**Docket No. SA-534**

**Exhibit No. 3-B**

# NATIONAL TRANSPORTATION SAFETY BOARD

**Washington, D.C.**

Metallurgical Group Chairman
Factual Report

(32 Pages)

**NATIONAL TRANSPORTATION SAFETY BOARD**
Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

February 9, 2011

MATERIALS LABORATORY FACTUAL REPORT Report No. 11-005

## A. ACCIDENT

| | | |
|---|---|---|
| Place | : | San Bruno, CA |
| Date | : | September 9, 2010 |
| Vehicle | : | Natural Gas Transmission Pipeline |
| NTSB No. | : | DCA10MP008 |
| Investigator | : | Ravi Chhatre, RPH-20 |

## B. COMPONENTS EXAMINED

Three pieces of 30 inch diameter pipe.

## C. DETAILS OF THE EXAMINATION

This report describes chemical analysis, mechanical testing, and metallographic examination of the 6 pups and 2 long joints that were assembled into the three pieces of pipe. The pipeline was assembled as illustrated by the schematic in figure 1. For convenience, pups 1 – 6 are numbered and abbreviated P1, P2, and so on through P6 from south to north and the girth welds between the pups are numbered C1, C2, and so on through C7 from south to north. In some instances, references to the long joint south of pup 1 are abbreviated LS and references to the long joint north of pup 6 are abbreviated LN. See the Materials Laboratory Report 10-119 for observations on the as-received condition of the pipe, non destructive testing, fractographic determination of the initiation site, and metallography of the longitudinal seams[1].

## C.1. CHEMICAL ANALYSIS

The chemical composition was measured on samples from all lengths of pipe: LS, P1 – P6, and LN. Sample location and orientation were selected in accordance with ASTM E1806-96[2]. Pieces of the pipe were removed using a plasma cutter approximately 90° from the longitudinal seams. The samples were 4 inch in the circumferential direction and 10 inch to 11 inch in the longitudinal direction, 5 inch on either side of a girth weld as shown in figure 2a. A water cooled abrasive saw was used to cut transverse slices 1 inch from each longitudinal plasma cut edge, 2.5 inch from the transverse plasma cut edge, and 2 inch from the edge of the weld as shown in figure 1b. Samples were cut at a 45° angle to the outer diameter surface to accommodate a 0.5 inch diameter analytical spot size. Chemical analysis was performed by an American Association for Laboratory Accreditation (A2LA) accredited analytical laboratory using optical emission spectroscopy (OES) on the transverse cross sections in accordance with ASTM E415-08[3]. Carbon and sulfur were measured by the graphite furnace method and nitrogen was measure by the inert gas method, all in accordance with ASTM E1019-08[4]. A section of welding rod found fused to the inside of pup 2 was cut from the inner diameter surface of the pipe and the chemistry analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) and the graphite furnace method. The results of the chemical analysis are shown in table 1. According to the operator's records, PG&E purchased 100,364 feet of double submerged arc welded (DSAW) cold expanded[i] X52[ii] pipe in 1948 for the original installation of L132[5]. Subsequent pipe purchases in 1949 (100,000 feet) and 1953 (35,743 feet) were also for DSAW X52 cold expanded pipe[6,7,8]. The maximum limits of alloying elements for PG&E pipe specifications in 1948 and 1949, for API 5LX – X42 from 1948, and for API 5LX - X52 cold expanded pipe from 1954 are shown in table 2. Prior to 1954, API did not provide guidance for chemical composition in grades above X42, but rather left the composition up to an agreement between supplier and purchaser. In 1954 API specification 5LX began specifying the chemical composition for X52 pipe and began to list separate limits for open hearth and acid-bessemer steel (which was not done in an earlier 1948 edition).

All lengths of pipe were within the maximum allowable limits for the PG&E pipe specification except P4, which had a phosphorous (P) concentration of 0.069% by weight. Pup 4 also had a silicon (Si) concentration of 0.185% by weight. The P and Si levels were consistent with killed rephosphorized steel and were within the limits of the API 5LX limits for killed, deoxidized, acid-bessemer steel[iii]. The concentration of manganese (Mn) in P6, LS, and LN, all DSAW pipe, ranged from 0.80% to 1.02%. The concentration range was within the 0.80% to 1.23% range of Mn reported for cold expanded X52 pipe purchased in 1949[9]. The concentration of Mn in P1, P2, P3, and P5 ranged from 0.32% to 0.62%, within the limits of the materials specifications, but not within the range of Mn reported in 1949[iv]. The concentration of carbon (C) in P1, P3, P5, P6, LS, and LN ranged from 0.20% to 0.29%, within the 0.20% to 0.32% range of C reported for pipe purchased in 1949. The concentration of C in P2 was 0.12% and the concentration of C in P4 was 0.18%, within the limits of the material specification, but not within the range of C reported in 1949.

## C.2. MECHANICAL PROPERTIES

The yield strength, tensile strength, elongation, and Charpy impact toughness of the parent material were measured from plates cut from each piece of pipe. Where possible, plates were taken 90° from the longitudinal seam in accordance with PG&E specifications

[i] Cold expanded pipe is made to a size less than the final diameter of the pipe and then expanded to its final size. The cold expansion process ensures a more uniform pipe diameter and provides a slight increase in yield strength.
[ii] High-test line pipe is referred to by the "X" prefix followed by a 2-digit number that represents the first two digits of the specified minimum yield strength. For example X52 would indicate a yield strength of 52,000 psi.
[iii] In steel making, "killed" refers to the practice of adding an oxygen scavenging element such as silicon or aluminum to the molten steel. A rephosphorized steel is one in which phosphorous has been added to the molten steel to improve its yield strength typically at the expense of ductility.
[iv] There are no known reports with chemistry data for pipe purchased in 1948 or 1953.

for pipe[5,6]. However if that location was plastically deformed due the rupture, a different location was selected that had curvature most closely matching that of the undeformed pipe. The plates were removed using a plasma cutter and were 12.0 inch in the transverse direction by 18.5 inch in the longitudinal direction. Tensile testing was conducted in accordance with ASTM A370a – 09 (including Annex 2)[10]. Charpy impact testing was conducted in accordance with ASTM E23 – 07ae1[11] and current API Specification 5L (including Appendix F)[12]. For each length of pipe, 5 tensile specimens and 6 impact specimens were tested. The tensile specimens had the following characteristics:

1) The samples were full thickness (nominally 0.37 inch) transverse strip test specimens. Specimens were flattened at room temperature with no post flattening heat treatment. Tensile specimen dimensions conformed to A370 – Annex 2.
2) The tensile sample gage length was 2.000 inch ± 0.005 inch.
3) The yield strength was measured using the 0.5% total elongation method and the 0.2% offset method.
4) Crosshead rate of separation conformed to the requirements of ASTM A370.

The Charpy impact tests had the following characteristics:

1) The samples were transverse[v] 2/3 subsize specimens (6.7 mm instead of 10 mm thick) with tapered ends as shown in Figure 3. Samples were fabricated with the notch on a through-thickness face. The bottom surface of the test specimen (closest to the inner diameter of the pipe) was machined flat. The top surface had a flat area a minimum of 28 mm in length centered about the notch.
2) The samples were not flattened or otherwise cold worked.
3) Impact test temperature was 32 °F.

The 0.5% yield strength, tensile strength, and elongation of the lengths of pipe are shown in Table 3. The strength requirements according to a PG&E material specification for pipe purchased in 1948[5] and 1949[6] and an API 5LX specification from 1954 for X52 and X42[vi] pipe are shown in table 4. The complete set of tensile test data and Charpy impact test data can be found in Appendix A. The yield strength for P1, P2, P3, and P5 ranged from 32.0 ksi to 38.5 ksi and did not meet the minimum requirements for the specifications listed in table 4. The yield strength for P4 and P6 ranged from 48.3 ksi to 50.5 ksi and met the minimum yield requirements for API X42 pipe. The yield strength for LS and LN ranged from 54.0 ksi to 57.0 ksi and met the requirements for all specifications listed in table 4. The tensile strength for P2 was 52.0 ksi and did not meet the requirements for the specifications listed in table 4. The tensile strength values for P1 and P3 ranged from 60.3 ksi to 63.6 ksi and met the requirement for API X42 pipe. The tensile strength for P5 was 71.8 ksi and met the requirement for API X52 pipe. Finally, the tensile strength for P4, P6, LS, and LN ranged from 76.9 ksi to 83.2 ksi and met the requirements for all specifications in table 4. The elongation for all lengths of pipe ranged from 30.0% to 48.8% and met the requirements for all specifications in table 4.

[v] Transverse to the axial direction of the pipe.
[vi] Documentation provided by PG&E indicated the presence of X42 pipe along this pipeline segment.

## C.3. METALLOGRAPHY OF PARENT METAL MICROSTRUCTURE

The general microstructure for all lengths of pipe was a mixture of ferrite and pearlite. The rolling direction of the steel plate in each length of pipe was determined by evaluating the orientation and relative length of manganese sulfide inclusions (stringers) on longitudinal and transverse metallographic cross sections taken from all lengths of pipe[vii]. Based on the cross sectional metallography, the stringer orientation was undetermined for P3 and P4 so for those lengths of pipe radial cross sections were prepared as well. The samples were mounted, ground, and polished according to standard metallographic procedures[13]. Samples were examined using a metallurgical microscope at 100X original magnification. Example longitudinal and transverse cross section micrographs from P1 are shown in figure 4a and 4b, respectively. Elongated stringers were visible on the transverse face compared with the longitudinal face. Table 5 lists the elongated stringer orientation observed on all lengths of pipe and example micrographs of all lengths of pipe are in Appendix B. Elongated stringers were observed in the longitudinal direction in pipe lengths LS, P6, and LN, consistent with plate rolled in the longitudinal direction. Elongated stringers were observed in the transverse direction in pipe lengths P1, P2, P3, and P5, consistent with plate rolled in the transverse direction. The long stringer orientation was undetermined for pipe length P4.

## C.4. METALLOGRAPHY OF GIRTH WELDS

The girth weld microstructure was examined by cross section metallography on girth welds C1 through C7. The girth weld cross sections C2, C4, C6, and C7 were taken from the same 10 inch x 4 inch samples of pipe from which the chemical analysis samples were taken (see figure 2a). Girth weld cross sections C1 and C3 were plasma cut individually approximately 90° or greater from longitudinal seams. C5 was taken along the east side of the pipe 90° from the true top, nominally in line with the longitudinal fracture along the pup 1 and pup 2 longitudinal seams. Metallographic cross sections were polished according to standard metallographic procedures[13] and etched using a 2% nital solution[14].

The appearance of the girth weld C1 cross section was consistent with a joint that was welded primarily from the outer diameter surface and subsequently welded from the inner diameter surface with inclusion discontinuities in the weld near the middle of the wall section[viii]. The cross section through girth weld C1 is shown in figure 5. The weld pool in the middle of the joint ranged from 0.252 inch near the inner diameter surface to 0.292 inch near the outer diameter surface. At the outer diameter surface the structure of the weld

---

[vii] The plate from which the pipe was made was in turn made from a billet of greater thickness. The thickness of the plate was achieved by reducing the billet thickness by passing it through a series of rolling mills. The rolling caused manganese sulfide inclusions to elongate in the rolling direction and are called “stringers”.

[viii] A discontinuity is an interruption of the typical structure of a material. A discontinuity is classified as a defect only if its size and concentration exceed certain acceptance criteria according to an accepted method such as radiography. See Materials Laboratory Report 10-119 for a list of acceptance criteria for weld discontinuities according to API 1104 and radiographic inspection results of the girth welds.

pool was consistent with multiple passes and was 1.110 inch at its widest and proud of the outer diameter surface by 0.115 inch at its highest point. The weld pool along the inner diameter surface was 0.450 inch at its widest, had a columnar microstructure, and was bounded by a heat affected zone.

The appearance of the girth weld C2 cross section was consistent with a joint that was welded from the inner diameter surface first followed by the outer diameter surface with lack of penetration and inclusion discontinuities in the joint. The cross section through girth weld C2 is shown in figure 6. There was a 0.124 inch radial offset between pup 1 and pup 2. API 1104 from 1956 specified an offset upper bound of 0.062 inch for pipe of the same thickness[15]. ASA B31.1.8-1955 (predecessor to ASME B31.8) specified that the ends of pipe to pipe joints should be aligned "as accurately as practicable giving consideration to existing commercial tolerances on pipe diameters, pipe wall thickness and out of roundness."[16] Lack of penetration was observed along a 0.195 inch length close to the outer diameter surface. Each length of pipe had a square end adjacent to the outer diameter surface. Pup 1 had a 50° bevel and pup 2 had a 35° bevel adjacent to the inner diameter surface. ASA B31.1.8-1955 recommended joint end preparation included a bevel on the outer diameter surface of the pipe with the angle between the bevel and the end of the pipe ranging from 30° to 40° (including tolerance allowances)[16]. The outer weld cap was 0.962 inch at its widest and 0.048 inch proud of the pup 1 outer diameter surface at its highest point. The inner weld cap was 0.345 inch at its widest. The heat affected zone from the weld applied to the outer diameter surface overlapped with the weld applied to the inner diameter surface. The microstructure of the weld applied to the inner diameter surface had a fine equiaxed grain structure inside the heat affected zone, consistent with recrystallization.

