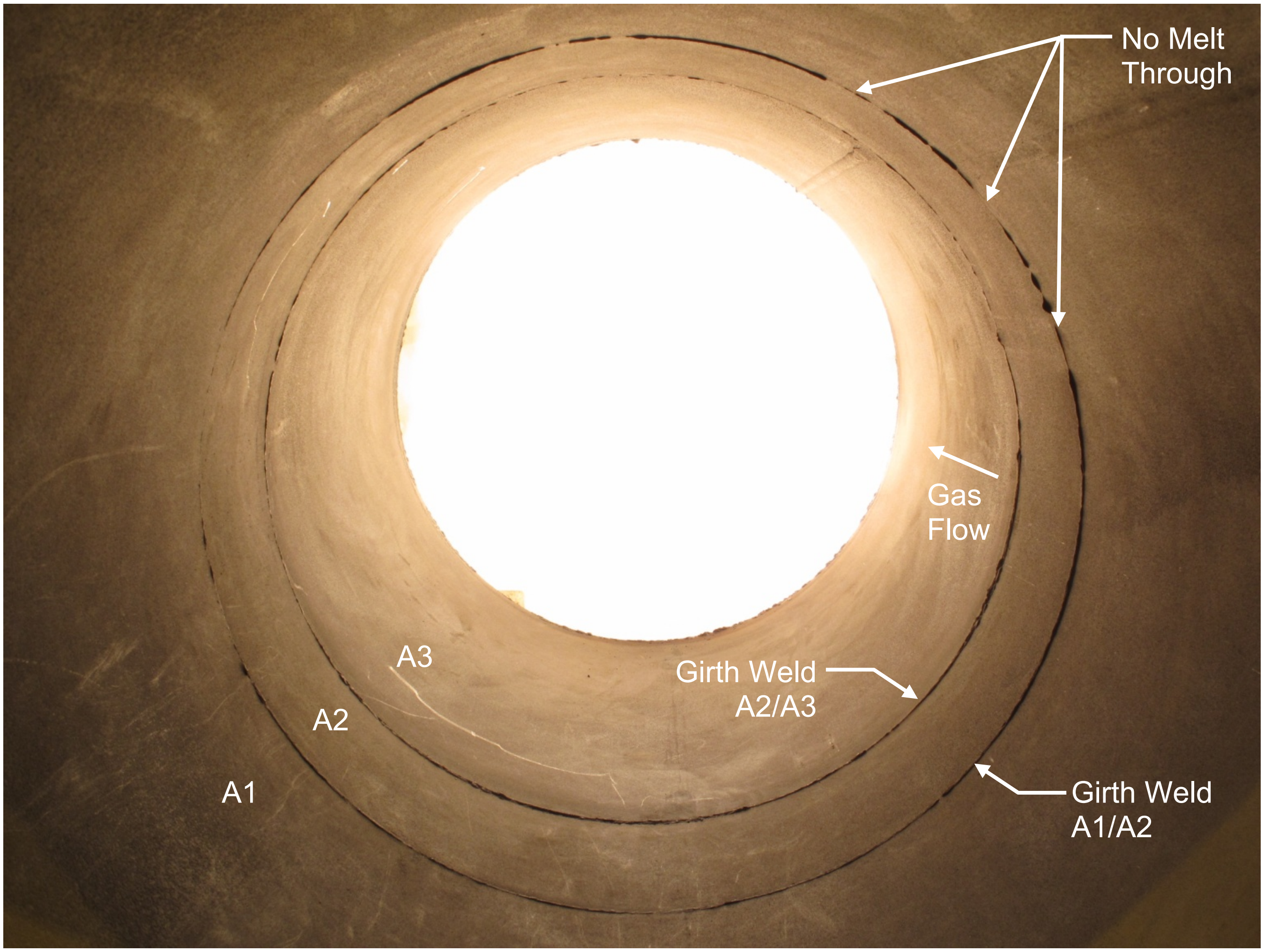


Figure 8: Interior view of the pipe showing the full inner circumference of the girth welds in profile.