The appearance of the girth weld C3 cross section was consistent with a joint that was welded from the inner diameter surface first followed by the outer diameter surface with lack of fusion and slag/porosity discontinuities in the joint[ix]. The cross section through girth weld C3 is shown in figure 7. Two lack of fusion/slag inclusion discontinuities oriented in the radial direction were observed near the center of the wall section. The discontinuities were 0.168 inch in the radial direction and were separated by 0.165 inch in the circumferential direction. A porosity/slag inclusion discontinuity 0.071 inch at its widest was observed in the middle. The weld in the middle of the joint was 0.165 inch wide. The weld applied to the outer diameter surface was 0.946 inch at its widest and proud of the surface by 0.114 inch at its highest point. The weld on the inner diameter surface was 0.386 inch at its widest and had an appearance consistent with undercutting at the toe of the weld adjacent to pup 3. The weld on the inner diameter surface was within the heat affected zone of the weld applied to the outer diameter surface and had a fine equiaxed grain structure, consistent with recrystallization. The end of pup 3 had an appearance consistent with a square end. The shape of the end of pup 2 was undetermined.

[ix] After wet sectioning, large groove tracks were observed emanating from the porosity discontinuities, consistent with pulled out slag inclusion fragments tracking across the section face.

The appearance of the girth weld C4 cross section was consistent with weld filler metal penetrating the joint from the outer diameter surface and subsequent welding from the inner diameter surface with lack of fusion and porosity discontinuities in the joint. The cross section through girth weld C4 is shown in figure 8. There was a 0.109 inch radial offset between pup 3 and pup 4. The appearance of the weld on the outer diameter surface was consistent with at least two welding passes. The first pass (or set of passes) penetrated flush with the inner diameter surface of pup 3 and was 0.384 inch at its widest as it approached the outer diameter surface. The appearance of the second pass (or set of passes) was consistent with application primarily on the outer diameter surface, was 0.849 inch at its widest, and proud of the pup 3 outer diameter surface by 0.095 inch at its highest point. The weld from the inner diameter surface was 0.645 inch at its widest. Multiple solidification fronts and heat affected zones were visible consistent with multiple weld passes. The porosity resided primarily with the weld applied along the inner diameter surface.

The appearance of the girth weld C5 cross section was consistent with a joint that was welded from the outer diameter surface and subsequently welded on the inner diameter surface with lack of penetration/fusion and porosity discontinuities in the joint. The cross section through girth weld C5 is shown in figure 9. The girth weld fractured in the circumferential plane as reported elsewhere[1]. There was a 0.071 inch radial offset between pup 4 and pup 5 and a 3° miter angle between the two pups. The lack of fusion/penetration had a “J” shape and was 0.13 inch in the longitudinal direction by 0.14 inch in the radial direction. There was a pore in the weld close to the inner diameter surface. The appearance of the weld on the outer diameter surface was consistent with at least two welding passes. The first pass (or set of passes) penetrated mid way into the joint and was 0.414 inch at its widest close to the outer diameter surface. The appearance of the second pass (or set of passes) was consistent with application primarily on the outer diameter surface and was 0.935 inch at its widest and 0.100 inch proud of the pup 4 outer diameter surface at its highest point. The weld on the inner diameter surface was 0.700 inch at its widest. Multiple solidification fronts were visible consistent with multiple weld passes..

The appearance of the girth weld C6 cross section was consistent with a joint that was welded primarily from the outer diameter surface and subsequently welded from the inner diameter surface with porosity discontinuities in the joint. The cross section through girth weld C6 is shown in figure 10. The appearance of the weld on the outer diameter surface was consistent with multiple welding passes. The width of the weld pool ranged from 0.264 inch near the inner diameter surface to 0.357 inch near the outer diameter surface. The final pass on the outer diameter surface was 0.728 inch at its widest and 0.057 inch above the outer diameter surface at its highest point.

The appearance of the girth weld C7 cross section was consistent with a joint that was welded primarily from the outer diameter surface and subsequently welded from the inner diameter surface with porosity and inclusion discontinuities in the weld pass along the inner diameter surface. The cross section through girth weld C7 is shown in figure 11. There was a 3° miter between pup 6 and LN. The weld pool in the joint ranged from 0.227

inch near the inner diameter surface to 0.351 inch below the outer diameter surface. The final pass on the outer diameter surface was 0.705 inch at its widest and 0.063 inch proud of the LN outer diameter surface at its highest point. A weld pass along the inner diameter surface contained features consistent with porosity and inclusion discontinuities.

## D. REFERENCES

1) "Materials Laboratory Report 10-119", National Transportation Safety Board, Office of Research and Engineering, January 21, 2011.
2) "ASTM E 1806 – 96 Standard Practice for Sampling Steel and Iron for Determination of Chemical Composition," ASTM International, West Conshohocken, PA, 2004.
3) "ASTM E 415 – 08 Standard Test Method for Atomic Emission Vacuum Spectrometric Analysis of Carbon and Low-Alloy Steel," ASTM International, West Conshohocken, PA, 2008.
4) "ASTM E 1019 – 08 Standard Test Methods for Determination of Carbon, Sulfur, Nitrogen, and Oxygen in Steel, Iron, Nickel, and Cobalt Alloys by Various Combustion and Fusion Techniques," ASTM International, West Conshohocken, PA, 2008.
5) "Pacific Gas and Electric Specifications for Pipe – Purchase Order 7R-61963," Pacific Gas and Electric Company, February 26, 1948.
6) "Pacific Gas and Electric Specifications for Pipe – Purchase Order 7R-66858," Pacific Gas and Electric Company, June 21, 1948.
7) Pacific Gas and Electric Company Purchase Order No. 7R 182222, October 16, 1953.
8) Pacific Gas and Electric Company Purchase Order No. 7R 183613, August 5, 1953.
9) Moody Engineering Co., "Inspection Order 7R-81743, Purchase Order 7R-66858, Consolidated Western Steel Corp., 30" O.D. x 3/8" Wall Line Pipe," July 19, 1949.
10) "ASTM A370 – 09 Standard Test Methods and Definitions for Mechanical Testing of Steel Products," ASTM International, West Conshohocken, PA, 2009.
11) "ASTM E23 – 07ae1 Standard Test Methods for Notched Bar Impact Testing of Metallic Materials," ASTM International, West Conshohocken, PA, 2007.
12) "API Specification 5L Specification for Line Pipe", 43rd Edition, American Petroleum Institute, Washington, DC, 2004.
13) "ASTM E3 – 01 Standard Guide for Preparation of Metallographic Specimens," ASTM International, West Conshohocken, PA, 2004.
14) "ASTM E407 – 99 Standard Practice for Microetching Metals and Alloys," ASTM International, West Conshohocken, PA, 2004."
15) API Standard 1104, "Standard for Field Welding of Pipe Lines," 4th Ed, API Publishing, Washington, DC, 1956.
16) ASA B31.1.8-1955, "Gas Transmission and Distribution Piping Systems," American Society of Mechanical Engineers, New York, 1955.

Donald Kramer, Ph.D.
Materials Engineer

**Table 1**: Weight percent of elements present in the 8 lengths of pipe as measured by optical emission spectroscopy, graphite furnace (C and S), and inert gas fusion (N). All elements at or above 0.01 weight percent were measured. The balance of the weight percent was Fe and is not listed. LS – Long joint south of pup 1; LN – Long joint north of pup 6; P1 – P6, pups 1 – 6; WR – Welding rod.

| Sample | C | Mn | P | S | Al | As | Co | Cr | Cu | Mo | N | Ni | Si | Sn | Ti | W |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LS | 0.29 | 1.02 | 0.02 | 0.025 | <0.01 | 0.01 | 0.03 | 0.02 | 0.06 | <0.01 | 0.01 | 0.07 | 0.09 | <0.01 | | |
| P1 | 0.24 | 0.34 | 0.012 | 0.023 | <0.01 | 0.01 | 0.01 | 0.05 | 0.12 | 0.01 | <0.01 | 0.06 | 0.01 | 0.01 | | |
| P2 | 0.12 | 0.35 | 0.008 | 0.022 | <0.01 | 0.01 | 0.01 | 0.05 | 0.08 | 0.01 | <0.01 | 0.05 | 0.01 | 0.01 | | |
| P3 | 0.21 | 0.32 | 0.012 | 0.026 | <0.01 | 0.02 | 0.01 | 0.05 | 0.12 | 0.01 | <0.01 | 0.06 | 0.01 | 0.01 | | 0.01 |
| P4 | 0.18 | 0.8 | 0.069 | 0.026 | 0.01 | 0.01 | 0.01 | 0.04 | 0.41 | 0.01 | 0.01 | 0.1 | 0.185 | 0.045 | 0.01 | 0.01 |
| P5 | 0.28 | 0.62 | 0.017 | 0.036 | <0.01 | 0.01 | <0.01 | 0.04 | 0.05 | 0.01 | <0.01 | 0.03 | 0.03 | 0.01 | | |
| P6 | 0.27 | 0.95 | 0.016 | 0.035 | <0.01 | 0.01 | 0.03 | 0.01 | 0.04 | <0.01 | <0.01 | 0.07 | 0.05 | <0.01 | | |
| LN | 0.2 | 1.02 | 0.011 | 0.025 | <0.01 | 0.01 | 0.03 | 0.03 | 0.04 | 0.02 | 0.01 | 0.13 | 0.07 | <0.01 | | 0.01 |
| WR | 0.1 | 0.49 | <0.005 | 0.018 | <0.01 | | | 0.02 | 0.13 | 0.01 | | 0.03 | 0.01 | 0.06 | | |

**Table 2**: Maximum allowable percentage by weight of carbon (C), manganese (Mn), phosphorous (P), and sulfur (S) according to PG&E material specification, API specification for X42 pipe from 1948, and API specification for cold expanded X52 pipe from 1954. The limits are “check” limits where added allowances are made for local material inhomogeneities and different analytical methods than those used for “ladle” or molten metal analyses.

| Specification | C | Mn | P | S |
|---|---|---|---|---|
| 7R-61963 PG&E Material Specification | 0.34 | 1.29 | 0.046 | 0.06 |
| API 5LX X42, 1st Ed. 1948 | 0.33 | 1.28 | 0.115 | 0.065 |
| Electric furnace / Open hearth, X52 cold expanded API 5LX 5th Ed. 1954 | 0.32 | 1.30 | 0.05 | 0.06 |
| Killed, deoxidized, acid-bessemer, X52 cold-expanded API 5LX 5th Ed. 1954 | 0.28 | 1.30 | 0.11 | 0.06 |

**Table 3**: Average and standard deviation of mechanical test data for all lengths of pipe.

| Sample | 0.5% Yield Strength, ksi | Tensile Strength, ksi | Elongation, % in 2 inch | 0.2% Yield Strength, ksi |
|---|---|---|---|---|
| LS | 57.0 ± 0.6 | 83.2 ± 0.3 | 30.0 ± 0.7 | 56.3 |
| P1 | 36.6 ± 0.3 | 63.6 ± 0.2 | 39.4 ± 0.5 | 35.2 |
| P2 | 32.0 ± 0.1 | 52.0 ± 0.0 | 48.8 ± 0.8 | 31.1 |
| P3 | 34.9 ± 0.5 | 60.3 ± 0.3 | 42.8 ± 0.4 | 33.6 |
| P4 | 48.3 ± 0.5 | 79.0 ± 0.0 | 34.0 ± 0.7 | 48.3 |
| P5 | 38.5 ± 0.3 | 71.8 ± 0.3 | 35.8 ± 1.1 | 37.4 |
| P6 | 50.5 ± 1.4 | 78.7 ± 0.3 | 30.8 ± 0.8 | 51.6 |
| LN | 54.0 ± 0.4 | 76.9 ± 0.2 | 30.4 ± 0.5 | 51.5 |

**Table 4**: Yield strength, tensile strength, and elongation requirements according to PG&E and API pipe specifications.

| Specification | 0.5% Yield Strength, ksi | Tensile Strength, ksi | Elongation % in 2 inch |
|---|---|---|---|
| 7R-61963 PG&E Material Specification | 52.0 | 72.0 | 22 |
| API 5LX X52, 1954 | 52.0 | 66.0 | 20 |
| API 5LX X42, 1954 | 42.0 | 60.0 | 25 |

**Table 5**: Elongated stringer orientation (long direction) relative to the longitudinal axis of each pipe section as observed by metallographic examination.

| Sample | Stringer Orientation |
|---|---|
| LS | Longitudinal |
| P1 | Transverse |
| P2 | Transverse |
| P3 | Transverse |
| P4 | Undetermined |
| P5 | Transverse |
| P6 | Longitudinal |
| LN | Longitudinal |