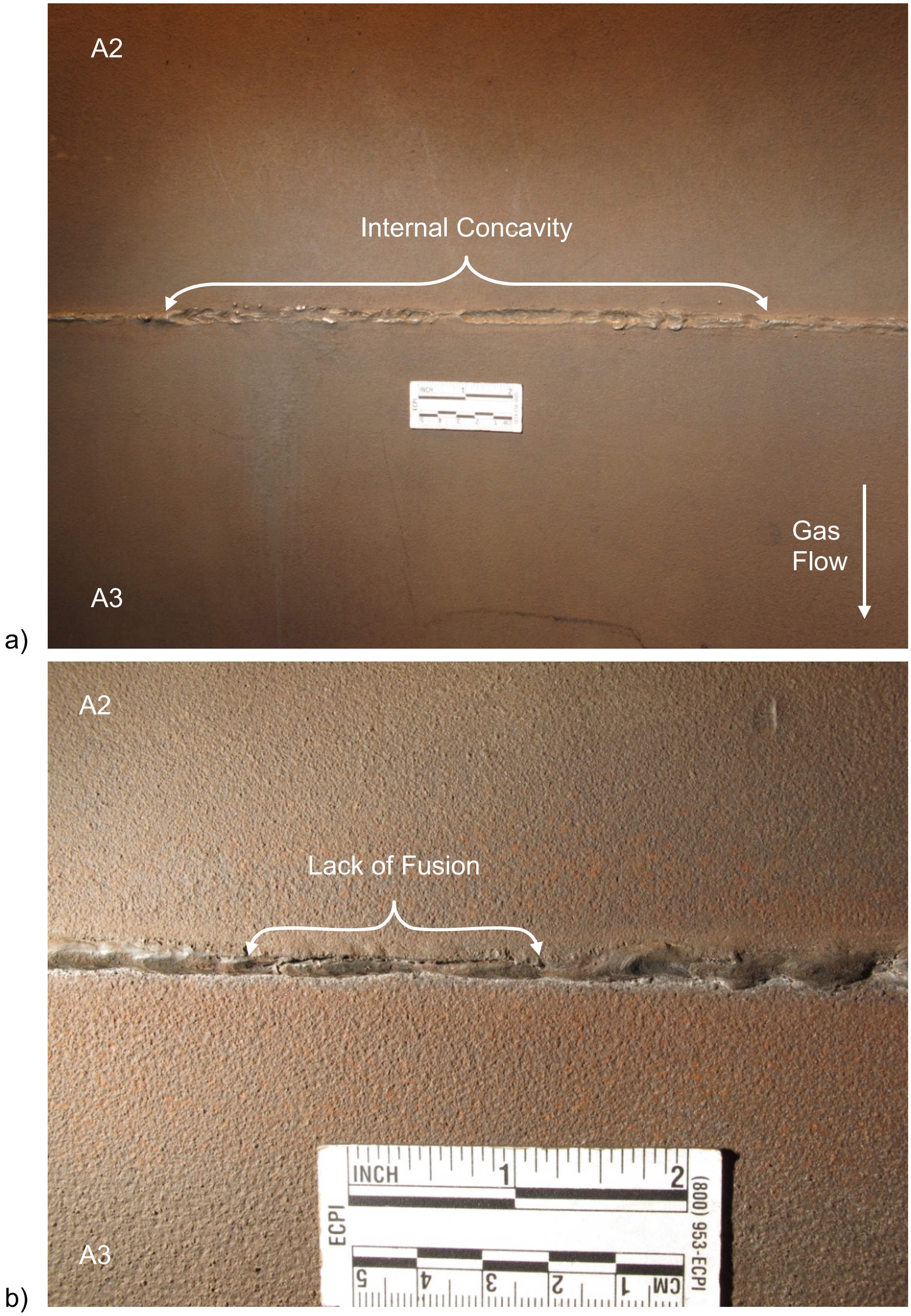


Figure 9: Visible weld discontinuities on the inner diameter surface of girth weld A2/A3; a) internal concavity between 180° and 240°; b) lack of fusion defect.

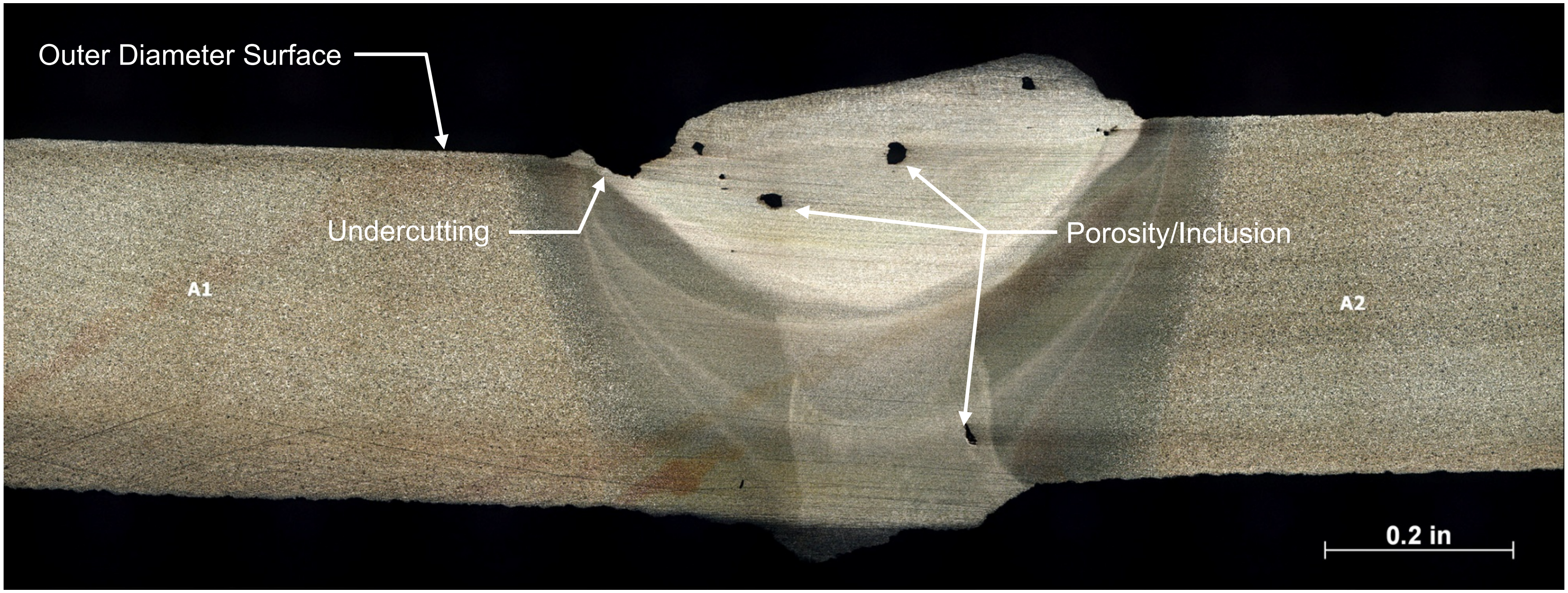


Figure 10: Cross section of girth weld A1/A2, etched using a solution of 4% nitric acid in ethanol.