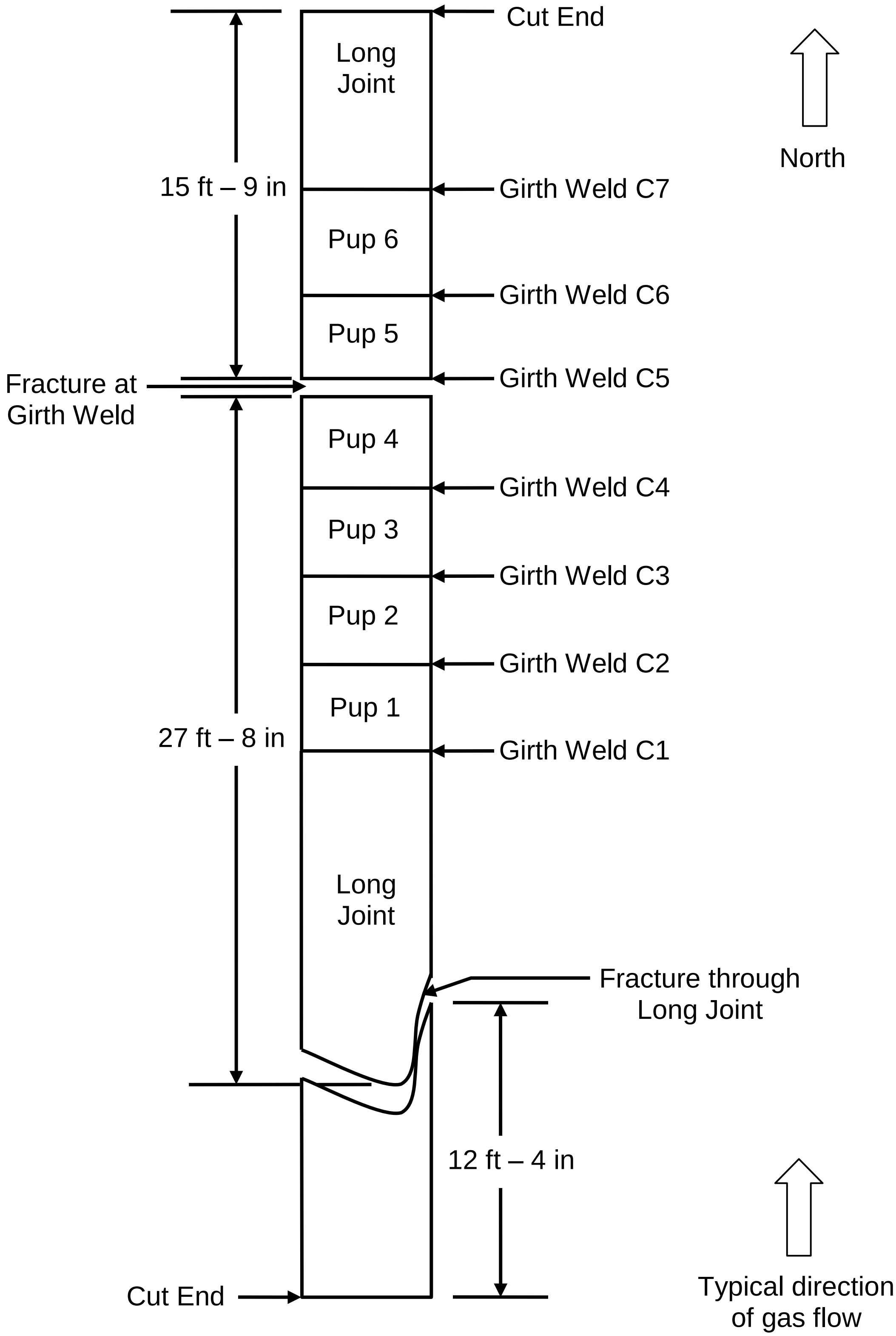



**Figure 1**: Schematic of pipe showing location of girth welds and fractures. Longitudinal fracture not depicted.

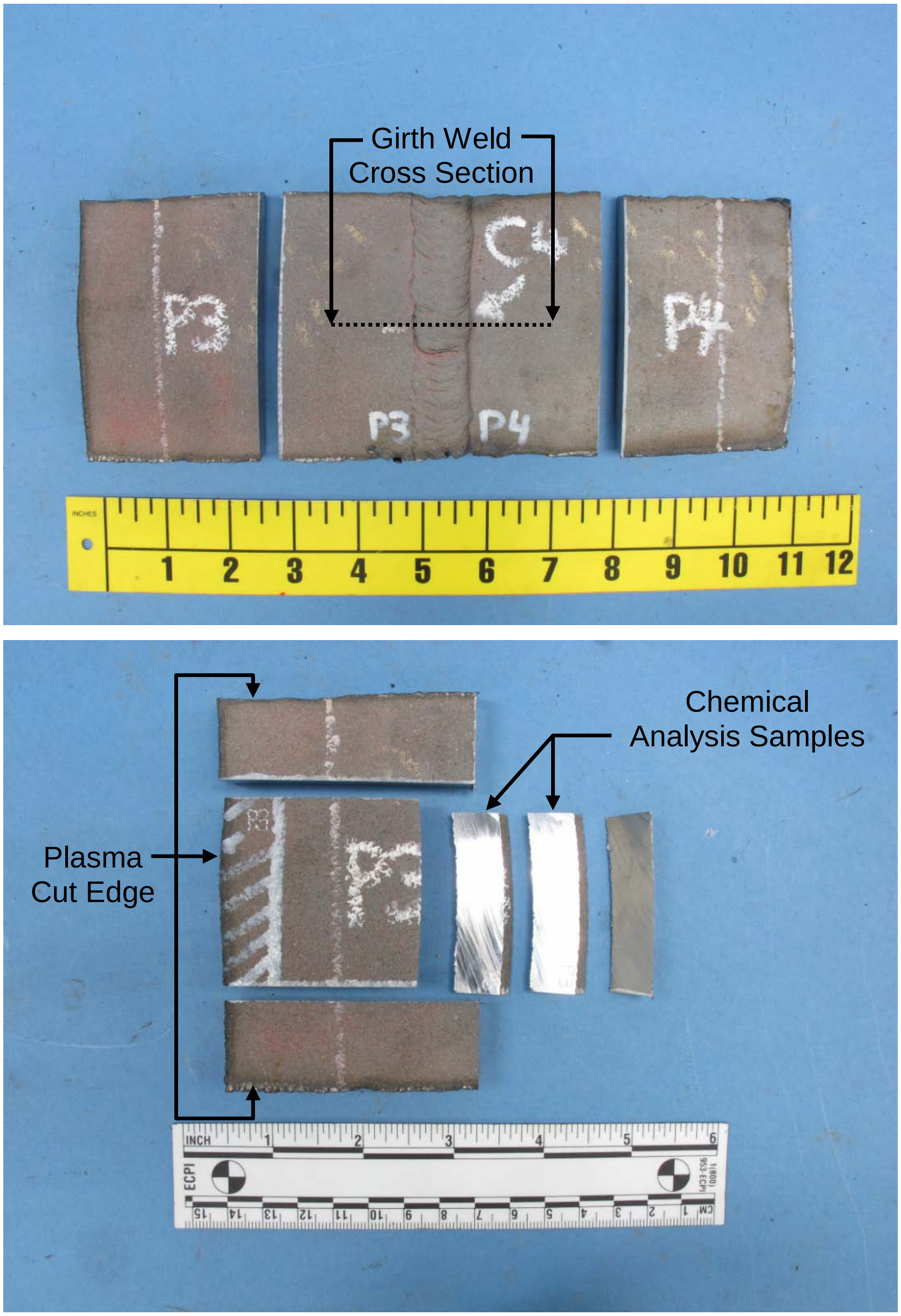



**Figure 2**: a) Plasma cut section of pipe centered on girth weld C4. Transverse cuts in pup 3 and pup 4 are in preparation for chemical analysis samples; b) Samples from pup 3 cut for chemical analysis. The samples were cut at 45° to the outer diameter surface to accommodate a 0.5 inch diameter analytical spot size.

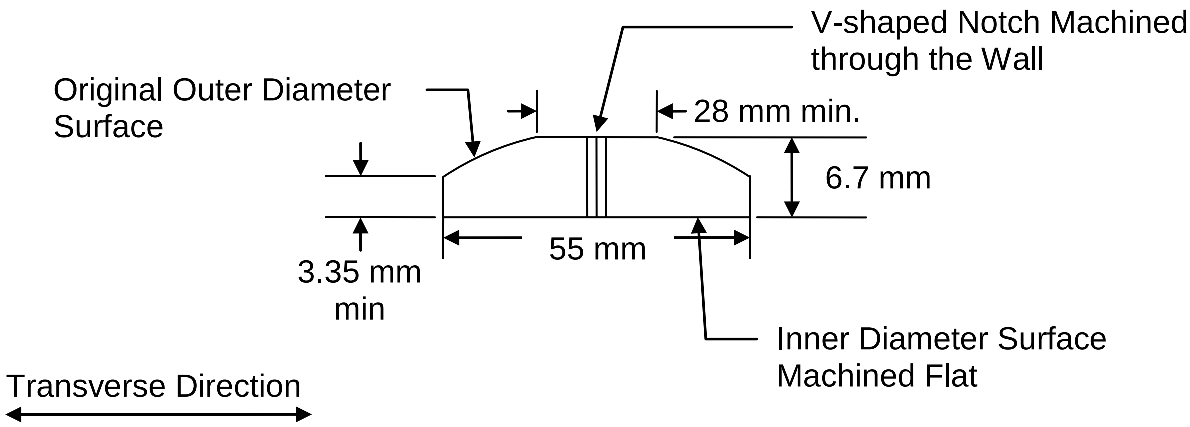
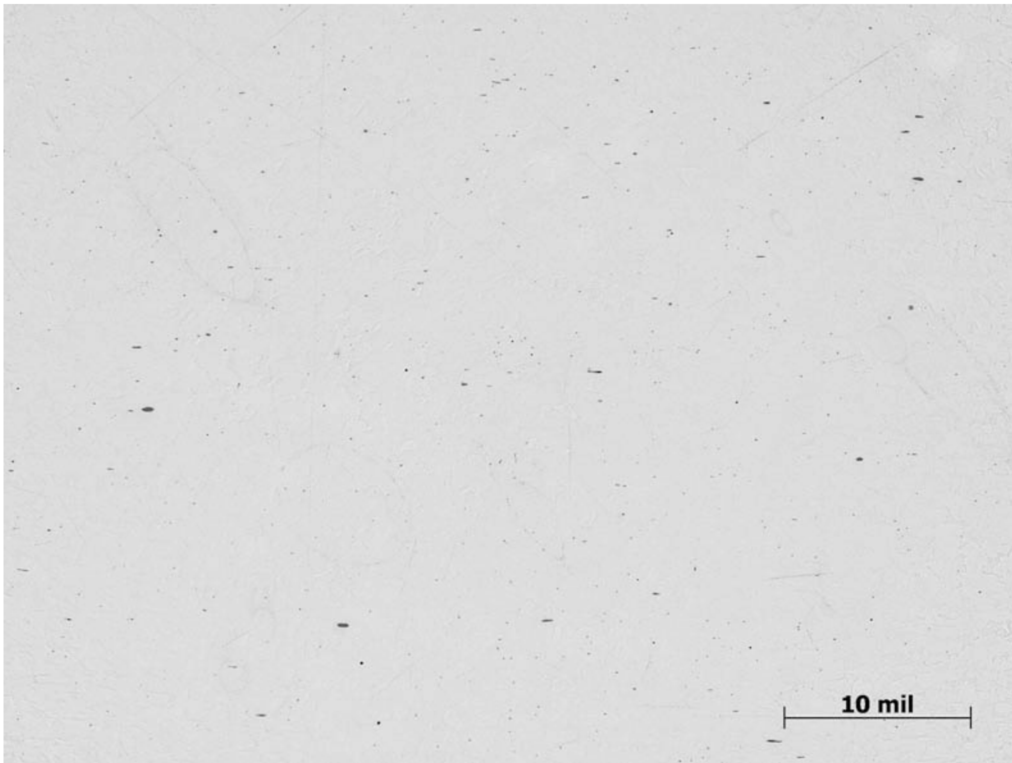
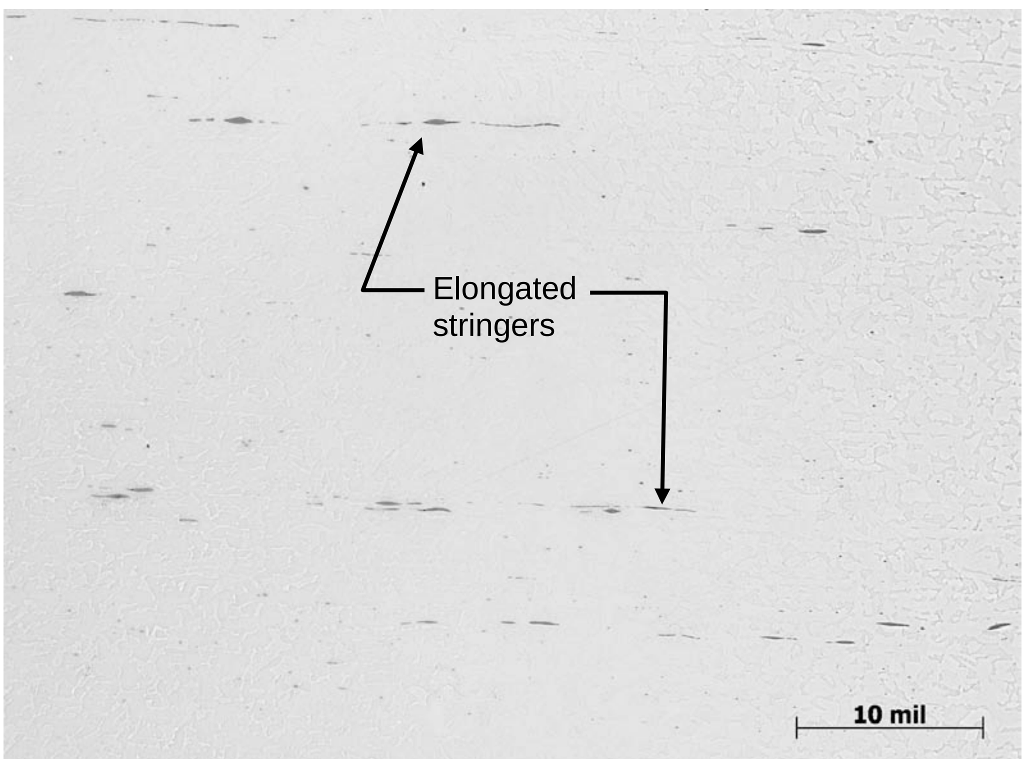