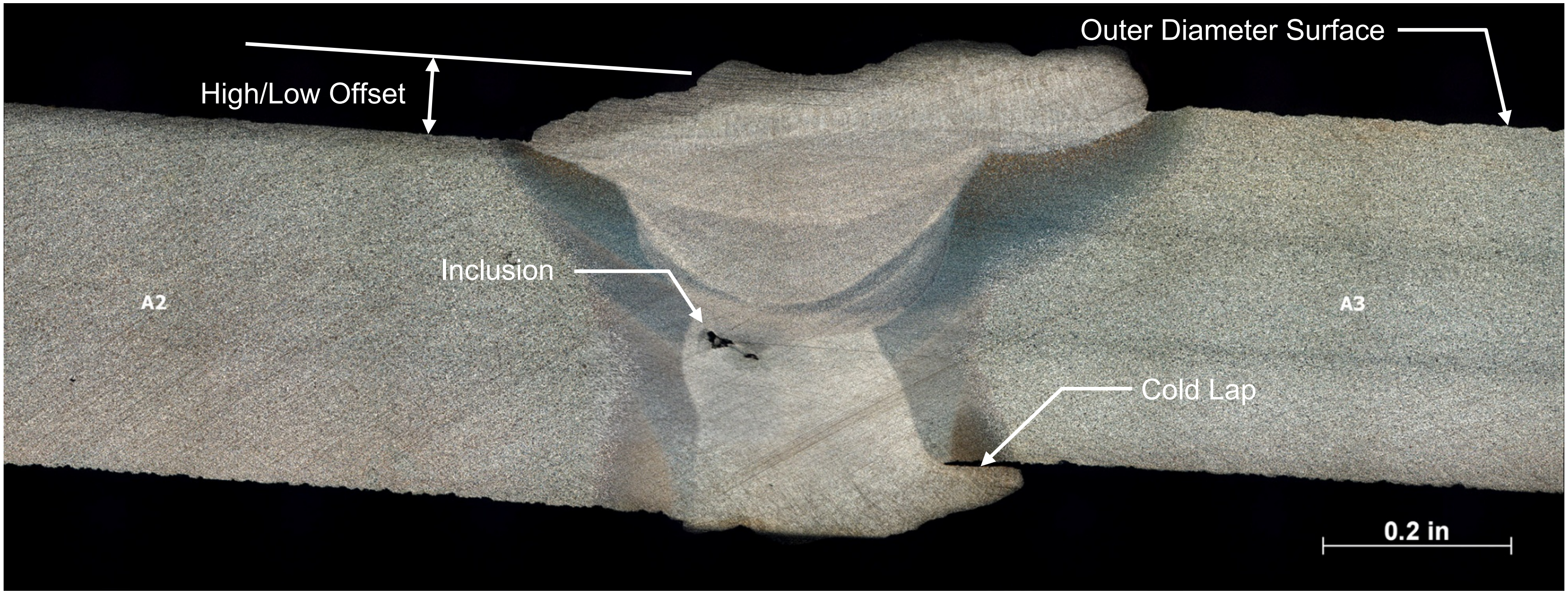
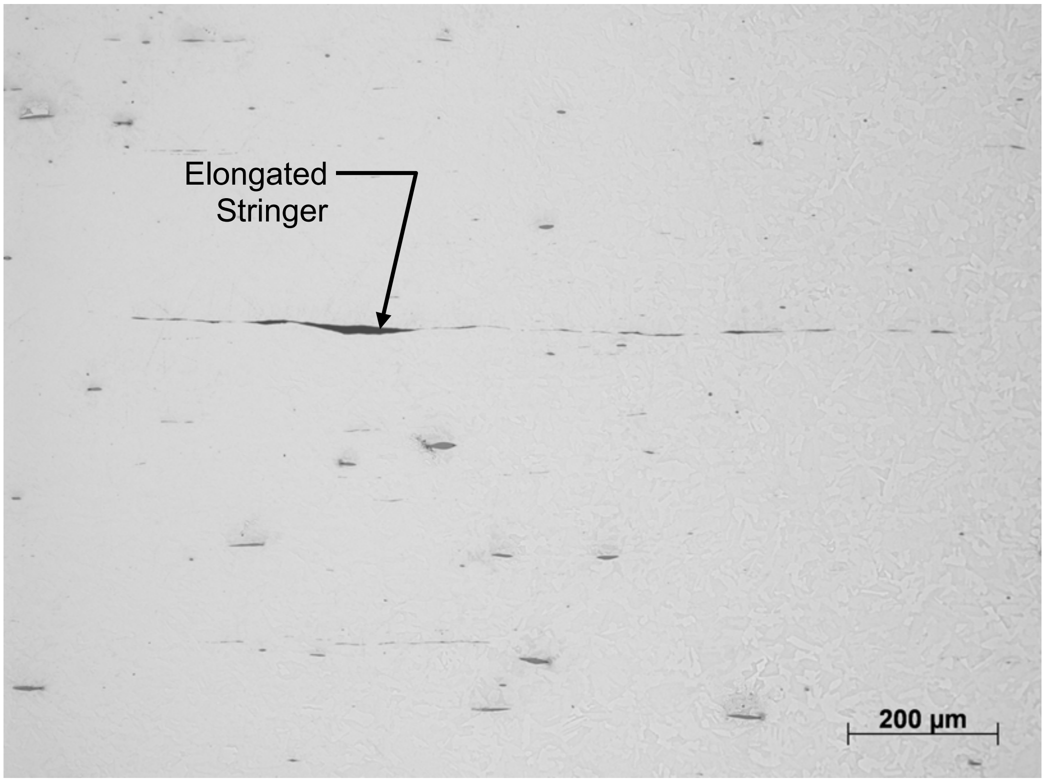