**Figure 3**: Schematic of Charpy impact test specimens taken from each piece of pipe. The longitudinal axis of the pipe runs in and out of the page.




a)




b)

**Figure 4**: Metallographic cross sections of pup 1; a) longitudinal cross section; b) transverse cross section.

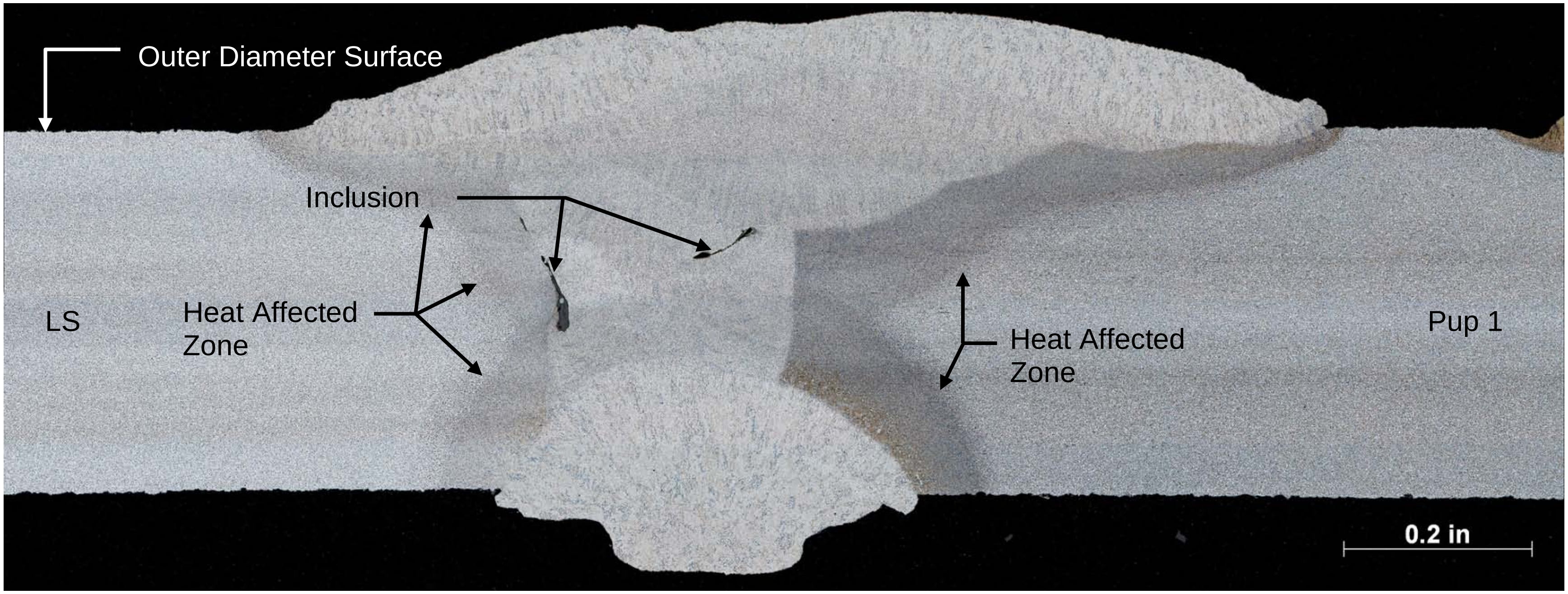



**Figure 5**: Etched metallographic cross section of girth weld C1 joining the long joint south of pup 1 and pup 1.

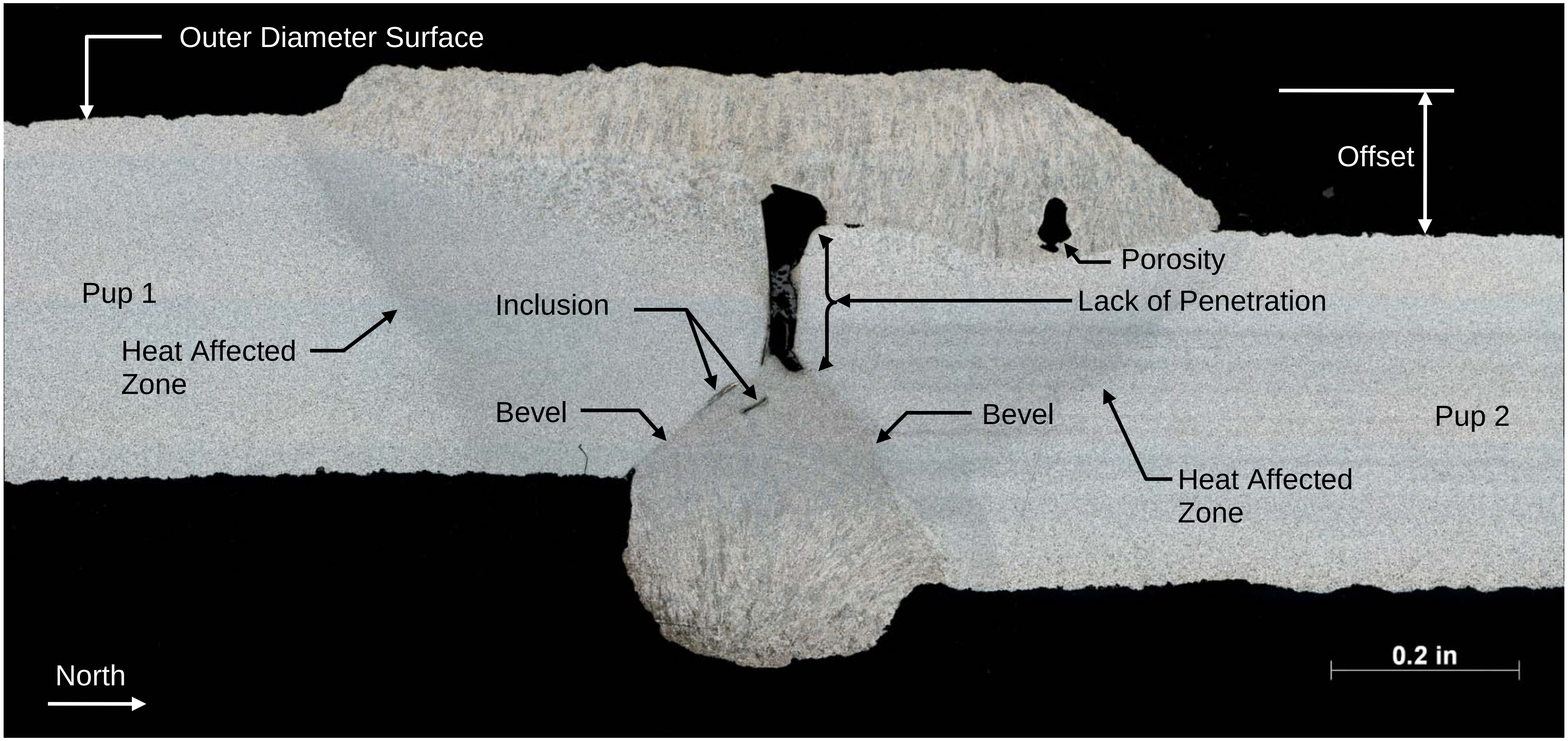



**Figure 6**: Etched metallographic cross section of girth weld C2 joining pup 1 and pup 2.

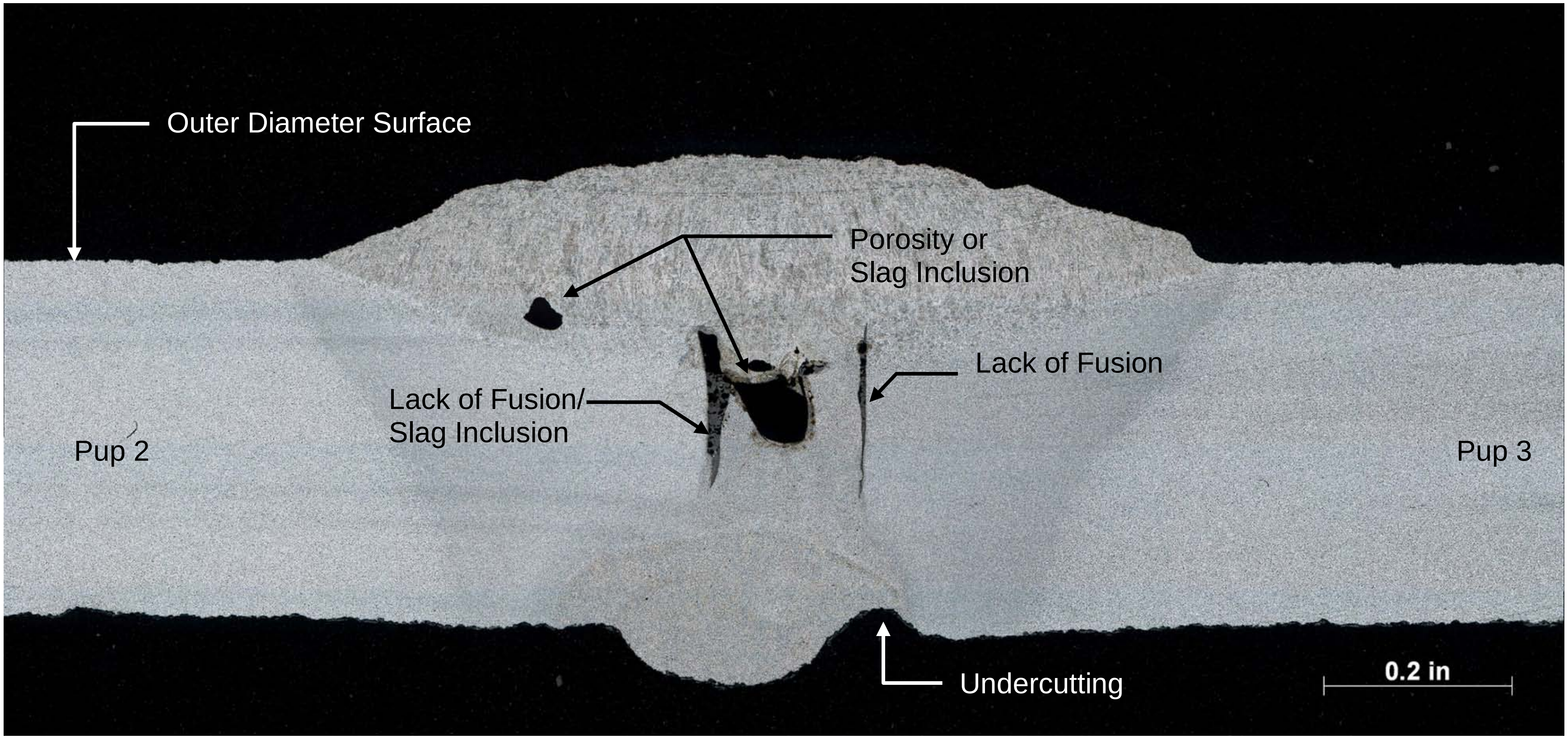



**Figure 7**: Etched metallographic cross section of girth weld C3 joining pup 2 and pup 3. Note some staining artifacts around some of the pores.

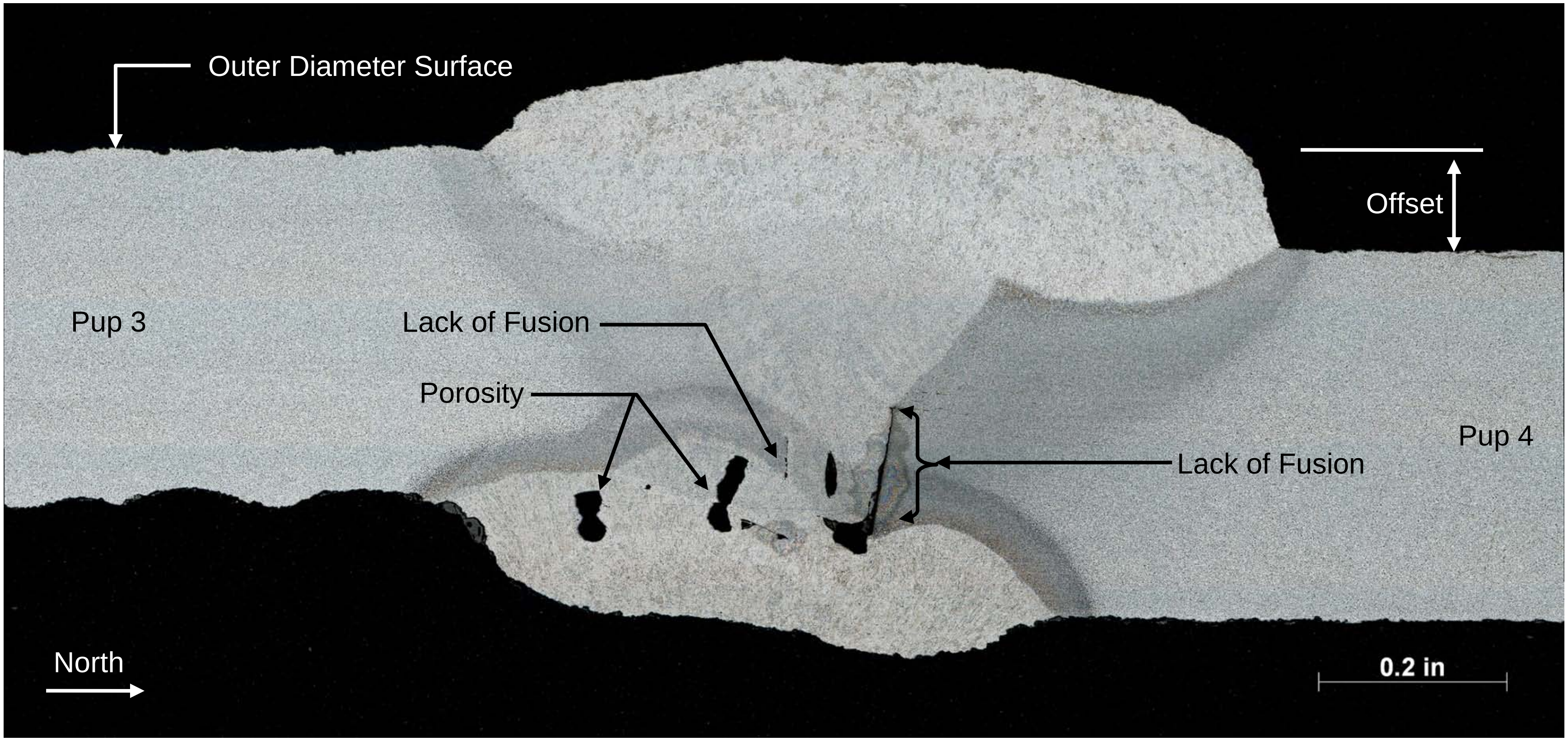



**Figure 8**: Etched metallographic cross section of girth weld C4 joining pup 3 and pup 4. Note some staining artifacts around some of the pores.

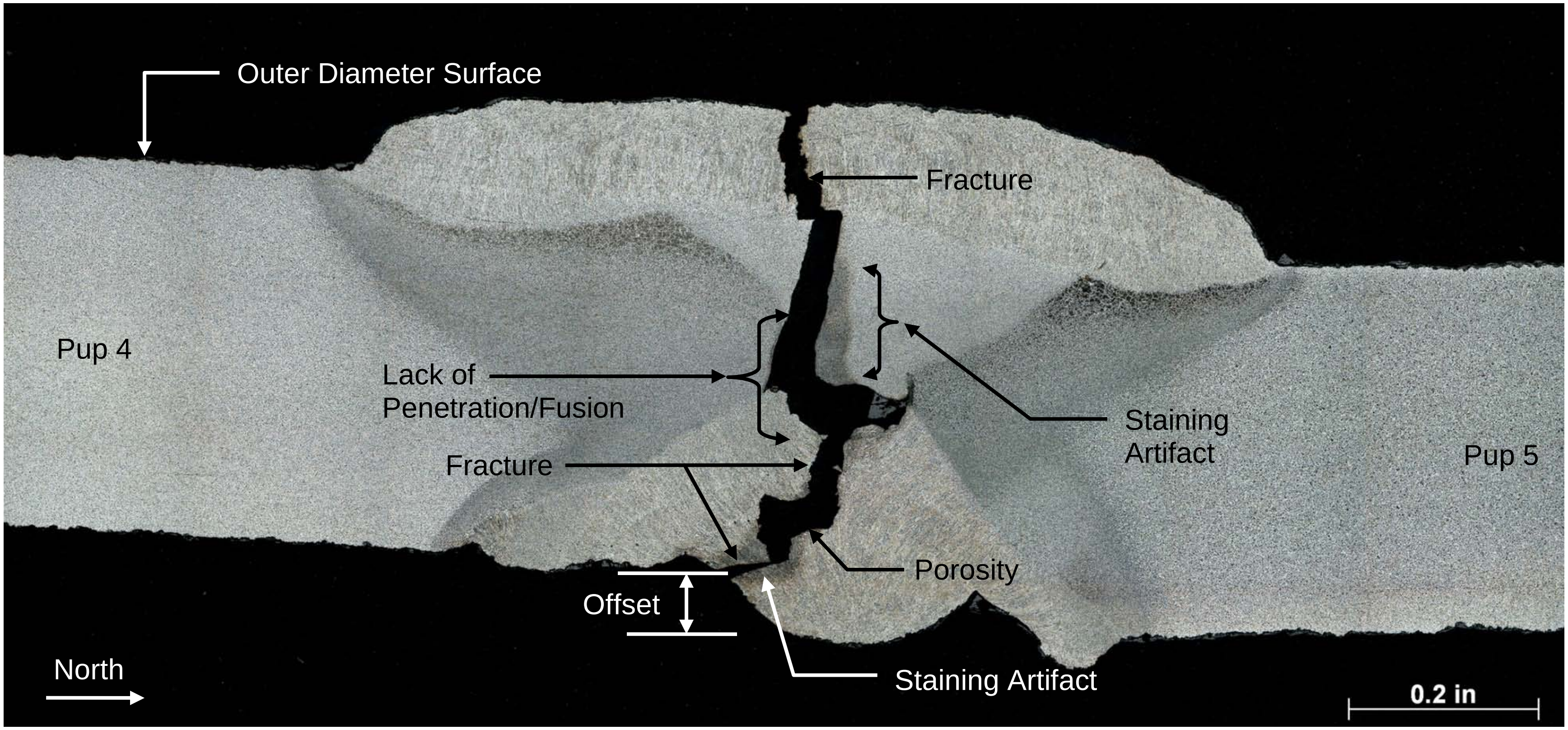



**Figure 9**: Etched metallographic cross section of girth weld C5 joining pup 4 and pup 5. Note some staining artifacts are present.

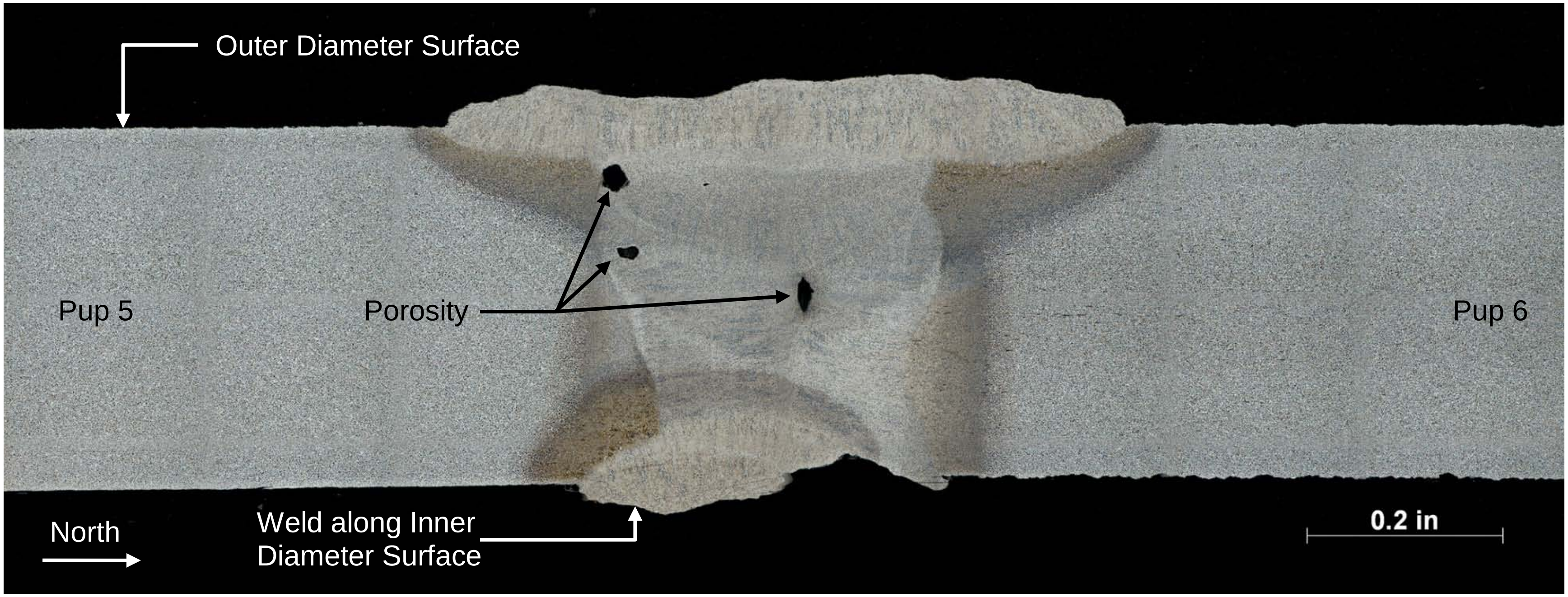



**Figure 10**: Etched metallographic cross section of girth weld C6 joining pup 5 and pup 6.

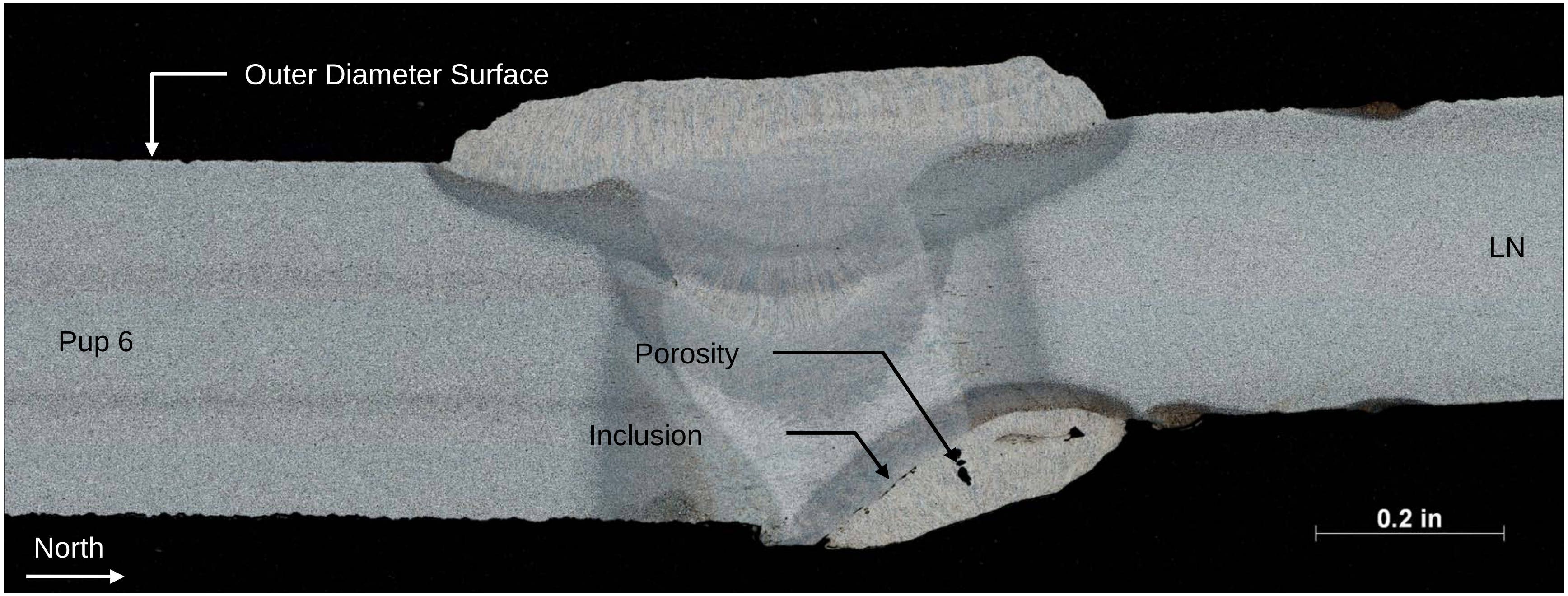



**Figure 11**: Etched metallographic cross section of girth weld C7 joining pup 6 and the long joint north of pup 6 (LN).