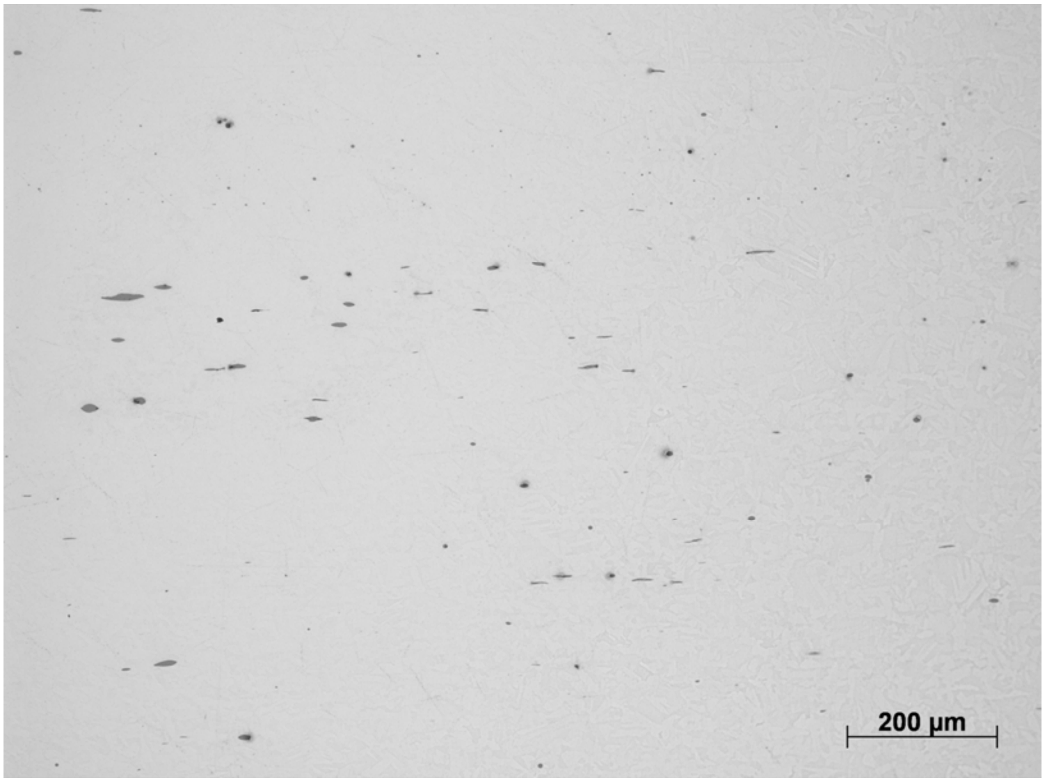