## APPENDIX A: MECHANICAL TESTING DATA

**Table A1**: Yield strength data using the 0.5% extension under load method for each tensile test specimen.

| Source | Test 1, ksi | Test 2, ksi | Test 3, ksi | Test 4, ksi | Test 5, ksi |
|---|---|---|---|---|---|
| LS | 56.0 | 57.0 | 57.0 | 57.5 | 57.5 |
| P1 | 36.9 | 36.3 | 36.8 | 36.6 | 36.3 |
| P2 | 32.1 | 32.0 | 31.9 | 32.0 | 32.1 |
| P3 | 35.3 | 34.9 | 34.1 | 34.9 | 35.3 |
| P4 | 47.7 | 49.1 | 47.9 | 48.3 | 48.4 |
| P5 | 38.9 | 38.4 | 38.6 | 38.6 | 38.2 |
| P6 | 48.5 | 51.5 | 50.5 | 50.0 | 52.0 |
| LN | 54.0 | 54.5 | 53.5 | 54.0 | 54.0 |

**Table A2**: Tensile Strength data for each tensile test specimen.

| Source | Test 1, ksi | Test 2, ksi | Test 3, ksi | Test 4, ksi | Test 5, ksi |
|---|---|---|---|---|---|
| LS | 83.5 | 83.0 | 83.0 | 83.0 | 83.5 |
| P1 | 63.5 | 63.5 | 64.0 | 63.5 | 63.5 |
| P2 | 52.0 | 52.0 | 52.0 | 52.0 | 52.0 |
| P3 | 60.5 | 60.5 | 60.0 | 60.0 | 60.5 |
| P4 | 79.0 | 79.0 | 79.0 | 79.0 | 79.0 |
| P5 | 72.0 | 72.0 | 72.0 | 71.5 | 71.5 |
| P6 | 78.5 | 78.5 | 79.0 | 79.0 | 78.5 |
| LN | 76.5 | 77.0 | 77.0 | 77.0 | 77.0 |

**Table A3**: Total elongation for each tensile test specimen.

| Source | Elongation, % in 2 inch | Elongation, % in 2 inch | Elongation, % in 2 inch | Elongation, % in 2 inch | Elongation, % in 2 inch |
|---|---|---|---|---|---|
| LS | 30 | 31 | 30 | 29 | 30 |
| P1 | 39 | 39 | 40 | 39 | 40 |
| P2 | 49 | 48 | 48 | 50 | 49 |
| P3 | 42 | 43 | 43 | 43 | 43 |
| P4 | 33 | 34 | 34 | 34 | 35 |
| P5 | 34 | 36 | 36 | 37 | 36 |
| P6 | 31 | 31 | 30 | 30 | 32 |
| LN | 31 | 31 | 30 | 30 | 30 |

**Table A4**: Yield strength data using the 0.2% strain offset method for each tensile test specimen.

| Source | Test 1, ksi | Test 2, ksi | Test 3, ksi | Test 4, ksi | Test 5, ksi |
|---|---|---|---|---|---|
| LS | 56.0 | 56.5 | 56.0 | 56.5 | 56.5 |
| P1 | 36.0 | 34.9 | 35.2 | 35.1 | 34.9 |
| P2 | 31.1 | 31.0 | 31.4 | 30.8 | 31.3 |
| P3 | 33.8 | 34.1 | 32.8 | 33.7 | 33.5 |
| P4 | 48.3 | 49.0 | 48.7 | 48.9 | 46.7 |
| P5 | 37.2 | 37.5 | 37.8 | 37.3 | 37.1 |
| P6 | 49.9 | 52.0 | 52.0 | 51.5 | 52.5 |
| LN | 51.5 | 51.5 | 50.5 | 51.5 | 52.5 |

**Table A5**: Impact toughness values for each Charpy test specimen.

| Source | Test 1, ft-lbs | Test 2, ft-lbs | Test 3, ft-lbs | Test 4, ft-lbs | Test 5, ft-lbs | Test 6, ft-lbs |
|---|---|---|---|---|---|---|
| LS | 10.0 | 11.0 | 10.0 | 10.0 | 11.0 | 10.0 |
| P1 | 9.0 | 6.0 | 7.0 | 6.0 | 6.0 | 8.0 |
| P2 | 76.0 | 25.0 | 99.0 | 52.0 | 27.0 | 18.0 |
| P3 | 8.0 | 8.0 | 8.0 | 9.0 | 9.0 | 8.0 |
| P4 | 13.0 | 10.0 | 12.0 | 11.0 | 11.0 | 14.0 |
| P5 | 14.0 | 7.0 | 7.0 | 6.0 | 7.0 | 9.0 |
| P6 | 10.0 | 11.8 | 8.0 | 8.0 | 10.0 | 10.0 |
| LN | 16.0 | 14.0 | 15.0 | 11.0 | 11.0 | 9.0 |

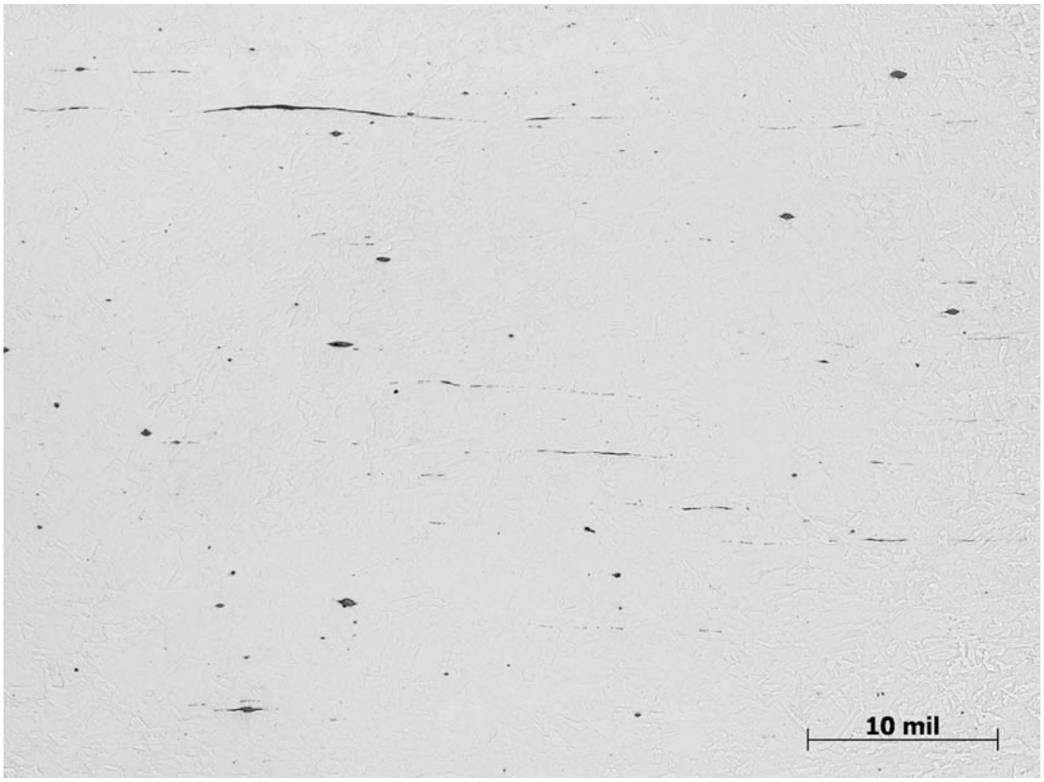
**Table A6**: Percent shear values for each Charpy test specimen.

| Source | % Shear | % Shear | % Shear | % Shear | % Shear | % Shear |
|---|---|---|---|---|---|---|
| LS | 0 | 0 | 0 | 0 | 0 | 0 |
| P1 | 0 | 0 | 0 | 0 | 0 | 0 |
| P2 | 80 | 30 | 100 | 70 | 30 | 30 |
| P3 | 0 | 0 | 0 | 0 | 0 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 | 0 |
| P5 | 0 | 0 | 0 | 0 | 0 | 0 |
| P6 | 0 | 0 | 0 | 0 | 0 | 0 |
| LN | 50 | 50 | 50 | 40 | 30 | 20 |

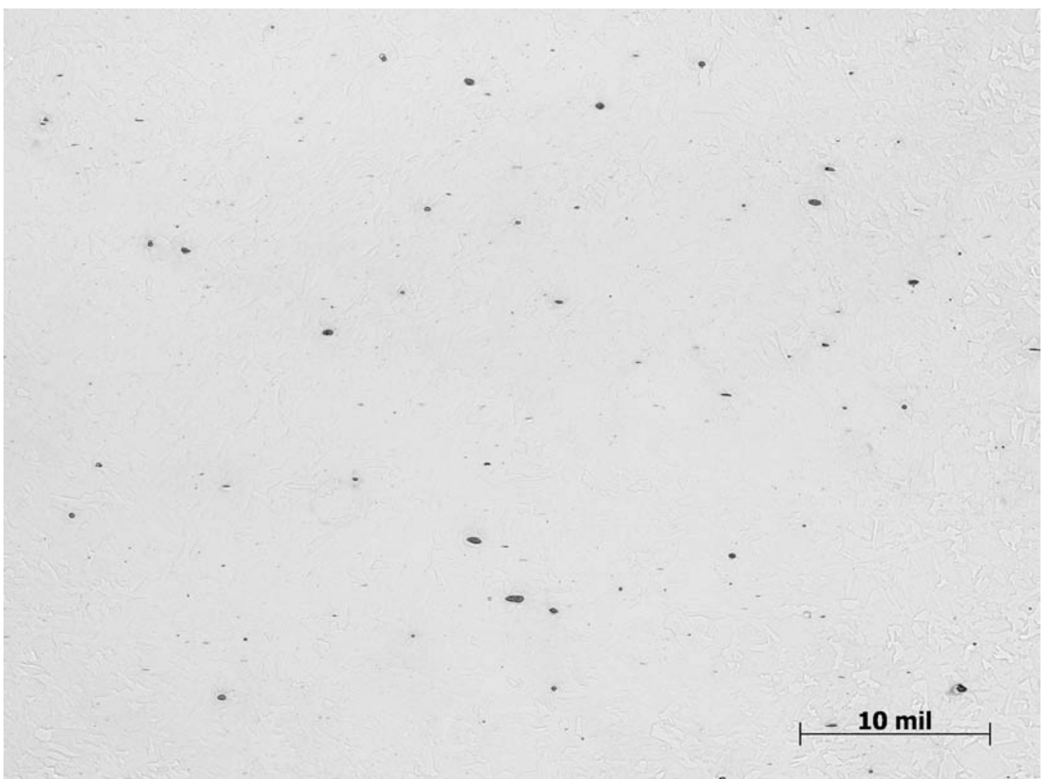
**Table A7**: Lateral expansion values for each Charpy test specimen.

| Source | Lat. Exp., mils | Lat. Exp., mils | Lat. Exp., mils | Lat. Exp., mils | Lat. Exp., mils | Lat. Exp., mils |
|---|---|---|---|---|---|---|
| LS | 9.0 | 12.0 | 9.0 | 10.0 | 10.0 | 10.0 |
| P1 | 11.0 | 5.0 | 9.0 | 6.0 | 5.0 | 10.0 |
| P2 | 76.0 | 35.0 | 61.0 | 63.0 | 38.0 | 27.0 |
| P3 | 9.0 | 10.0 | 9.0 | 9.0 | 11.0 | 7.0 |
| P4 | 15.0 | 11.0 | 13.0 | 12.0 | 13.0 | 16.0 |
| P5 | 15.0 | 7.0 | 5.0 | 6.0 | 6.0 | 11.0 |
| P6 | 12.0 | 12.0 | 8.0 | 8.0 | 10.0 | 11.0 |
| LN | 22.0 | 19.0 | 17.0 | 11.0 | 13.0 | 13.5 |

# APPENDIX B: LONGITUDINAL AND TRANSVERSE MICROGRAPHS OF POLISHED CROSS SECTIONS




a)




b)

**Figure B1**: Metallographic cross sections of the long joint south of pup 1 parent metal; a) Elongated stringers in longitudinal direction; b) no elongated stringers in transverse direction.

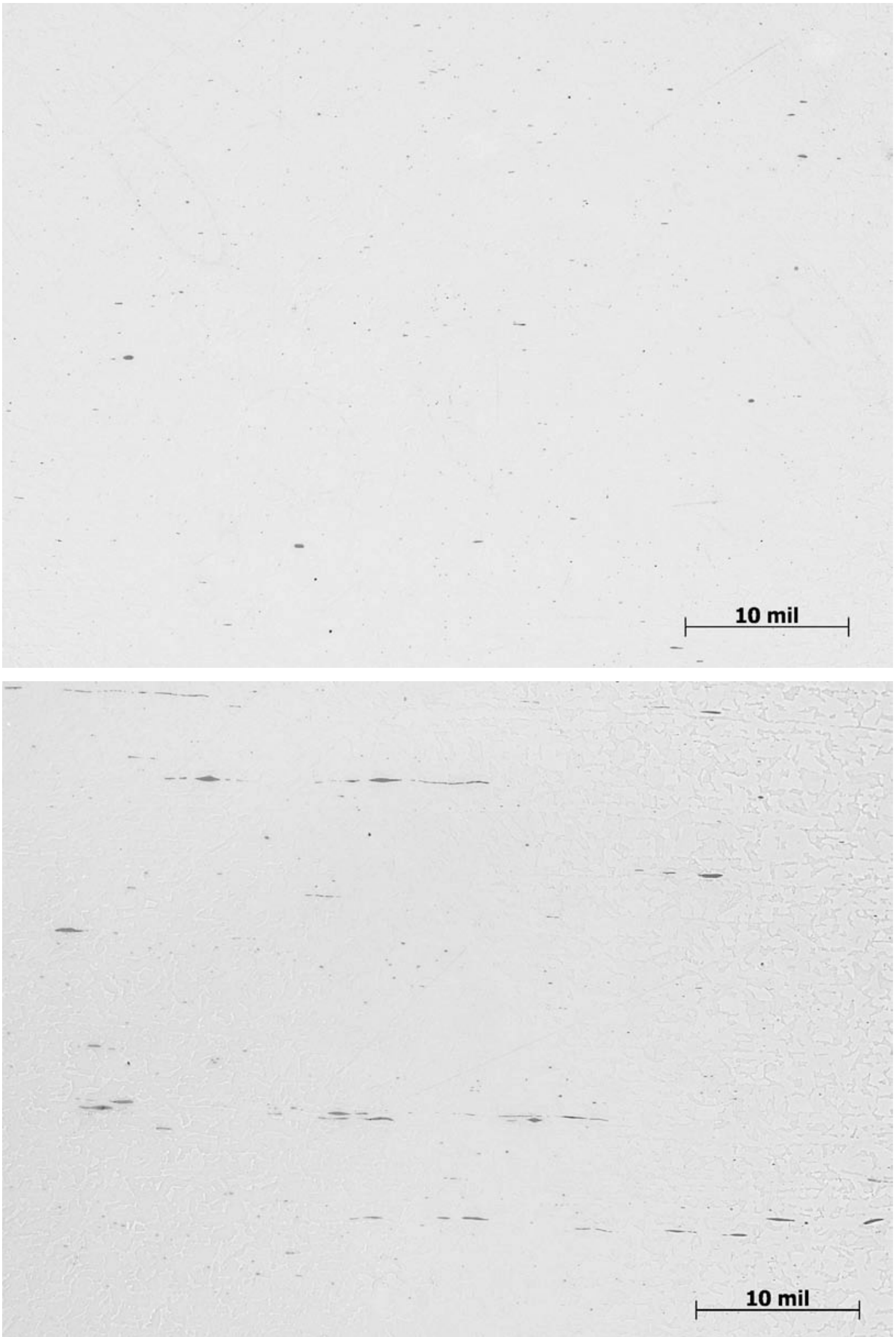



**Figure B2**: Metallographic cross sections of pup 1 parent metal; a) no elongated stringers in longitudinal direction; b) elongated stringers in transverse direction.

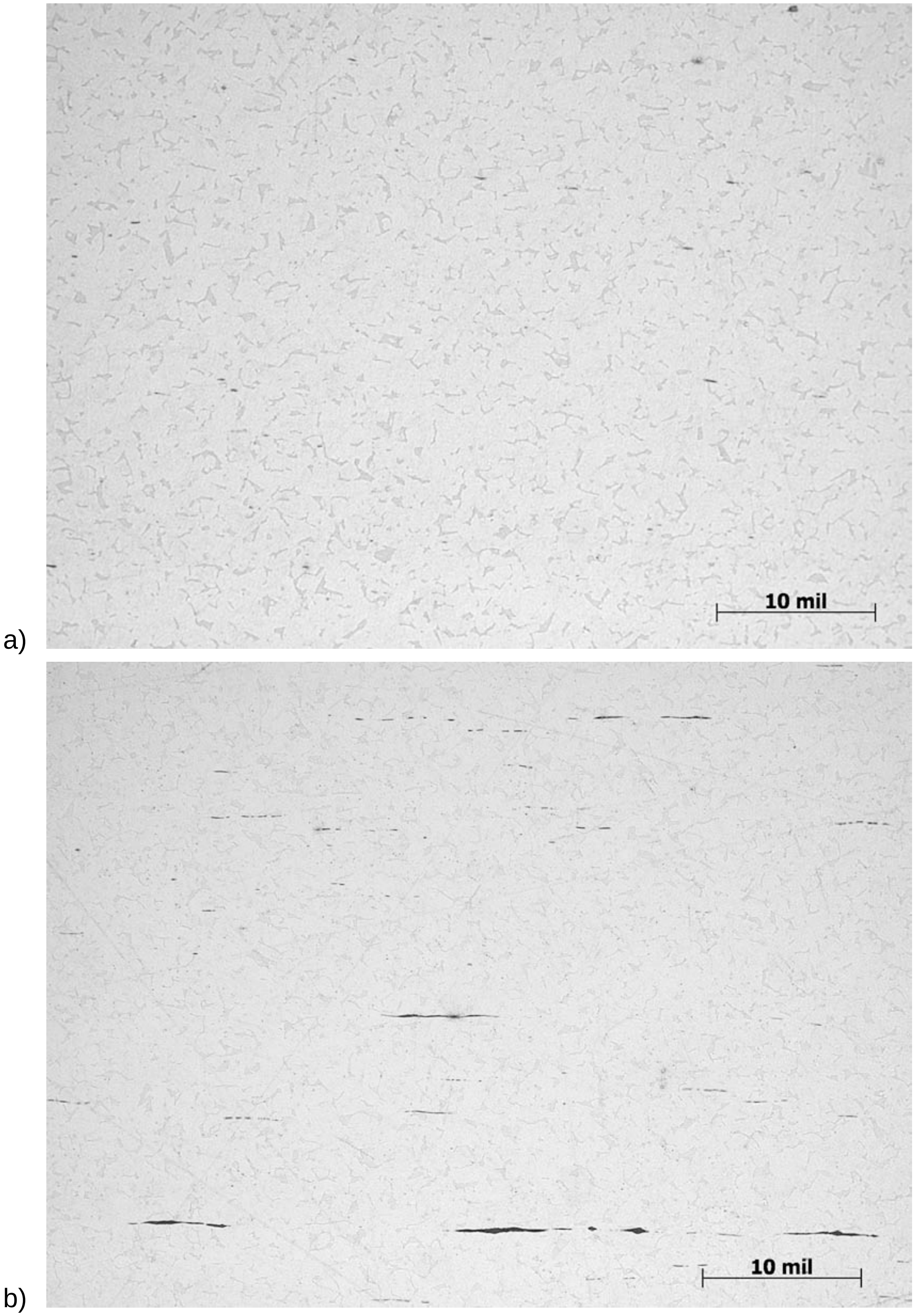



**Figure B3**: Metallographic cross sections of pup 2 parent metal; a) no elongated stringers in longitudinal direction; b) elongated stringers in transverse direction.

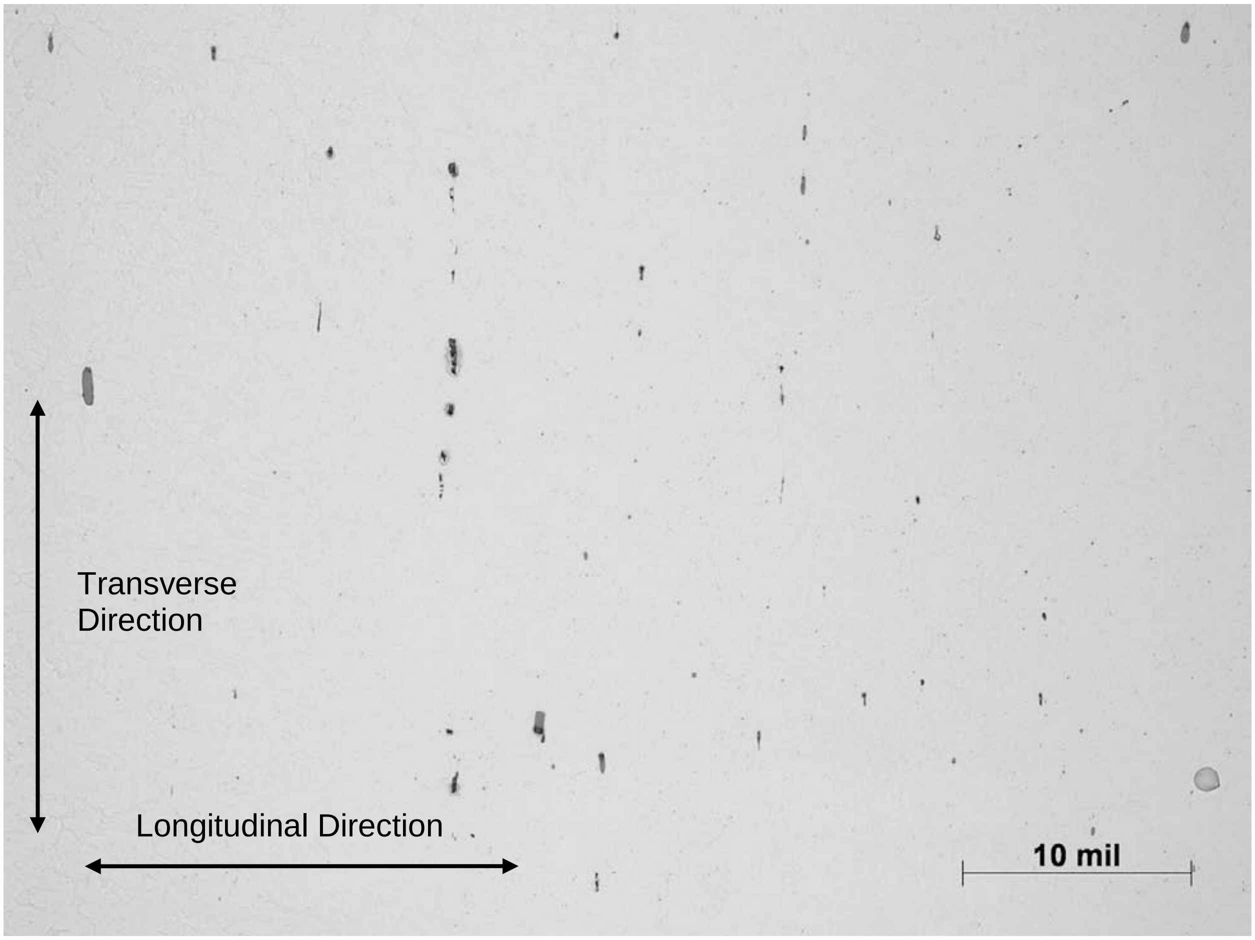



**Figure B4**: Radial cross section of pup 3 showing inclusion elongation in the transverse direction. Longitudinal and transverse cross sections were inconclusive as to the primary direction of inclusion elongation.

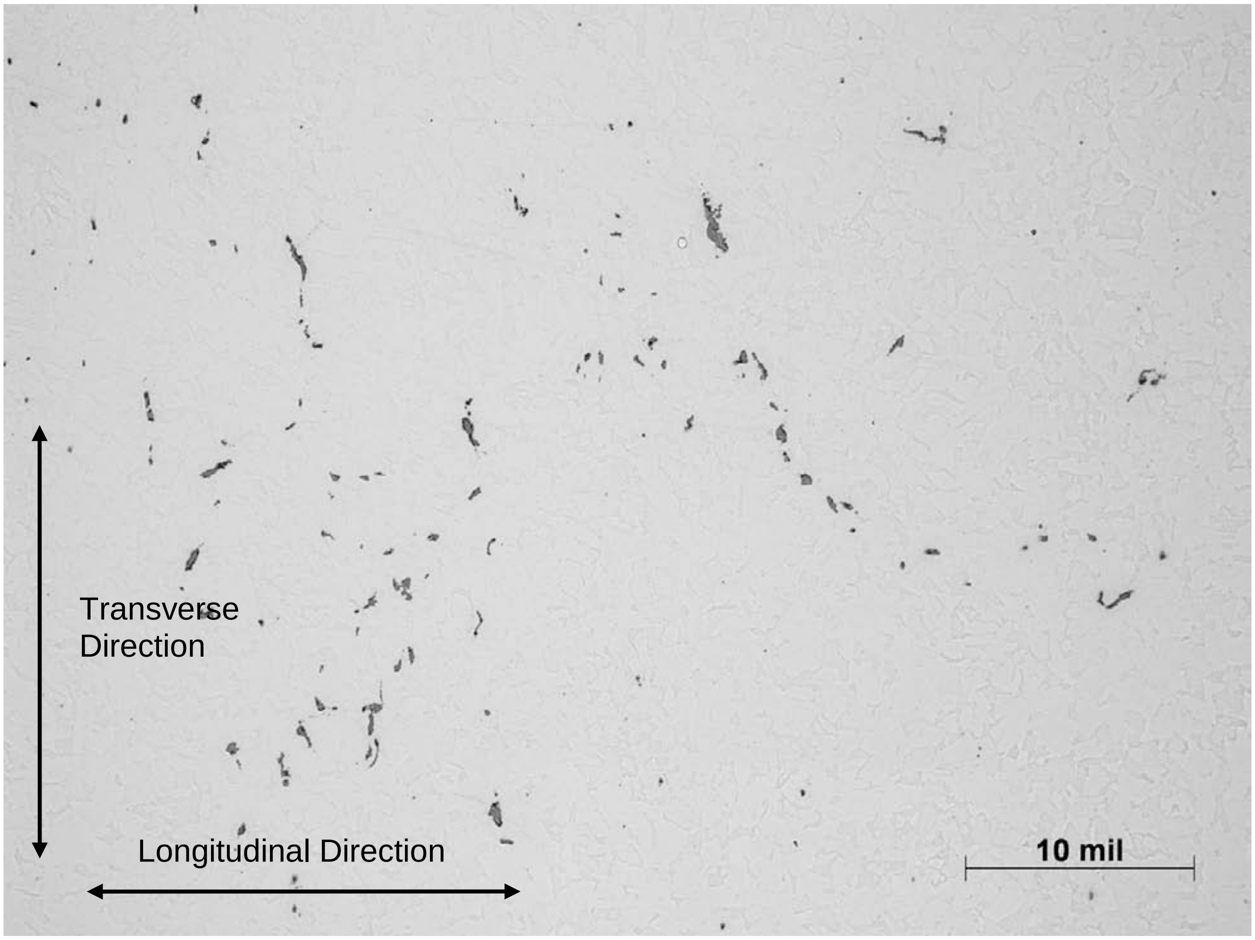



**Figure B5**: Radial cross section of pup 4 showing undetermined inclusion elongation orientation. Longitudinal and transverse cross sections were undetermined as well.