Figure 11: Cross section of girth weld A2/A3, etched using a solution of 4% nitric acid in ethanol.



a)



b)

Figure 12: Metallographic cross sections of A2; a) longitudinal cross section; b) transverse cross section.

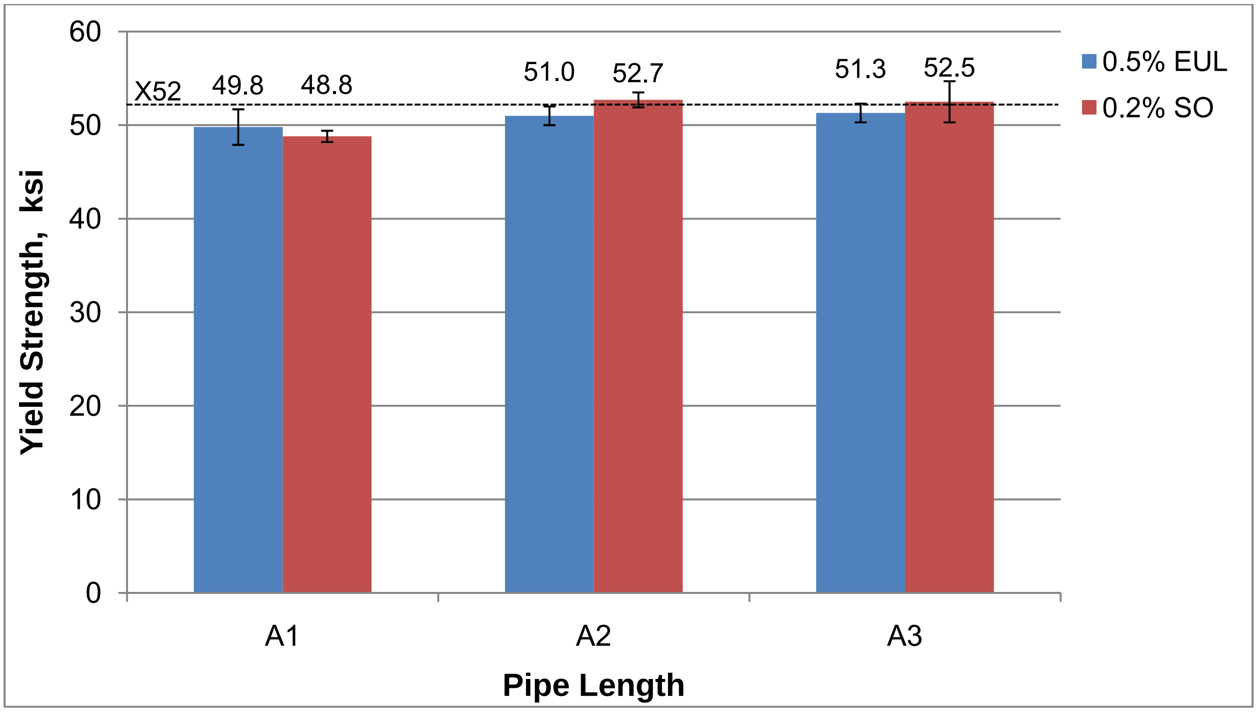


Figure 13: Yield strength data for A1, A2, and A3. The yield strength was measured by the 0.5% extension under load (EUL) method and the 0.2% strain offset (SO) method. The specified minimum yield strength was 52.0 ksi.

APPENDIX A: MECHANICAL TESTING DATA

Table A-1: Yield strength data using the 0.5% extension under load (EUL) method.

Source	**Yield Strength, 0.5% EUL — Test 1, ksi**	**Yield Strength, 0.5% EUL — Test 2, ksi**	**Yield Strength, 0.5% EUL — Test 3, ksi**
A1	51.5	50.0	47.8
A2	52.0	50.0	51.0
A3	52.5	50.5	51.0

Table A-2: Yield strength data using the 0.2% strain offset (SO) method.

Source	**Yield Strength, 0.2% SO — Test 1, ksi**	**Yield Strength, 0.2% SO — Test 2, ksi**	**Yield Strength, 0.2% SO — Test 3, ksi**
A1	49.5	48.3	48.6
A2	53.5	52.0	52.5
A3	55.0	51.5	51.0

Table A-3: Tensile strength data.

Source	**Tensile Strength — Test 1, ksi**	**Tensile Strength — Test 2, ksi**	**Tensile Strength — Test 3, ksi**
A1	74.5	74.0	73.5
A2	80.5	80.0	80.5
A3	82.0	82.0	82.5

Table A-4: Elongation data.

Source	**Elongation — Test 1, % in 2 inch**	**Elongation — Test 2, % in 2 inch**	**Elongation — Test 3, % in 2 inch**
A1	33	35	35
A2	32	32	32
A3	29	31	31