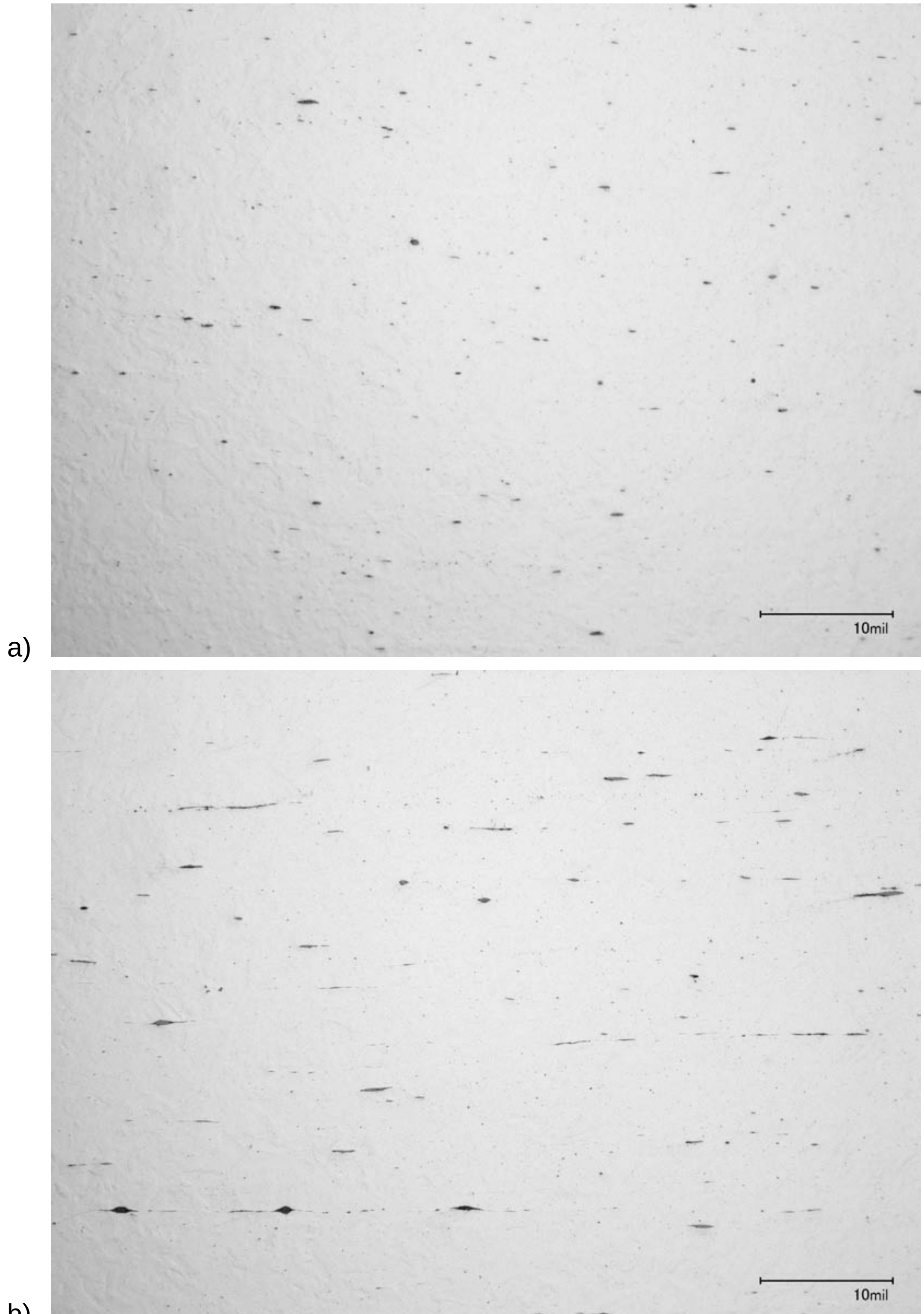
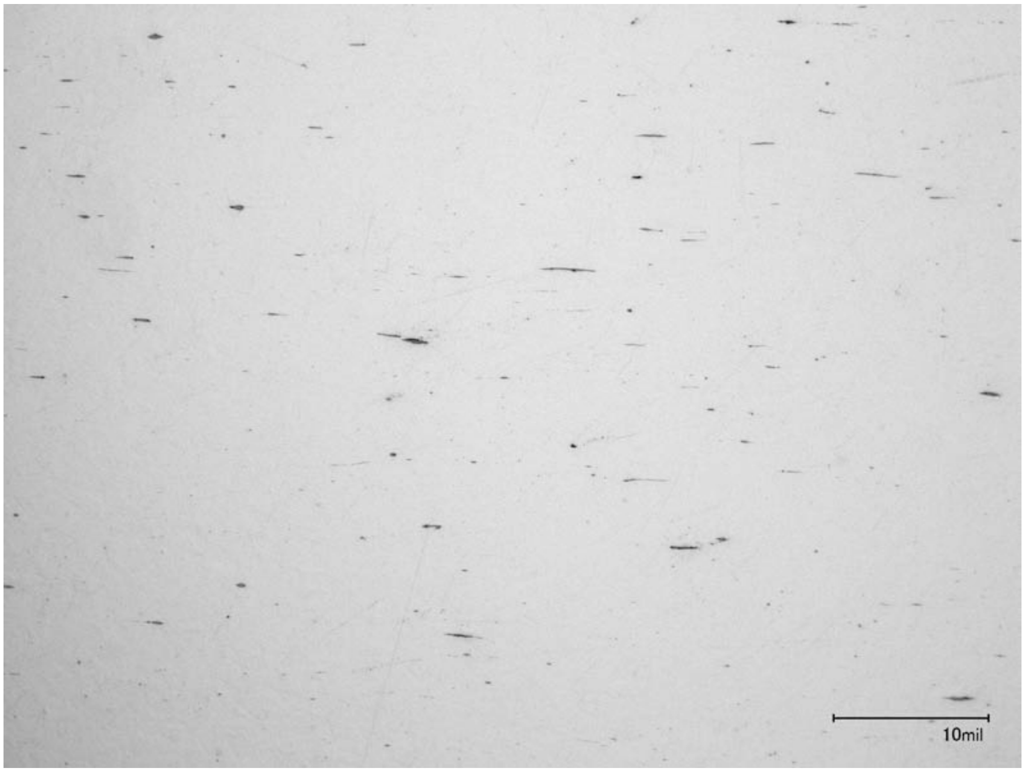
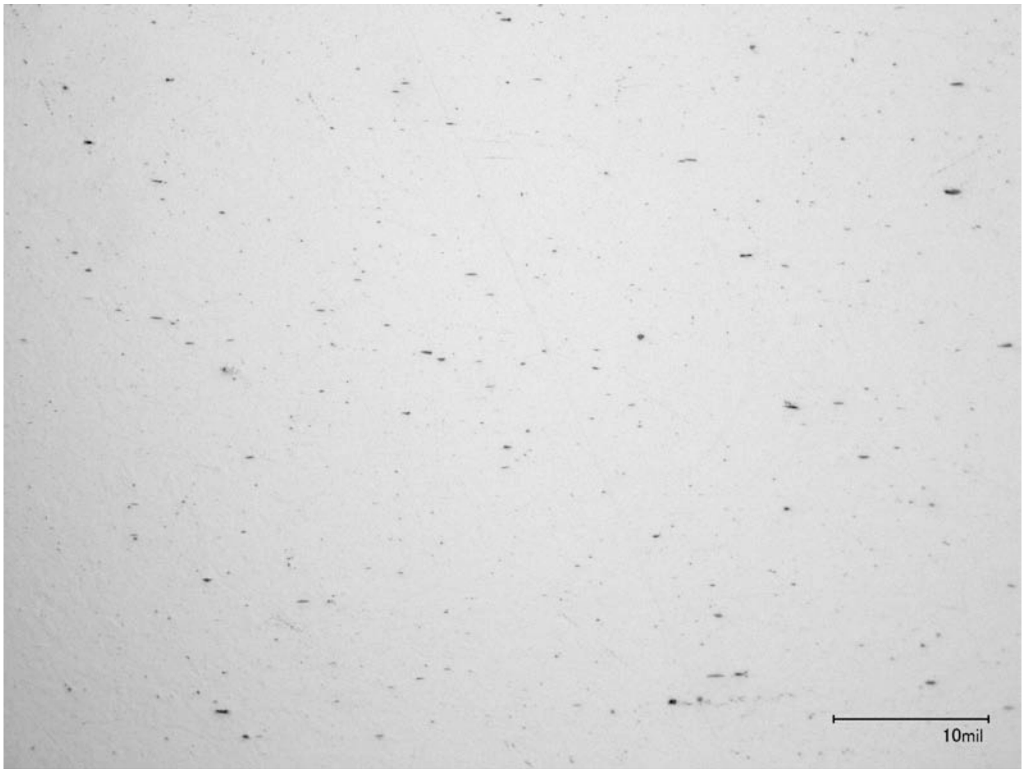



**Figure B6**: Metallographic cross sections of pup 5 parent metal; a) no elongated stringers in longitudinal direction; b) elongated stringers in transverse direction.

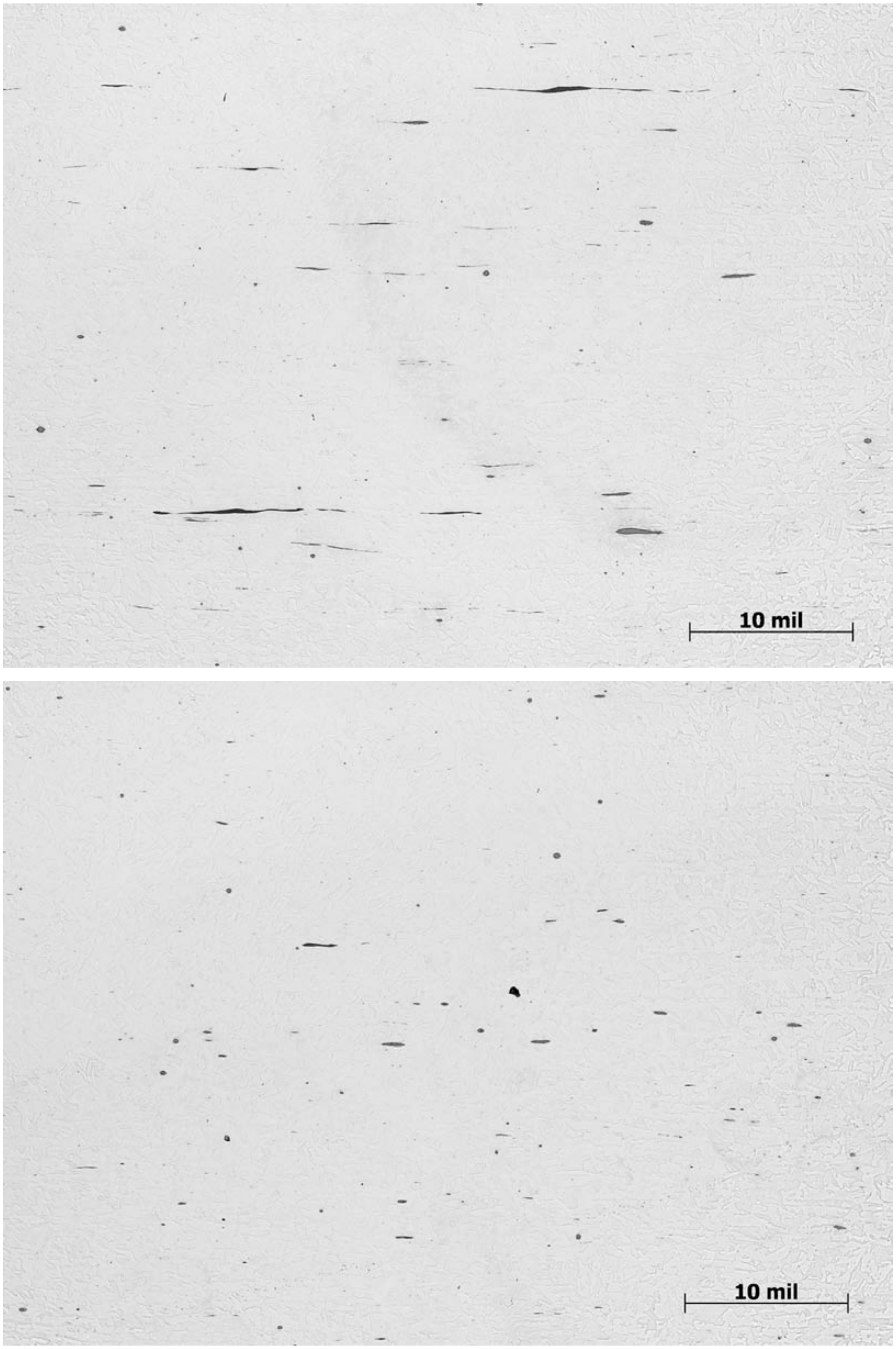



a)




b)

**Figure B7**: Metallographic cross sections of pup 6 parent metal; a) elongated stringers in longitudinal direction; b) no elongated stringers in transverse direction.




a)

b)

**Figure B8**: Metallographic cross sections of the long joint north of pup 6 parent metal; a) elongated stringers in longitudinal direction; b) no elongated stringers in transverse direction.